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Nutrient transport, shear strength and hydraulic characteristics of topsoils amended with mulch, compost and biosolids

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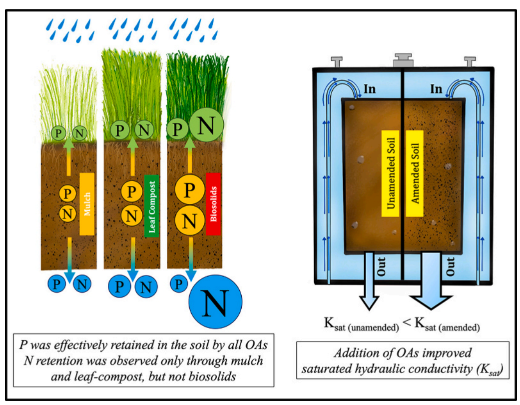
HIGHLIGHTS

- Different types of OAs improved shear and soil hydraulic properties.
- Treated biosolids addition improved P retention in soils, while it incurred N losses.
- Mulch caused lower outputs of N and P in the leachate.
- P was retained by leaf-compost and N leaching reduced over time.
- Across soil-water-plant nexus, leaf compost was the preferred OA.

GRAPHICAL ABSTRACT



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ABSTRACT

Anthropogenic disturbance of soils can disrupt soil structure, diminish fertility, alter soil chemical properties, and cause erosion. Current remediation practices involve amending degraded urban topsoils lacking in organic matter and nutrition with organic amendments (OA) to enhance vegetative growth. However, the impact of OAs on water quality and structural properties at rates that meet common topsoil organic matter specifications need to be studied and understood. This study tested three commonly available OAs: shredded wood mulch, leaf-based compost, and class A Exceptional Quality stabilized sewage sludge (or biosolids) for nutrient (nitrogen and phosphorus) water quality, soil shear strength, and hydraulic properties, through two greenhouse tub studies. Findings showed that nitrogen losses to leachate were greater in the biosolids amended topsoils compared to leaf-compost, mulch amended topsoils, and control treatments. Steady-state mean total nitrogen (N) concentrations from biosolids treatment exceeded typical highway stormwater concentrations by at least 25 times. Soil total N content combined with the carbon:nitrogen ratio were identified to be the governing properties of N leaching in soils. Study soils, irrespective of the type of amendment, reduced the applied (tap) water phosphorus (P)

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concentration of ~0.3 mg-P/L throughout the experiment. Contrary to the effects on N leaching, P was successfully retained by the biosolids amendment, due to the presence of greater active iron contents. A breakthrough mechanism for P was observed in leaf compost amended soil, where the effluent concentrations of P continued to increase with each rainfall application, possibly due to an saturation of soil adsorption sites. The addition of OAs also improved the strength and hydraulic properties of soils. The effective interlocking mechanisms between the soil and OA surfaces could provide soil its required strength and stability, particularly on slopes. OAs also improved soil fertility to promote turf growth. Presence of vegetative root zones can further reinforce the soil and control erosion.

1. Introduction

A direct effect of urbanization and human activity is evident in the declining physical and chemical properties of urban soils, particularly those along roads and highways. Grading, compaction, and other disturbances associated with roadside construction activities can damage the soil structural functionality and downgrade soil fertility status (Gray and Sotir, 1996). These urban soils are also often low in organic matter and both macro- and micronutrients, structurally unstable, and inhospitable for vegetation (Heyman et al., 2019). Bare topsoil or subsoil predisposes it to erosion during rain events, and subsequent discharges of heavy loads of sediment and pollutants (e.g., nutrients and trace metals) into downstream waterbodies (such as the Chesapeake Bay) via stormwater runoff (Zuazo and Pleguezuelo, 2009). Nutrient-rich waters enhance algae growth, resulting in eutrophication and hypoxia (US EPA, 2015). Plants act as natural filters for pollutants, improve water quality, reduce runoff volume, intercept rainfall, stabilize slopes, and improve carbon sequestration, all of which together makes vegetation a cornerstone for preventing soil erosion (Bloorchian et al., 2016; Muerdter et al., 2018; Chen et al., 2021). Therefore, to improve vegetation establishment alongside roads, many jurisdictions are opting for more sustainable and less expensive soil treatments.

According to the U.S. EPA, in 2018, 2.2 kg/day of Municipal Solid Waste was generated per capita (US EPA, 2022). Approximately 50 % of this waste was either recycled, composted, combusted with energy recovery, or utilized for other food management techniques (US EPA, 2022). This suggests that there is a recoverable fraction of available compost and other organic materials that could be used in lieu of expensive and potentially unsuitable commercial fertilizers for promoting vegetative growth on marginal soils. Since the early 2000s, compost materials have been sought-after by many U.S. state Departments of Transportation (DOTs) for their potential to enhance soil quality. Associated research continues to show beneficial effects when they are mixed with low-grade urban soils due to the addition of organic matter (OM) and nutrients to the soil, which improves soil fertility and thereby prevents erosion alongside roads and highways (Batjiaka, 2016; Kranz et al., 2020).

Selecting (amended) soils with stable structure, increased soil porosity, decreased bulk density, and increased water retention capacity for highway or road slopes, particularly those with steep embankments, is vital for alleviating soil erosion and stormwater drainage/quality issues, and promoting vegetative growth. Although the physical and chemical characteristics of urban soils have been studied extensively, many other important variables will control stability, erosion, and vegetative growth. Knowledge of shear properties can help evaluate the strength of soils, which is indispensable in the context of sloughing or shallow infinite failures (Singh and Thompson, 2016; Zheng et al., 2020). Only a few works have focused on soil geotechnical properties when mixed with organic materials such as compost and biosolids (Benson and Othman, 1993; Puppala et al., 2007; Duzgun et al., 2021). This highlights the need for further research investigating roadside topsoils enhanced with such amendments.

Excess application of OAs to soil can have adverse effects when it comes to nutrient leaching. For example, biosolids (EPA Class A Exceptional Quality Biosolids) are one of the most abundantly produced and available organic materials, yet they typically contain high levels of leachable macro nutrients (N and P) (Paramashivam et al., 2016; Silveira et al., 2019) and possibly toxic metals (Cd, Cu, Pb, Zn) (Torri and Corrêa, 2012; Marguí et al., 2016). Puppala et al. (2011) assessed runoff leachate quality from topsoil amended with dairy-manure compost and biosolids and found that total phosphorus and total Kjeldahl nitrogen (TKN = organic N + ammonia; a standard (waste) water test; EPA Method 351.2) were high in the amended topsoils compared to the control soil. Similarly, Owen et al. (2021) noted greater P-losses from both green-waste (e.g., leaf compost) and biosolids composts compared to the unamended topsoil. Previous studies also indicated that leaching characteristics of soils depend on the compost source material (Hansen et al., 2012; Owen et al., 2021). This loss of N and P to surface waters can impair downstream waterbodies and exacerbate eutrophication. Excess soil nutrients from organic amendments, especially nitrogen species, have the potential to infiltrate through the soil profile and affect groundwater quality (a possible potable water issue). Caution should therefore be exercised, and an instructive investigation should be carried out to understand the leaching potential of organic amendments when mixed into topsoils.

Previous studies have typically focused on either the geotechnical properties or nutrient leaching aspects of soils amended with organic materials. In this research, the primary goal is to understand the effects of three commonly utilized organic amendments: shredded wood mulch, leaf-based compost, and biosolids, on soil geotechnical properties and nutrient water quality, when these amendments are applied in amounts that regulate soil organic matter (MDOT SHA, 2017). In addition, another aspect of this research sheds light on the influence of the same OAs on turf establishment (Morash, 2024). Collectively, these insights will be useful in evaluating the performance of traditionally used organic amendments in the nexus of soil-water-vegetation and recommend their use for roadside projects.

Specific objectives of this study were to (1) compare soils independently amended with mulch, compost, and biosolids for nutrient contents in leached water and geotechnical properties (shear and hydraulic), (2) identify critical soil parameters that govern nutrient leaching dynamics from amended soils, and (3) evaluate varied soils obtained directly from topsoil suppliers which are incorporated with the above OAs to assess environmentally relevant soils.

2. Materials and methods

2.1. Greenhouse tub studies

Two macrocosm 'tub' studies (principal and supportive), designated as PTS and STS, were conducted at the University of Maryland Research Greenhouse Complex to monitor vegetation growth and water quality of unamended and amended topsoils. This work focuses on the water quality and geotechnical properties of the topsoils used in the tub studies; the effect of these characteristics on the vegetative growth, nutrient uptake and overall suitability are provided in Morash (2024).

2.1.1. Organic amendments and tub study soils

2.1.1.1. Organic amendments. In July 2020, our research team

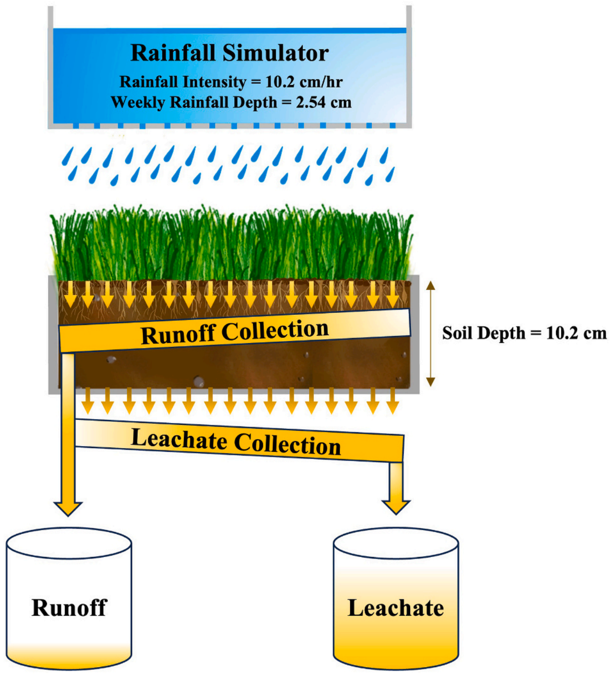


Fig. 1. Schematic diagram of the greenhouse tub experiment.

interviewed topsoil blend producers across Maryland (Morash, 2024). Among the soil amendments that meet the Maryland Department of Transportation State Highway Administration (MDOT SHA) furnished topsoil requirements for OM content of 4–8 % (MDOT SHA, 2017), the top two preferred amendments were leaf or yard waste-based compost and wood mulch, due to their cost and availability. Given its broad availability in the Maryland/Washington DC area and its verified reputation for improving soil fertility, the tub studies also included Fresh Bloom® (EPA Class A Exceptional Quality Biosolids) as the third amendment of interest. Thus, each study included: Control Unamended Topsoil, Mulch Amended Topsoil, Leaf compost Amended Topsoil, and Biosolids Amended Topsoil.

2.1.1.2. Principal tub study soils. In Morash (2024), the principal tub study (PTS) is referred to as tub study 2 (TS2). To determine the effects of each organic material, the base soil in PTS was kept constant across all the treatments. The unamended base (control) soil (CUT2 at 4.34 % OM) came from a MDOT SHA qualified soil producer. The base soil was then separately amended with finely shredded and aged tree mulch (M; acquired from the same topsoil producer who provided the base soil), composted leaves and grass clippings (L; Leafgro®, Maryland Environmental Services), and biosolids (B; Fresh Bloom®, DC Water), yielding MAT2, LAT2 and BAT2 respectively. After determining the OM contents in the amendments, the required volume of OA to be mixed into the soil for increasing the OM was estimated using regression analysis (OM% vs percent addition (by volume) of each organic material to CUT2). In the end, 3.06 L of mulch, 2.08 L of leaf compost and 3.98 L of biosolids were admixed into the control soil to create the treatments (Morash, 2024). The final OM contents of the PTS soils are 6.86 %, 5.92 %, and 5.64 % for MAT2, LAT2, and BAT2, respectively.

2.1.1.3. Supportive tub study soils. In Morash (2024), the supportive tub study (STS) is designated as tub study 1 (TS1). In each PTS treatment, the same base soil was kept constant. However, in STS, soils were sourced from *different* producers, each with distinct physical and chemical characteristics. This allowed a comparative evaluation of the amendments in the two tub studies – aiming to determine whether the effects of the amendments remained consistent despite varying sources of the soils. The research team sourced CUT1, MAT1 and LAT1 directly from MDOT SHA- qualified topsoil producers. BAT1 however was custom-made by the research team. The soil for BAT1 was obtained from a qualified topsoil producer and biosolids (Fresh Bloom®) was added to raise the OM content of the soil by approximately 1 % to meet the MDOT SHA minimum OM concentration standard (4 %). This article primarily discusses the outcomes obtained from the PTS study, and where applicable, incorporates insights from STS to strengthen the depth of these findings. Additional details related to STS soils and water quality data are included in the supplemental material section.

2.1.2. Tub study setup (design and water collection)

Sixteen transparent plastic tubs (0.51 m × 0.74 m) were designed and constructed to accommodate four topsoil treatments with quadruplicates (Morash, 2024). Fig. S1 displays a constructed tub system on a 4 % inclined (25H:1V engineering slope) wooden frame that enabled the separate collection of surface runoff and leachate and Fig. 1 shows a schematic representation of the experiment. For water to percolate freely, a meshed screen was placed inside the tub, overlain with a permeable green roof *Separation Fabric* (Conservation Technology, Baltimore, MD). Topsoil was spread to a depth of 10.2 cm on top of the fabric in each tub. A standard MDOT SHA turfgrass seed mix (Newsome Seed; Fulton, MD) consisting of two tall fescue cultivars and one Kentucky Bluegrass: *Festuca arundinacea* 'Wichita' (49.39 %), *Festuca arundinacea* 'Leonardo' (45.82 %) and *Poa pratensis* 'Blue Coat' Kentucky Bluegrass (4.96 %) was applied to each tub at a rate of 22.2 g/m^2 (~8.32 g of seed mix per tub). Wheat straw was scattered over the soil after seeding to ensure the simulated rainwater treatments were evenly distributed over the tub soil surface.

A rainfall simulator (Fig. 1 and Fig. S1) was made by drilling 1 mm holes into a 0.51 m × 0.74 m plastic tub. The rainfall simulator produced 2.54 cm rainfall at an intensity of 10.2 cm/h using tap water. A total of 22.9 cm rainfall over 9 weekly events were simulated during PTS, and a total of 20.3 cm rainfall (8 weekly events) during STS. The difference between the rainfall events resulted because STS was completed during summer; the rain events in STS had to be cut short as the grasses started to senesce. PTS was a fall experiment. Therefore, a longer study was conducted as the conditions for the growth of the cool-season grasses were more favorable. For each replicate, tub leachate and runoff were collected in a clean 18.9 L bucket. Upon attaining complete drainage of the leachate and runoff, the volumes of the collected leachate samples were measured in lab-grade plastic graduated cylinders and transferred into clean, acid-washed 1 L HDPE sample bottles.

2.2. Analysis of water quality parameters

Tub study water samples were analyzed in the University of Maryland Environmental Engineering Laboratories. Samples were measured for pH and Electrical Conductivity (EC) within a few hours of collection. Following this, 200 mL of sample was filtered through a 0.22-μm mixed cellulose esters membrane for dissolved nutrient analysis. An aliquot of 100–300 mL of the sample, depending on the turbidity, was filtered for total suspended solids (TSS) (Standard Method 2540D). For nutrient (N and P) analysis, unfiltered (total organic carbon, TOC; total nitrogen, TN; total phosphorus, TP) and filtered (for nitrate, NO_3-N; ammonium, NH_4-N; total dissolved phosphorus, TDP and orthophosphate, PO_4-P) samples were stored at 4 °C without any acidification as the species were measured within 72 h of sample collection. Total Organic Nitrogen (TON) was calculated using Eq. (1), assuming that the nitrite (NO_2-N) fraction was negligible (<0.01 mg-N/L detection limit) in the water samples that were not analyzed for NO_2-N. Particulate (PP) and dissolved organic phosphorus (DOP) species were calculated using the mass balance Eqs. (2) and (3). Table S1 indicates the test method and instrument information of the analyzed water quality parameters.

$$TN = [NH_4 - N] + [NO_3 - N] + [NO_2 - N] + [TON] \quad (1)$$

Table 1
Shear properties of the principal tub study (PTS) soils.

Shear Properties	At optimum water content (w_{opt})				At wet of optimum water content ($w_{opt+3\%}$)			
	CUT2	MAT2	LAT2	BAT2	CUT2	MAT2	LAT2	BAT2
c' (kPa)	6.2	11	6.9	13.8	5.5	9	2.1	6.9
ϕ' (°)	40.4	36.6	38	32.5	34.8	35.2	37	32.8

$$TP = TDP + PP \quad (2)$$

$$TDP = [PO_4 - P] + DOP \quad (3)$$

2.3. Analysis of soil chemical, physical and geotechnical properties

2.3.1. Soil chemical procedures

All soil samples used in the tub studies were tested for the parameters listed in Table S2. Prior to any chemical analysis, soils were oven-dried at 55 °C for 72 h and screened through a 2-mm opening sieve. Table S2 shows soil analyses and related test method information, and Table S3 shows the chemical properties of the soils.

2.3.2. Soil physical characterization

2.3.2.1. Particle size distribution. Soil samples (500 g) were initially wet sieved through a 75 μm (#200) sieve. The retained soil and the fines were oven-dried at 55 °C for 72 h. Soil particles >75 μm were then subjected to dry sieving as described in standard method AASHTO T 88 for particle size distribution. The oven-dried fines (<75 μm) were analyzed using a SALD-2300 laser diffraction particle size analyzer (PSA). The particle size distribution curves were developed using the sieve analysis and PSA data in order to classify the soils per USDA soil classification system (Fig. S2, Table S4).

2.3.2.2. Compaction analysis. Compaction tests were performed using the Standard Proctor Test method (ASTM D698). Calculated dry densities and corresponding moisture contents were plotted, and a curve was fitted passing through these data points to determine the optimum moisture contents (w_{opt}) and the maximum dry densities ($\rho_{d,\ max}$) of the TS soils (Table S5).

2.3.2.3. Direct shear tests. Shear tests were performed per guidelines listed in ASTM D3080. A DigiShear™ Automated Direct Shear System with GeoJac load actuators was used to consolidate and shear samples under specified loading conditions. Prior to sample preparation, the oven-dried soils were screened through a 4.75-mm opening sieve to avoid any interference of larger particles with shear readings. The soil specimens were compacted at optimum water content (w_{opt}) and slightly wetter ($w_{opt+3\%}$) conditions to fit into a shear box of 2.54 cm height and 6.35 cm diameter. Three normal loads were chosen for each specimen: 15 kPa (low), 50 kPa (moderate) and 100 kPa (high). Under these loading conditions, each specimen was consolidated for 24 h until the criteria were met per ASTM D2435 and sheared at a displacement rate of 0.5 mm/min. Shear strength parameters cohesion (c') and friction angle (ϕ') were calculated from the shear stress vs. normal stress plots.

2.3.2.4. Saturated hydraulic conductivity tests. (a) Falling-head tests: Falling head tests were conducted in flexible-wall permeameters (GEOTAC, TX) using the ASTM D5084 test procedure. The specimens (102 mm diameter and 116 mm height) were prepared at their w_{opt} in standard Proctor molds and transferred into the flexible-wall permeameters without disturbing the compaction conditions. The samples were first saturated for 7–14 days and upon meeting the saturation criteria of B > 0.95 as given in ASTM D5084, the samples were then consolidated under an effective stress of 20 kPa for at least 48 h, prior to taking conductivity readings. The test was terminated upon achieving the criterion of 4 or more determinations, to fall within ±25 % of a steady-state hydraulic conductivity reading.

(b) Constant-head tests: Constant head hydraulic conductivity tests using a GEOTAC bubble tube permeameter were conducted to determine saturated hydraulic conductivities (K_{sat}) at tub soil bulk densities (ρ_d) to mimic tub-soil compaction conditions. Soil cores from the tubs were collected using 76.2 mm diameter Shelby tubes after the growth study was completed to estimate soil ρ_d in the tubs. At these tub-soil densities, test specimens (76.2 mm diameter and 76.2 mm height) were prepared in the soil test section of the apparatus. The soil specimen sits on a perforated steel plate which was double-layered with a #100 mesh and the fabric (geotextile) that was used in the tubs, to retain the soil. The experiment was maintained at a constant hydraulic gradient of 0.9 across all soil samples. Once the sample was saturated, the Mariotte bottle was filled to a desired mark, the hydraulic conductivity readings were taken, and the criterion employed for the falling head tests was used to terminate the tests.

2.4. Data analysis and statistics

Depending on the data groups in the study, different statistical tests were selected to reveal correlations among parameters. When comparing nutrient mass transport in the leachate among different topsoil blends, a one-way analysis of variance (ANOVA) was completed for statistical significances. Pairwise differences among the four treatment groups were calculated using post-hoc tests with a Bonferroni correction ($P \leq \alpha$; $\alpha = 0.05/6 = 0.008$) if the ANOVA results showed significant variability. A regression analysis for correlations between leachate and soil parameters was carried out at $\alpha = 0.05$ to calculate the probabilistic significance (P) value. When an exponential correlation between parameters was noted, the *P*-value was determined by log transforming the dependent variable data and adding a linear fit to log (y) vs. x plots.

3. Results and discussion

3.1. Soil geotechnical properties

3.1.1. Direct shear

Results of the direct shear experiments are presented in Table 1. With the addition of organic amendments, the effective cohesion (c') of the soils slightly improved compared to the control soil (CUT2), following the order of BAT2 > MAT2 > LAT2 > CUT2. On the contrary, the effective friction angle (ϕ') of the amended treatments was lower than CUT2 and stayed in a range of 32.5°–40.4°. Similarly, CUT2 has an effective cohesion of 4.1 kPa and compost amendment caused an increase of 3.5 to 7 kPa. Since the blends were non-plastic (i.e., lacking clay particles), it is speculated that the observed increase in cohesion is not true cohesion and may be due to a pore filling mechanism caused by the fine particles in topsoil.

A recent study (Duzgun et al., 2021) that tested shear properties of topsoils showed an increase in both Mohr-Coulomb shear parameters, friction angle and cohesion, with compost addition. Although this trend conforms with the c' results of this study, it deviated from that of the friction angle (ϕ'). The difference in the application rates of amendments, compost type, and base soil properties between the two research studies could have contributed to this change in trend. Additionally, an

Table 2
Saturated hydraulic conductivities of the principal tub study (PTS) soils.

Tub Study Soil	K_{sat} (at ρ_{tub}) (cm/s)	K_{sat} (at $\rho_{d,\ max}$) (cm/s)
CUT2	1.8×10^{-3}	1.6×10^{-7}
MAT2	3.6×10^{-3}	7.5×10^{-7}
LAT2	2.5×10^{-3}	5.4×10^{-7}
BAT2	2.1×10^{-3}	1.2×10^{-7}

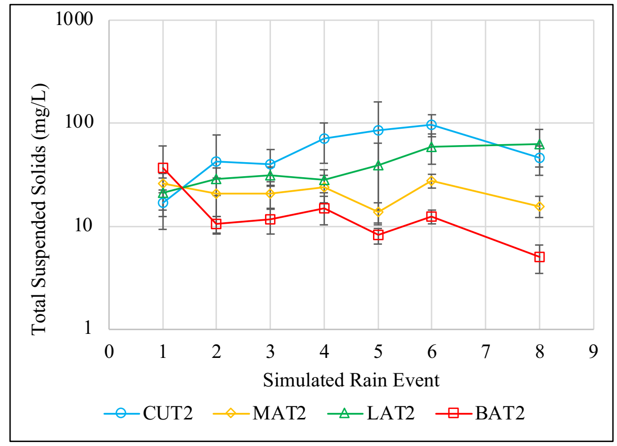
absence of fibrous elements in the amended soils could have impacted the friction angle. Per STS, although the soils are distinct in their properties, the effective cohesion was higher for the amended soils compared to the control, and vice-versa with respect to the friction angles (Table S6). Since cohesion had a smaller range among the unamended and amended soils, it is unlikely that the stability of the slope would be significantly influenced by the addition of OAs under current additive rates.

As can be observed in the Mohr-Coulomb shear parameters (Table 1), treatments under $w_{opt+3\%}$ showed a decline in the c' values compared to those compacted at w_{opt}. This difference in c' was highest in BAT2 (6.9 kPa), followed by LAT2 (4.8 kPa), and the least was MAT2 (2 kPa) and CUT2 (0.7 kPa). Similarly, wetter compactions decreased the friction angles across all the treatments, with an exception for BAT2 (ϕ' at w_{opt} = 32.5° and ϕ' at $w_{opt+3\%}$ = 32.8°). This occurs because as the water content increases, the cohesive forces between the soil particles decrease as the moisture occupies the void spaces in the soil matrix. All in all, the cohesion values and friction angles of PTS soils align with those of non-plastic silty/sandy soils (9.5–14 kPa, and 31–35°, respectively) and not plastic clays (c' > 15 kPa and ϕ' < 30°) (Holtz et al., 2011). Earlier work conducted on soils amended with compost (biosolids and dairy manure) showed the presence of organic matter (at <30 % addition) increased the shrinkage resistance and shear strength of expansive clays (Puppala et al., 2007). Donn et al. (2014) showed that the impact of green compost on shear parameters (cohesion and friction angle) was minimal ($p > 0.05$) at the applied rates; however, a reinforced root system as a result of vegetation growth over time increased the peak shear stress in soils. From a strength perspective, it can be concluded that addition of organic amendments will improve the soil structure and can be recommended for use on highway slopes, even though the contribution of OM to shear parameters will vary depending on the amount, characteristics, and sources (Duzgun et al., 2021).

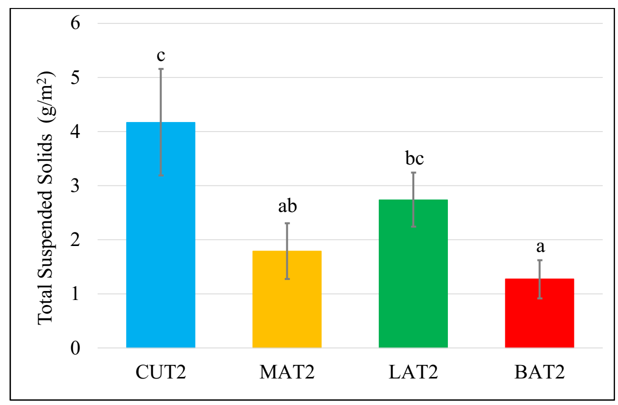
3.1.2. *Saturated hydraulic conductivity*

Table 2 provides information on saturated hydraulic conductivities (K_{sat}) of the soils at their maximum dry densities and tub bulk densities. K_{sat} of the PTS soils varied within the range of 1.2–7.5 × 10^{-7} cm/s, with MAT2 exhibiting the highest value. Organic amendments increased the K_{sat} of the CUT2 soil by 4.7 times in MAT2 and 3.4 times in LAT2. However, K_{sat} of CUT2 was slightly higher (1.35 times) than the K_{sat} of BAT2. Mulch application is known to contribute to increased soil pores (Onwuka and Uzoma, 2018), therefore MAT2 (and also MAT1, Table S7) outperformed other soils. In general, addition of compost or compost-like materials increase soil void ratio as a result of the "fluff" phenomena (Layman et al., 2010; Kranz et al., 2020). These observations are in line with the results of other studies, where compost additions enhanced the saturated hydraulic conductivity of the base soil (Bhatt and Khera, 2006; Olson et al., 2013; Cannavo et al., 2014; Duzgun et al., 2021).

A difference of 3–5 orders of magnitude of K_{sat} was noted among the soils compacted at their maximum dry density ($\rho_{d,\ max}$) and at tub bulk density (ρ_{tub}). This can be expected given the loose packing of soils, allowing a freer movement of water through the soil matrix even under saturated conditions. A decrease in hydraulic conductivity and infiltration rates of topsoils due to compaction associated with road construction has been reported in earlier studies (Bochet and García-Fayos, 2004; Haynes et al., 2013). Therefore, while incorporating OAs can loosen compacted soils, the presence of plant roots can also promote hydraulic conductivity and alleviate compaction conditions (Chen et al., 2021).



(a) Total suspended solids mean concentrations (mg/L)



(b) Average of CMT (g/m^2) of TSS

Fig. 2. Mean of (a) TSS concentrations (b) Average of TSS CMT from treatments used in PTS.
Note: soils with the same letters are not significantly different at a 95 % confidence level.

3.2. *Tub studies leachate and runoff analysis*

3.2.1. *Vegetative establishment and growth*

The findings and mechanisms related to the growth of a MDOT-SHA standardized turf mix in the two studies are detailed in Morash (2024). To briefly summarize these results, mean vegetation (green) coverage after 6 weeks of growth was LAT2 (96.9 ± 0.8 %); BAT2 (94.9 ± 2.3 %); CUT2 (90.7 ± 1.8 %); MAT2 (32.8 ± 1.3 %). The presence of biosolids and leaf compost in soils generally improved plant development, while incorporating mulch impeded turf establishment. The availability of macro- and micro-nutrients satisfied plant growth requirements in LATs and BATs, but several deficiencies were highlighted in plants in MAT soils.

3.2.2. *Runoff and leachate volume*

PTS had 9 simulated rainfall events (SREs) during the study. MAT2 and BAT2 produced no runoff during the experiment, while CUT2 and LAT2 treatments produced runoff in the later SREs (7, 8, 9), but not in adequate quantities (<20 mL) for analytical analysis. Therefore, the water quality data only includes leachate effluents. The cumulative infiltrated volume collected from MAT2 was the highest at 55.1 ± 5.4 % of the influent followed by BAT2 (50.9 ± 1.2 %), CUT2 (48.5 ± 3.5 %), and LAT2 (46.9 ± 4.4 %). In the K_{sat} experiment, it was similarly noted

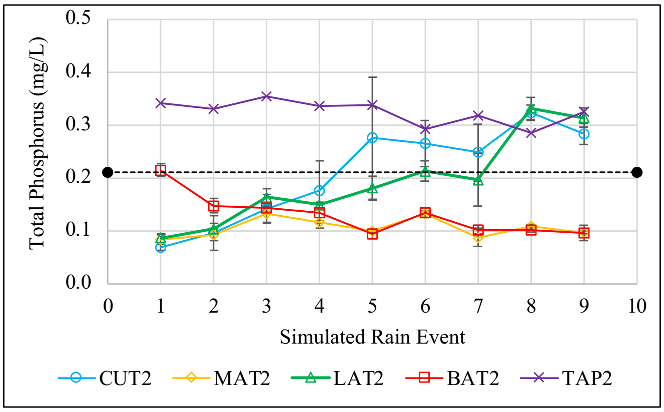


Fig. 3. Average concentrations of TP from treatments used in Principal Tub Study (PTS). Dashed line indicates typical urban stormwater mean concentration of TP = 0.21 mg-P/L (Pamuru et al., 2022).

that infiltration reached its highest level when the soil was mixed with mulch. However, the quantity of cumulative leachate exiting the tubs from SREs 1 to 9 was not significantly different ($p > 0.05$) across treatments and their replicates. Since the tubs were constructed on an incline of 4 % (25:1 engineering slope), the slope was not steep enough to discharge surface runoff in the experiments.

3.2.3. *Water quality*

In PTS, 9 SREs were applied of which the TP and TN were measured for all events, and the remainder of the water quality parameters were analyzed for all except SRE 7 and 9. Sediment/nutrient mass transport (g or mg/m^2) from each replicate was calculated by multiplying the concentration by the collected volume and normalizing with the tub area. Cumulative mass transport (CMT) was calculated by summing the individual mass transported for each replicate across the total simulated rain events.

3.2.3.1. Sediment transport. Since PTS soils contained the same base soil (CUT2), specific treatment impacts on the water quality can be discerned. No common trend was seen in the TSS concentrations within the soils as time progressed. MAT2 and BAT2 followed a declining pattern of TSS leaching, while CUT2 and LAT2 showed the converse (Fig. 2a). The addition of mulch and biosolids to the control (CUT2) led to statistically lower ($p < 0.008$) CMT through leachate, at 1.79 ± 0.52 g/m^2 and 1.27 ± 0.35 g/m^2 from MAT2 and BAT2, respectively (Fig. 2b). LAT2 exported lower CMT compared to CUT2, however it was not significant ($p > 0.008$). Overall, despite the controlled addition of OA to the soil, reduction in TSS was noted, which can be promising in mitigating soil erosion. Given the complexity of sediment transport through soils, estimating TSS concentrations for the excluded SREs (#7 and #9) for each treatment could not be done, and so the calculated CMT values (in Fig. 2b) should be regarded as underestimates for total sediment mass loss.

3.2.3.2. Phosphorus losses. P (predominantly as PO_4-P) was present in the applied tap water (influent) at a mean concentration of ~0.3 mg-P/L. Influent TP concentrations were higher than the leachates across all the rain events, except for SRE 8, where average TP concentrations in the LAT2 and CUT2 effluents were only 1.16 and 1.13 times, respectively, higher than the influent. CUT2, MAT2 and LAT2 leached statistically identical (p > 0.008) TP concentrations (0.069 ± 0.01 to 0.087 ± 0.01 mg/L) during SRE 1, while BAT2 leached 0.215 ± 0.01 mg/L, statistically greater (p < 0.008) than others (Fig. 3). However, BAT2's removal capability of P was demonstrated in the subsequent SREs, where steady state mean effluent concentrations reduced to ~0.1 mg/L. A sustained removal (independent of the SRE) of influent TP was noted in MAT2. CUT2 and LAT2 treatments, starting with apparent adsorption of influent P, but later TP leachate concentrations escalated to 0.28 ± 0.02 mg/L and 0.31 ± 0.18 mg/L respectively (which are close to the influent TP = 0.33 mg/L) in the last SRE. Cumulatively, from SREs 1 through 9, more TP mass was leached from the CUT2 treatments (20.5 ± 2.5 mg/m^2), immediately followed by LAT2 (17.9 ± 2.1 mg/m^2), BAT2 (13.7 ± 0.6 mg/m^2), and finally the lowest occurring in MAT2s (11.5 ± 1.3 mg/m^2).

A complete speciation of P was determined for the leachate samples collected from the treatments to better understand the details of nutrient transport in the amended soils. P appeared as dissolved (readily-available) P (PO_4-P), DOP, and PP in the leachates (Fig. 4). PTS soil treatments indicated that a considerable fraction of PP contributed to the

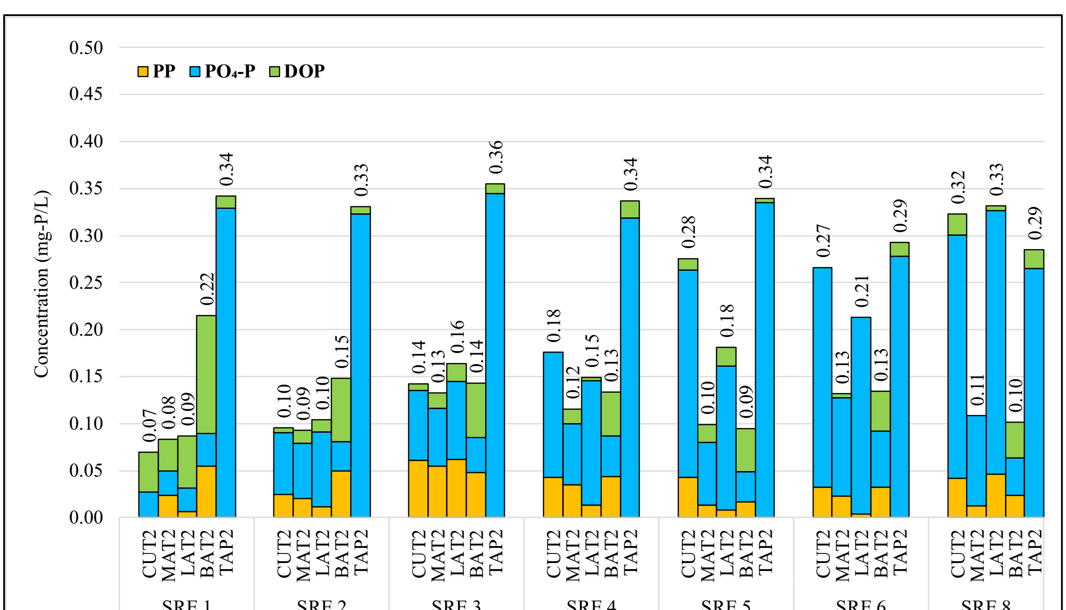


Fig. 4. Average concentrations of phosphorus species across treatments. Values on top of the bar plots denote the respective TP concentrations. Error bars were not included in the bar plots to enhance readability of the plot.

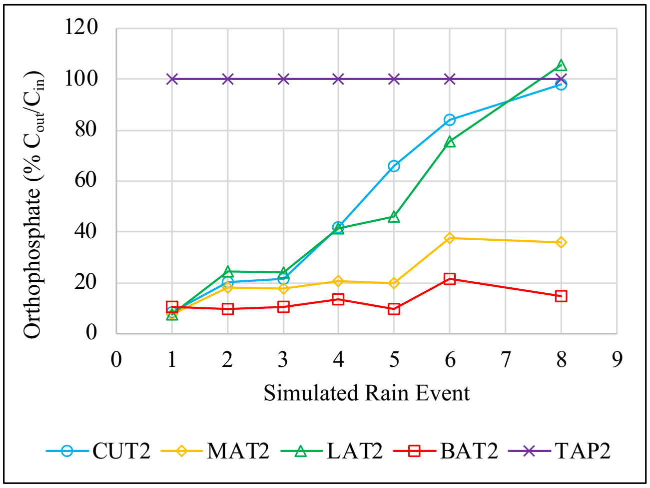


Fig. 5. Orthophosphate (% C_{out}/C_{in}) in the PTS treatment leachates.

total leachable P in the water samples. PP was as high as 42.7 %, 41.5 %, 37.8 % and 33.4 % of TP (noted after SRE 3) for CUT2, MAT2, LAT2 and BAT2, respectively, during the study. Generally, in the context of surface runoff, PP is linked with TSS (Sandström et al., 2020). However, this association was not statistically signficant ($p > 0.05$) in the PTS leachates. This might be explained by the lower concentrations of sediment discharging from the amended soils, as well as the fact that the leachates are infiltrated waters rather than surface runoff.

The majority of the DOP was leached from the soils during the initial SREs (first flush); as the turf cover grew (Morash, 2024) and as the soils continued to receive approximately 0.3 mg-P/L of PO_4-P influent with each SRE, PO_4-P became the dominant form in the leachates (Fig. 4). The temporal trends of DOP (descending) and PO_4-P (ascending) species in PTS soils (Fig. 4) corroborated with a recent study that tested compost/biosolids amended bioretention media (Owen et al., 2023). Also in agreement were the P speciation results of the STS leachates (Fig. S3b). Although the BAT2 DOP fraction reduced with time, the final average concentration still was 0.038 mg-P/L (37.5 % of TP), reduced from 0.13 mg-P/L (58 % of TP, SRE 1), while CUT2, MAT2 and LAT2 declined from 60 to 7 %, 40 to 0 %, 63 to 2 %, respectively, between SREs 1 and 8. This suggests that the rate of mineralization of the organic P from the biosolids treatment is slower than leaf compost or mulch, and/or because the amount of organic P in BAT2 is greater than LAT2 or MAT2. Continued production of DOP was noted not just in the PTS leachates (Fig. 4) but also the STS leachates (Fig. S3b), particularly in BATs, suggesting that DOP has the potential to be released along with PO_4-P in organic amended soils (McDowell et al., 2021). Unlike observed in some past studies (Jay et al., 2017; Owen et al., 2023), the BAT not just retained “leachable” or dissolved soil P but also reduced the incoming PO_4-P. These results agree with those from Alvarez-Campos and Evanylo (2019), where the PO_4-P concentrations in the leachate of biosolids-applied soil were flagged as below-detectable (<0.01 mg/L) despite an increased application of phosphorus via biosolids.

Wastewater biosolids are typically treated with iron coagulants or iron salts (in their amorphous reactive form) to chemically retain or immobilize P and other contaminants (Elliott et al., 2002; Silveira et al., 2003; Korving et al., 2019). A recent review (synthesized from many studies) also indicated reduced P leaching due to Fe/Al rich water treatments residuals (a byproduct of drinking water treatment) when added to the bioretention media (Chen et al., 2021). Of all the treatments, BATs contained the highest Fe content (BAT1 = 850 mg-Fe/kg; BAT2 = 577 mg-Fe/kg), and the soils were slightly more acidic (BAT1 pH = 6.19; BAT2 pH = 6.79) among their respective treatments (Table S3). Therefore, PO_4-P could be stabilized by binding to the active surfaces of the iron minerals, thereby reducing the P release into the effluent beyond the first-flush of DOP from the biosolids treatment. Wood mulch soils (MAT1 and MAT2) retained the incoming PO_4-P throughout the course of the experiments. An effective removal of phosphorus by woodchips was also noted in other experimental studies (Xuan et al., 2010; Dougherty, 2018; Sanchez Bustamante-Bailon et al., 2022). Sanchez Bustamante-Bailon et al. (2022) conducted batch tests and ascribed the removal of PO_4-P to the existence of Ca, Mg, Fe and Al elements in wood chips. In PTS, MAT2 contained greater Ca, Mg, Al and Fe than CUT2, and a soil P deficiency (Table S3). MAT2 also had a slightly alkaline soil pH of 7.31, which suggests that calcium-induced adsorption of PO_4-P in MAT2 is the primary method for reducing this nutrient’s export via infiltrated waters (Penn and Camberato, 2019).

The PO_4-P concentrations (and fraction) from CUT2 and LAT2 leachates showed an upward trend with each SRE (Fig. 4 and Fig. 5).

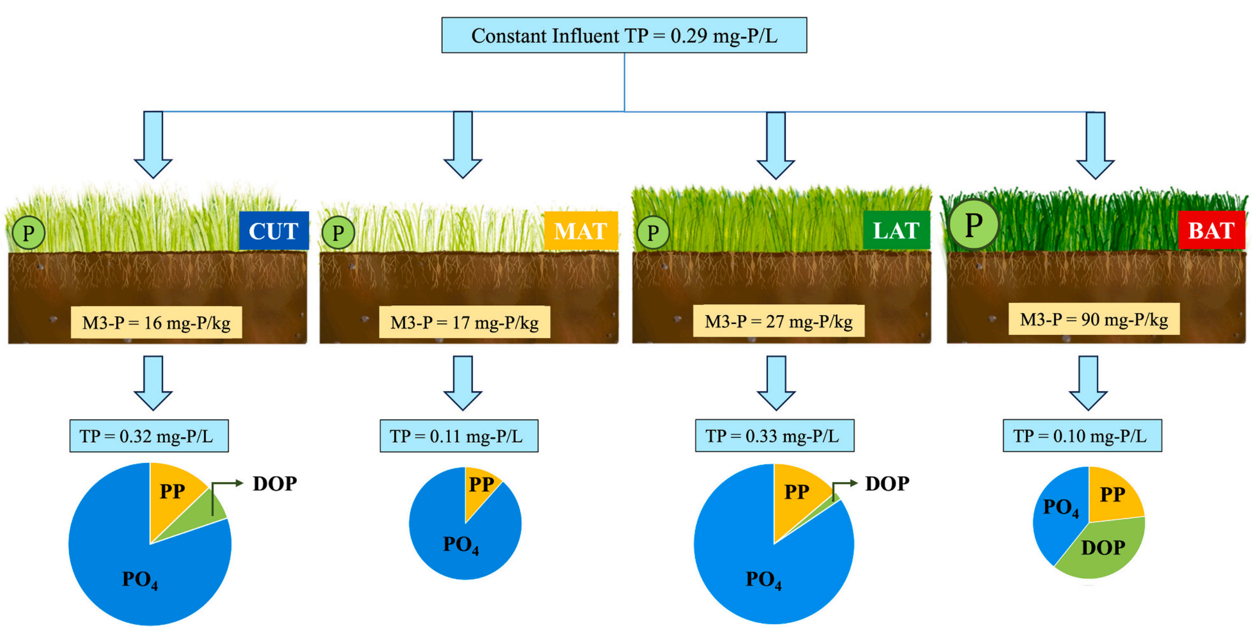


Fig. 6. Phosphorus distribution in the steady state leachate and uptake as affected by the addition of OAs. Information related to plant coverage, color and uptake is provided in Morash (2024).

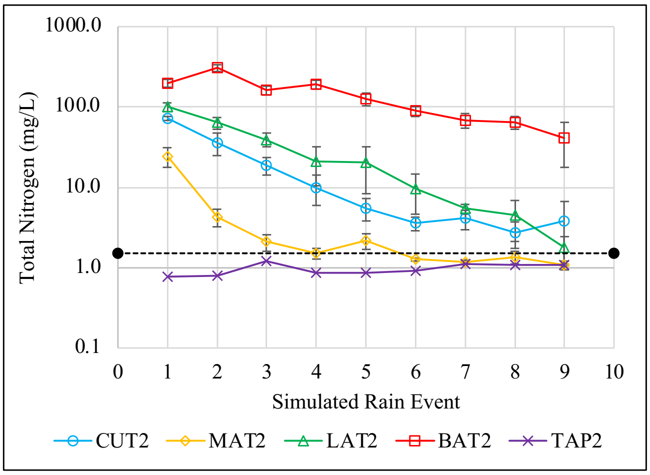


Fig. 7. Average concentrations of TN from treatments used in the Principal Tub Study (PTS). Dashed line indicates typical urban stormwater concentration of TN = 1.47 mg-N/L (Pamuru et al., 2022).

Although leaf compost addition increased the soil mineral (Ca, Mg, Al and Fe) content in CUT2; it also resulted in elevated soil P. Because a continuous input of PO_4-P from tap water was applied during the study period, it is difficult to discern if the increase in PO_4-P over time is associated with its mineralization to PO_4-P, due to the inability of the soil to adsorb any further PO_4-P, or both in CUT2 and LAT2. Although, it can be speculated that since the plant tissue experienced P deficiencies (less than the sufficiency range of 0.3 to 0.6 %P) in all the PTS (or TS2) soils (Morash, 2024), it is possible that the mulch and biosolids tied up P (reduced leaching and plant availability), and the saturation of adsorption sites in the LAT2 and CUT2 soils contributed to causing an adsorption breakthrough phenomenon of PO_4-P from the influent (as seen in Fig. 5). Phosphorus distribution in the soil-water-vegetation nexus based on the study findings is presented in Fig. 6.

P concentrations in precipitation ranged between 2 and 31 μg/L in New Jersey (Koelliker et al., 2004) during 1999–2001, and 16–36 μg/L near the Chasepeake Bay (collection period: 1976–1981, Boynton et al. (1995)). The influent in this study contained at least 10 times these concentrations and yet the tub study soils demonstrated an ability to retain P, indicating a potential long term adsorption of P in amended soils when the OAs are added at appropriate OM rates.

3.2.3.3. Nitrogen losses. CUT2 TN discharge ranged between 2.7 ± 0.96 to 72.6 ± 3.88 mg-N/L (Fig. 7). The TN was the highest in the leachate from BAT2 (peak average concentration = 309 ± 29.3 mg-N/L, SRE 2). Also in STS, the biosolids amendment (BAT1) produced the highest release with a peak average of 191 ± 26.1 mg-N/L during SRE 3 (Fig. S4a). A trending decline in TN (mg/L) leached was noted for all soils, with LAT2 showing the sharpest downward curve (Fig. 7). The order of concentrations (in mg-N/L) after the first and final SREs are: BAT2 (198 ± 24, 41.1 ± 23.5) > LAT2 (101 ± 12.9, 1.8 ± 0.7) > CUT2 (72.6 ± 3.9, 3.9 ± 2.8) > MAT2 (24.3 ± 6.7, 1.1 ± 0.1). Significantly greater nitrogen release ($p < 0.008$) was noted from biosolids (BATs) in comparison to MATs and LATs, in both PTS and STS experiments.

Addition of biosolids and leaf compost contributed to higher TN leaching than CUT2 (Fig. 7). This was noted in past stormwater research where amendments like leaf compost and biosolids compost exported higher N compared to the control media (Mangum et al., 2020; Owen et al., 2023). Conversely, mulch OM showed reduced N concentration (by up to an order of magnitude) compared to LAT2 and BAT2 even though the soil analysis showed that mulch increased the TN content of the control soil. TN CMT from MAT2 (464 ± 50 mg/m^2) was the lowest compared to others (CUT2: 1577 ± 232, LAT2: 2727 ± 236, and BAT2: 15,142 ± 596 mg/m^2).

Previous research has noted a negative correlation of soil C:N with TN loss from media (Dise et al., 1998; Zhou, 2017; McPhillips et al., 2018). Soil C:N ratio is identified as a key soil property in determining TN leaching from the amended soils examined in this study. Fig. 8 shows the leachate TN CMT vs. initial soil C:N ratio for all PTS and STS soils. A decreasing exponential trendline best fit the data and the computed goodness of fit (R^2) of 0.84 indicates a strong statistical correlation ($p < 0.05$). Of the eight soils, the treatments with the lowest C:N ratios (7:1, BAT1 and 8:1, BAT2), given their high N content, leached statistically more TN by mass (p < 0.008) compared to the others (Fig. 7 and Fig. S4a). Contrary to this, MAT1, MAT2 had C:N ratios >19:1 and

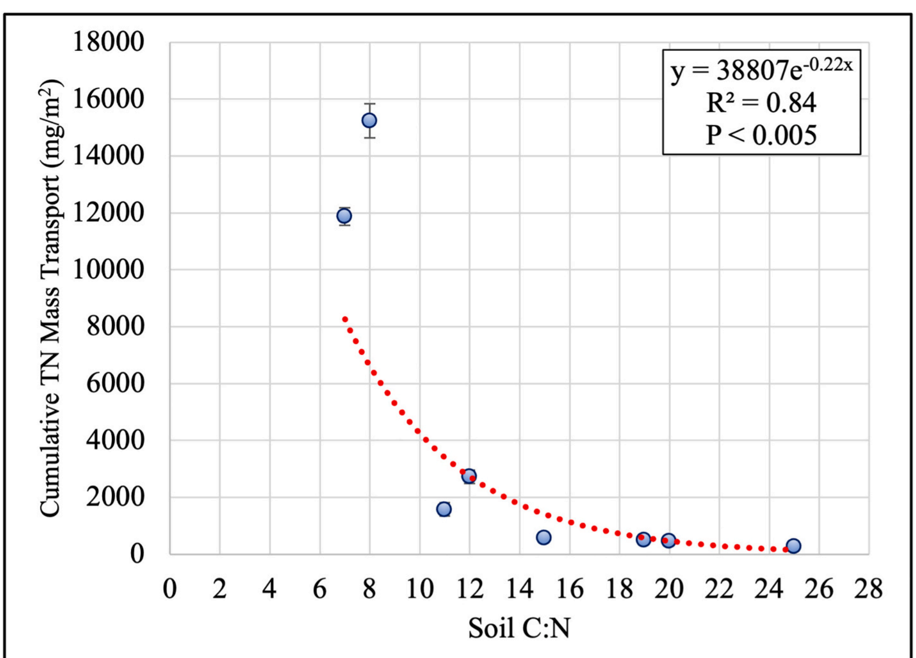


Fig. 8. Effects of soil C:N ratio on TN cumulative mass export as determined from the eight-tub study soils.

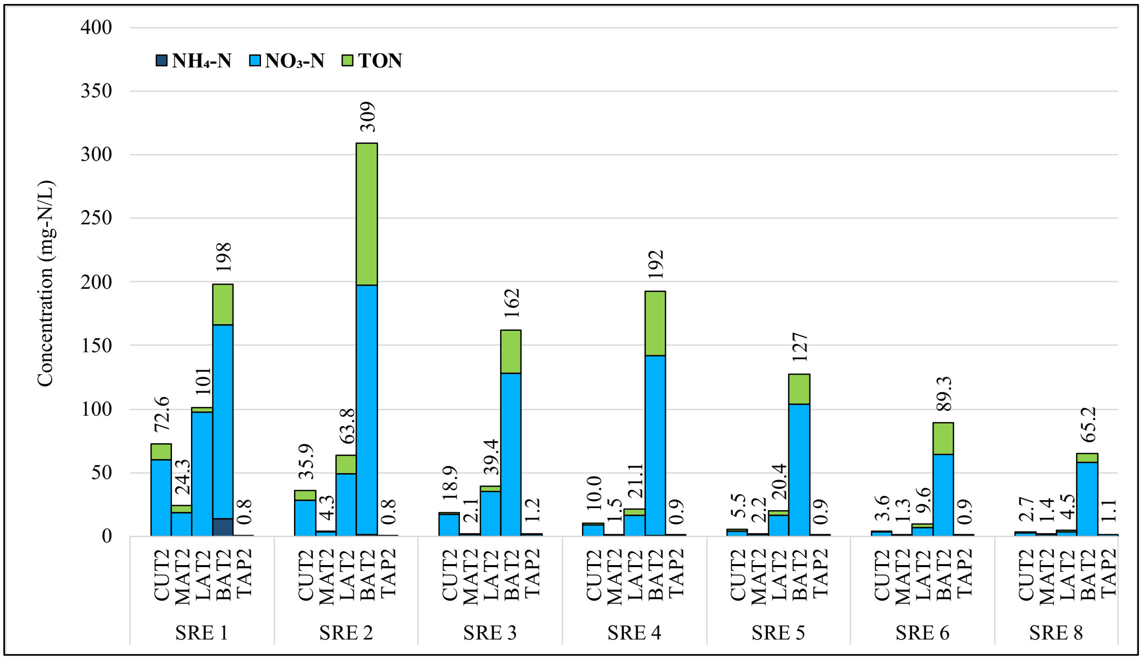


Fig. 9. Average concentrations of nitrogen species across treatments. Values on top of the bar plots denote the respective TN concentrations. Error bars were not included in the bar plots to enhance readability of the plot.

leached <25 mg/L TN (Fig. 7 and Fig. S4a). Soil microorganisms sequester N while feeding on C (cellulose in the case of mulch) to meet their N demands when the soil C:N ratio is >20:1 (Chapin et al., 2002; McPhillips et al., 2018). Carbon-rich organic materials like mulch could also prompt denitrification in MATs when anaerobic microsites are created with weekly rain simulations. This denitrification process has been discussed in woodchip bioreactor studies in the context of nitrate removal (Halaburka et al., 2017; Ashoori et al., 2019; Aalto et al., 2020; Fan et al., 2022). This renders the nutrient (temporarily) unavailable for plant uptake, thus transforming it into a limiting factor for vegetative growth in these soil blends, as evidenced in the N tissue uptake from the studies (Morash, 2024). Therefore, from the vantage of water quality, mulch-like OAs that increase soil C:N > 20:1 reduce N leaching; however, at the cost of compromised rapid vegetation establishment.

Tap water N was 91.5 to 100 % in the form of NO_3-N. Unlike P speciation, major N forms were in the dissolved phase (Fig. 9). NO_3-N

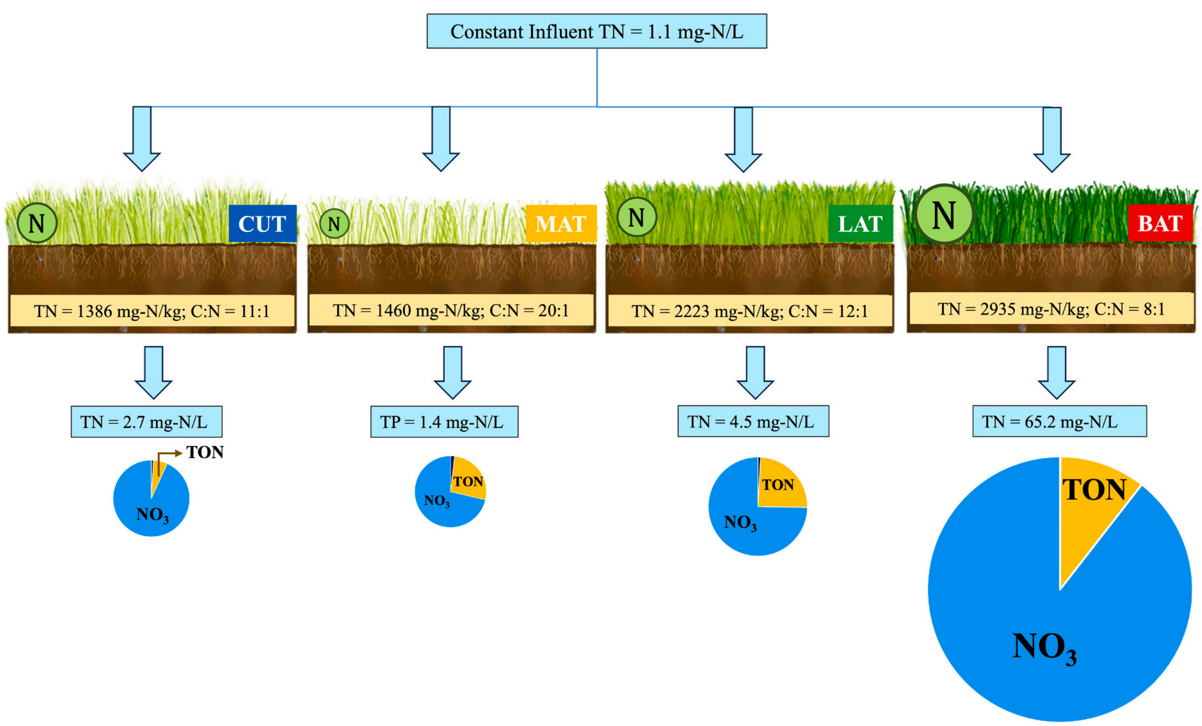


Fig. 10. Nitrogen distribution in the steady state leachate and uptake as affected by the addition of OAs. Information related to plant coverage, color and uptake is provided in (Morash, 2024).

and TON were predominately found in all leachates, while NH_4-N appeared only in the BAT2 leachates. A small amount of NH_4-N (7 % of TN) was found after the first SRE in BAT2 leachate. However, NH_4-N release from BAT1 was quantifiable throughout the course of the STS experiment (Fig. S4b). The same biosolid material (originally procured in May 2021) used in the BAT1 blend was stored in closed-lid buckets and reused in September 2021 to prepare BAT2. Since a more aged material was used for BAT2, it is possible that NH_4 might have mineralized to NO_3 causing a higher fractional output of NO_3 over NH_4 in the BAT2 leachates. This brief appearance of NH_4-N in both soil and aqueous environments could also occur as a result of volatilization (Lea-Cox et al., 2001), although gaseous N forms were not measured in the current study. Soil NH_4-N information was available only for PTS soils (Table S3), and NH_4-N was the highest in BAT2 compared to other soils. This confirmed and reflected the existence of NH_4-N only in the BAT2 leachates.

Although effective for P retention, the biosolids increased the risk of NO_3-N pollution to ground- and surface water pathways, which has been highlighted in several past studies as well (Correa et al., 2006; Rigby et al., 2009; Alvarez-Campos and Evanylo, 2019; Owen et al., 2023). Effluents from BAT2 and LAT2 treatments contained greater NO_3-N concentrations, compared to CUT2. NO_3-N remained the dominant N species leached from all the PTS soils, with TON (albeit fractionally lower compared to NO_3-N) next through successive SREs. A transient product of nitrification, nitrite (NO_2-N) was analyzed for a few events (not shown in Fig. 9) and was found to be negligible (all <2 % of TN) in the mass balance of N species for all soils. Soil NO_3-N concentrations followed the order: BAT2 > LAT2 > CUT2 > MAT2 (Table S3). This same sequence was noted in the corresponding leachates, with MAT2 exporting the least (61–92 % less nitrate compared to CUT2). Similar to biosolids, leaf compost used in PTS also contributed to excessive nitrate leaching in the initial flush but was rapidly reduced from 97.9 ± 13.9 to 3.36 ± 1.41 mg-N/L. A continued reduction in LAT2 N species and TN concentrations was observed, unlike other soil leachates which attained steady state (Fig. 7 & Fig. 9). This implies that further reduction in N release could have occurred if the experiment prolonged beyond the 9 weeks of study. It is important to note that in this study, the soils were consistently exposed to weekly rain events and the study was carried out in the fall season. This consistent watering ensured that the soils remained moist throughout the period between each rain event. However, this differs from natural field conditions, where soils typically undergo cycles of drying and wetting. In those environments, a phenomenon known as the Birch Effect can be experienced, where increased soil microbial activity and respiration follow the rewetting of dry soil, which can significantly alter soil nitrogen dynamics (Birch, 1958, 1960). Nitrogen distribution in the soil-water-vegetation nexus based on the study findings is presented in Fig. 10.

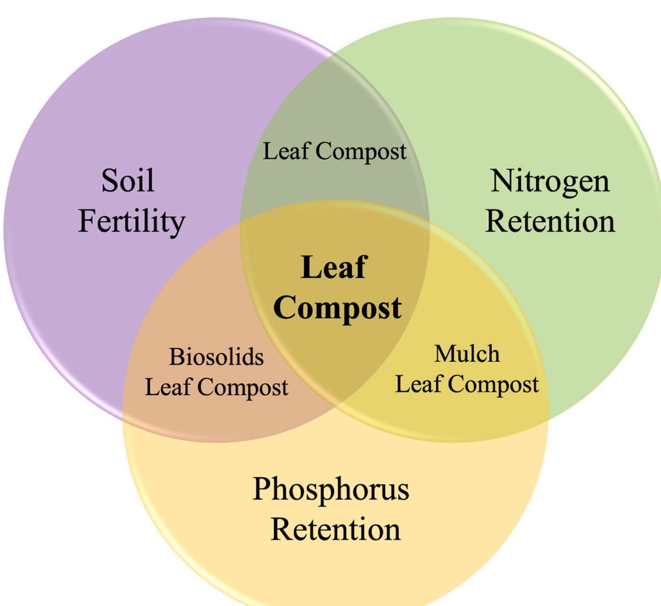


Fig. 11. Venn diagram showing the positive influences of mulch, leaf compost and biosolids in the areas of soil fertility, nitrogen retention and phosphorus retention.

According to the National Atmospheric Deposition Program (NADP) database, the annual mean rainfall nitrate concentrations in the Beltsville region of Maryland (site ID: MD99, http://nadp.slh.wisc.edu/data/NTN/) between Dec 2020 and 2021 was ~0.14 mg-N/L. This suggests that the composition and characteristics of the roadside soils are more important factors in determining nitrogen movement than the small amount of nitrogen that is introduced from rainfall in the field.

4. Environmental implications

1. Biosolids amendment should be added into roadway topsoil soils based on nitrogen requirements and not be used as a means to raise the soil OM content.
2. At inclines >25:1 used in this study, lateral surface- and subsurface-flows could occur. Since the tub studies determined that biosolids significantly increased N concentrations in leachate, the risk of high runoff N concentrations could be greater at steeper inclines.
3. Due to their high C:N ratio, MATs effectively retained N in the soils. Concurrently, in terms of plant growth, the wood-mulch caused tissue N and other nutrient deficiencies (Morash, 2024). Given its widespread use, it is recommended to complement mulch with fertilizers rather than relying solely on this OA as the primary source of OM and nutrients. This approach is essential for achieving the desired vegetation outcomes while also maintaining water quality.
4. N release from LAT2 continued to decline with each rainfall application, and this soil also removed P from the influent albeit following a breakthrough-like phenomenon. Therefore, leaf compost-like amendments are suggested as the preferred materials to be incorporated into soils for improving the OM content in the context of soil fertility (Morash, 2024), with reduced concerns around water quality.
5. Given its potential for a reduced risk of nitrogen release and the ability to retain phosphorus, leaf compost is a suitable choice from a water quality and nutrient availability perspective (Morash, 2024), when applied at suitable soil organic matter rates (MDOT SHA, 2017).

5. Conclusions

Three distinct organic amendments (shredded wood-mulch, leaf compost, and biosolids) were tested in greenhouse tub studies to assess their efficacy in promoting turf coverage, improving soil physical characteristics, and protecting water quality. This research was divided into two sections, and the present paper specifically examined the influences of OAs on geotechnical and environmental properties.

5.1. Geotechnical properties

Shear properties of all the OA-amended study soils were comparable to those of earthen materials. Compacting the soils at $w_{opt+3\%}$ reduced the overall shear strength of the soils as expected, even though differences in LAT and BAT treatments at w_{opt} and $w_{opt+3\%}$ were greater. Conclusions about how these differences could affect erosion potential could not be determined in this study. All amended soils improved hydraulic conductivities at $\rho_{d,\ max}$ and ρ_{tub} compared to the unamended controls in both tub studies.

5.2. Leaching

Water quality analysis of N species demonstrated that biosolids caused 1–2 orders of magnitude increased in N export when compared to other amendments. An exponential decay relationship was evident between soil C:N ratio and the TN CMT data. The soils with a combination of low C:N ratio and high TN content (BATs) released more N in the leachate. The opposite was also true, in that MATs (high C:N ratio) leached the lowest N. Although leaf compost leached greater N at the beginning of the SREs, the concentrations dropped down to influent (tap water) N concentrations at the end of the study.

Biosolids amendment successfully reduced the influent tap water P. Irrespective of the high P in BATs; the abundance of reactive iron along with other background minerals (Al, Ca, Mg) in biosolids effectively complexed P for the duration of the study. Low P content and high minerals (particularly Ca) were characteristics of the wood mulch amendment and MATs also minimized the P release into the leachate. Although LAT2 removed tap water P at the initiation of SREs, the effluent concentrations did not statistically differ from the influent after 203 mm of simulated rainfall, suggesting a possible breakthrough due to oversaturation of P adsorption sites in these soils. After holistic evaluation of the study OAs, leaf-compost proved to be effective in terms of improving geotechnical properties, soil fertility, plant growth (Morash, 2024), while minimizing nutrient water quality concerns when added into the soil at regulated rates (Fig. 11), specifically not exceeding a 1–2 % increase in soil OM to protect the environment.

CRediT authorship contribution statement

Sai Thejaswini Pamuru: Data curation, Investigation, Writing – original draft, Methodology. **Jennifer Morash:** Investigation, Writing – review & editing, Methodology. **John D. Lea-Cox:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing, Methodology. **Andrew G. Ristvey:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing, Methodology. **Allen P. Davis:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing. **Ahmet H. Aydilek:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing, Methodology.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sai Thejaswini Pamuru, Jennifer Morash, John D. Lea-Cox, Andrew G. Ristvey, Allen P. Davis, and Ahmet H. Aydilek report financial support was provided by Maryland Department of Transportation – State Highway Administration. Sai Thejaswini Pamuru & Jennifer Morash report financial support was provided by NSF Research Traineeship (UMD Global STEWARDS) Grant 1828910.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.170649.

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