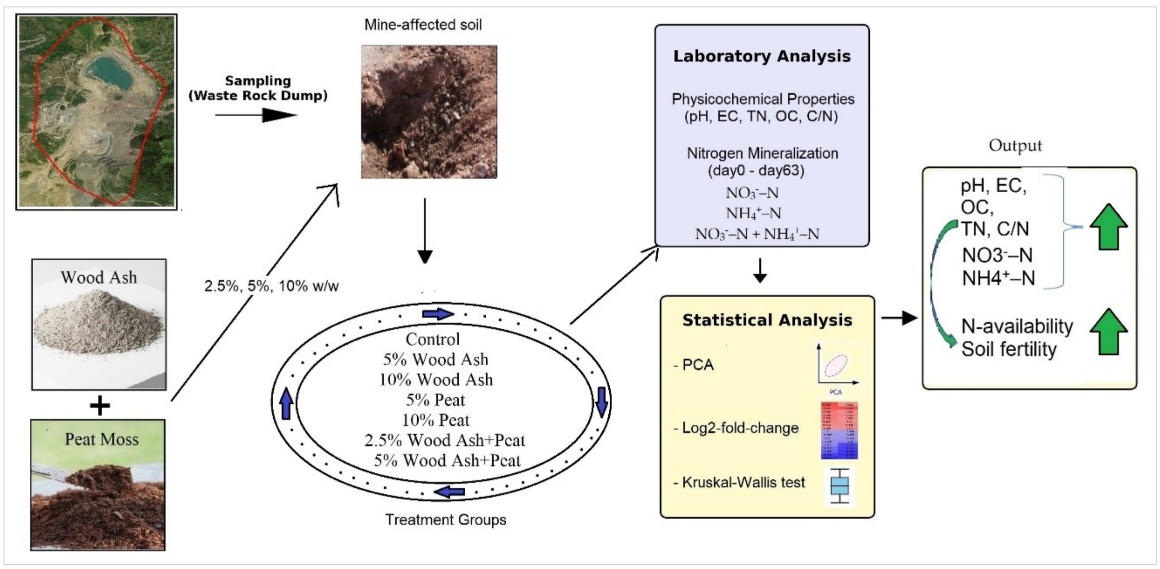
Soil Quality Improvement Potential of Wood Ash and Peat Moss in Copper Mine Waste Rock Dumpsite: A Case Study in Artvin, Turkey

Mehmet Küçük, and İsmet Yener ,*

* Corresponding author: yener@artvin.edu.tr

DOI: 10.15376/biores.21.3.7703-7727

GRAPHICAL ABSTRACT



Soil Quality Improvement Potential of Wood Ash and Peat Moss in Copper Mine Waste Rock Dumpsite: A Case Study in Artvin, Turkey

Mehmet Küçük, and İsmet Yener,*

With the ultimate goal of facilitating *in situ* phytostabilization and ecological restoration of mining sites rather than agricultural use, the present study aimed to investigate the effects of wood ash and peat on the physicochemical properties and nitrogen mineralization in copper-mine-affected soils. To this end, soil samples were collected from copper mine waste rock dumpsites and amended with wood ash, peat moss, and their mixture, at various rates. Various soil properties were determined at two incubation periods (day 0 and day 63). To reveal differences among soil amendments, a post hoc test with the Bonferroni correction, principal component analysis (PCA), PCA biplot, and Log2 fold change heat map analyses were applied. As a result, all soil properties, except the ammonium level at day 63, differed significantly for at least one type of amendment ($P < 0.05$). The overall effects of the treatments on physicochemical soil properties and nitrogen mineralization, as determined by PCA, indicated that wood ash had the greatest effect on pH and EC. In contrast, peat moss dominated nitrogen dynamics, as reflected by organic carbon and organic matter. The results of this study could be used to remediate mine-polluted, acidified, and nutrient-depleted soils.

DOI: 10.15376/biores.21.3.7703-7727

Keywords: Mining; Nitrogen mineralization; Remediation; Soil amendments; Acidified soils

*Contact information: Department of Forest Engineering, Faculty of Forestry, Artvin Çoruh University, 08100-Artvin, Turkey; *Corresponding author: yener@artvin.edu.tr*

INTRODUCTION

Since ancient times, humans have sought innovative energy and raw material sources and adapted land use to accommodate the growing population. Such developments have led to significant environmental challenges, including pollution, deforestation, soil erosion, drought-induced desertification, and global climate change, underscoring the urgent need for sustainable land management practices (Mahmood *et al.* 2010; Deng *et al.* 2013). Among these activities, mining–for instance, Line Cave, one of the oldest mining operations, which dates back to 43000 BC (Mkpuma *et al.* 2015), has emerged as a major contributor to environmental deterioration, with profound hydrological, biological, and societal impacts, such as blasting, subsidence, air pollution, and alterations to land surfaces (Allgaier 1997; Mkpuma *et al.* 2015). Furthermore, acid mine drainage (AMD) is a primary environmental concern in both operating and abandoned mines, contaminating surface waters with various cations, including Fe, Cu, Zn, and Mn (Barbu *et al.* 2017).

Mining activities have frequently caused widespread land degradation, primarily by removing topsoil, altering soil structure, and contaminating it with heavy metals (Saglam *et al.* 2020; Karn *et al.* 2021; Haghighizadeh *et al.* 2024). Topsoil removal eradicates vital organic matter and microbial communities essential for plant growth, while exposing soil layers can induce acidification and a decline in soil fertility. Moreover, the toxicity of heavy metals (Cr, Cu, Ni, Pb, and Zn) from mining activities reduces the activity of microorganisms that are crucial for organic matter decomposition, leading to depletion of essential soil nutrients and reduced carbon sequestration, both of which are vital for the life cycle (Karn *et al.* 2021; Campillo-Cora *et al.* 2025).

In addition, mining disrupts the balance of soil ecosystems, causing erosion (Mkpuma *et al.* 2015), decreased plant-available water capacity (AWC) and water quality (Westcott 1998; Karn *et al.* 2021), reduced cation exchange capacity, and increased soil compaction (Hu *et al.* 2018). Consequently, soil is one of the ecosystem components directly or indirectly affected by mining activities (Williams and Thomas 2023). Mine tailings are a critical component of mining infrastructure and a significant global environmental concern, as they can cause land deterioration by impounding mine waste that covers large areas and contains higher levels of metals than surrounding surface soils (Dold 2008). The rehabilitation process includes shaping the dump to restore the site's physiography and provide drainage, replacing the topsoil, and subsequently planting the area (Allgaier 1997). Rehabilitation minimizes differences in soil quality between pre- and post-mining conditions (Westcott 1998). A range of techniques has been employed to rehabilitate mining sites contaminated with heavy metals, primarily encompassing physical, chemical, and biological approaches (Mkpuma *et al.* 2015). These techniques include soil immobilization, which reduces metal mobility by adding various amendments, such as clay or cement, directly to the contaminated soil. The other technique is soil washing, which physically or chemically extracts contaminants from excavated soil using solutions such as acids or chelating agents. Additionally, phytoremediation, a biological method, uses specific plants to either extract (phytoextraction) or stabilize (phytostabilization) heavy metals in soil, offering an environmentally sustainable solution (Wuana and Okieimen 2011; Karn *et al.* 2021; Haghighizadeh *et al.* 2024; Wang *et al.* 2024). Therefore, *in-situ* remediation techniques such as phytoremediation and soil amendments (*e.g.*, organic carbon addition and vegetation residues) are essential for rapidly and cost-effectively improving the physicochemical and hydrogeochemical properties of disturbed soils and tailings to address land degradation and heavy metal contamination (Dold 2008; Maljanen *et al.* 2014; Jansone *et al.* 2020).

Among soil amendments, peat and wood ash are commonly used to immobilize heavy metals in soils by enhancing chemical stabilization, thereby reducing their mobility and bioavailability through mechanisms such as sorption, precipitation, and complexation (Wuana and Okieimen 2011; Haghighizadeh *et al.* 2024). In addition to their soil-ameliorative effects, the use of peat and wood ash, produced as waste in significant quantities by the forest industry and energy plants (Nieminen *et al.* 2005; Gómez-Rey *et al.* 2012), provides environmental benefits, such as reduced need for landfilling or storage, lower costs, and mitigation of adverse environmental impacts, thereby promoting sustainable practices (Maljanen *et al.* 2014; Jansone *et al.* 2020).

Although raw wood ash (WA) is highly alkaline (pH 10 to 13) (Barbu *et al*. 2017), applying it to acidic soils at typical rehabilitation levels (*e.g*., 5% to 10% w/w) buffers the mixture to pH values of 6 to 8. This range minimizes the solubility of aluminum and manganese through precipitation, avoiding the formation of soluble aluminate at higher pH levels (Aide 2022; Dourado *et al*. 2021; Nkana *et al*. 2002). Furthermore, wood ash contains high amounts of hydroxides, carbonates, and essential soil nutrients, and is often used as an alternative to limestone fertilizer (Hytönen 2003; Jansone *et al.* 2020). Peat, on the other hand, is one of the most widely used biologically active additives, along with activated sludge and straw, which improve soil processes, strengthen nutrient cycles, and reduce the impact of heavy metals on soil tailings (Wang *et al.* 2024). Furthermore, its application is conducive to restoring disturbed borrow pits and oil and natural gas well sites (Nawu *et al.* 2024).

The application of peat and wood ash to forest and agricultural soils degraded by human activities, such as mining, is essential, as it replenishes nutrients lost, counteracts soil acidification, and enhances plant growth (Heiskanen *et al.* 2022). Chemically, wood ash contains abundant base cations, such as Ca (18%), K (2.2%), Mg (1%), and Na, all of which originate from the mineralization of organic compounds during combustion (Demeyer *et al.* 2001). Rolka *et al.* (2023) reviewed the remedial effects of wood ash, considering its physical, chemical, and mineralogical characteristics, on the properties of forest and acid soils (*e.g.*, nutrient availability, water retention, acidity, and porosity), as well as on plant growth.

In contrast, peat or peat moss consists mainly of cellulose, lignin, and polar functional groups (*e.g.*, acids, phenolic hydroxyls, ethers, aldehydes, alcohols, and ketones). It contains abundant organic matter (up to or exceeding 90%), providing effective adsorption sites for binding and immobilizing potentially toxic elements, thereby supporting soil restoration (Nawab *et al.* 2019). The alkaline nature of wood ash either reduces the solubility of toxic elements (*e.g.*, aluminum and manganese) (Barbu *et al.* 2017) or stabilizes heavy metals by increasing pH (Mortensen 1963; Kabata-Pendias 2000; Weng *et al.* 2002). In addition to its immobilizing potential—primarily by increasing pH—wood ash also improves hydrophysical properties (*e.g.*, water-holding capacity) and N mineralization by stimulating soil microbial activity (Rolka *et al.* 2023). For example, WA is applied annually to hectares of Finland's acidic peatlands due to its alkalinizing properties. However, its use in farmland soils is not recommended because of the potential presence of Cd, Hg, As, Co, Cr, and Ni (Maljanen *et al.* 2014). Unlike WA, peat moss prevents additional salt accumulation and buffers the pH (Nawab *et al.* 2019). Additionally, it promotes ground cover, shoot biomass, and root biomass by increasing the availability of macronutrients, particularly nitrate and phosphorus (Reid and Naeth 2005). Furthermore, the application of peat moss improves soil properties (*e.g.*, porosity, cation exchange capacity, soil holding capacity, organic matter content) and immobilizes heavy metals, as does WA (Forsberg and Ledin 2003; Reid and Naeth 2005; Nawab *et al.* 2019). Peat application also facilitates the removal of metalloids and the reduction of nitrate in AMD (Naghoum *et al.* 2025).

The ultimate land-use aim in the reclamation of metalliferous tailings is generally not agricultural production due to the severe health risks associated with heavy-metal biomagnification through the food chain (Antonelli *et al.* 2021). Therefore, the intended end use of the copper mine tailings investigated in this study is *in situ* phytostabilization and long-term ecological restoration. This approach aims to establish a vegetative cover using native, metal-tolerant pioneer plant species to minimize wind and water erosion and physically stabilize the hazardous waste (Li *et al.* 2013; Benidire *et al.* 2022). To achieve this goal, the barren tailings must first be transformed into functional soils that support plant growth and nutrient cycling (You *et al.* 2018).

Given the ongoing challenges of land degradation and toxic metal contamination at mining sites, developing effective and sustainable remediation techniques is vital. The objective of the present study was, therefore, to examine the effectiveness of peat moss and

WA, which are readily available and economical amendments, in ameliorating the physicochemical and biological properties (*e.g.*, N-mineralization) of mine-affected soils.

EXPERIMENTAL

Study Area

The study area is situated between 41°13′ N and 41°16′ N, and between 41°34′ E and 41°36′ E, within the Murgul district of northeastern Turkey (Fig. 1), which is characterized by deeply incised valleys surrounded by steep mountainous slopes (Acatay 1968). The area's mean altitude was approximately 600 m, with slope angles ranging from 40% to 60%. The geological structure in the region varies from sedimentary marl and acidic volcanic rocks, such as dacite, rhyodacite, and rhyolite (Anonymous 2002). Depending on the varied lithology, soil texture ranges from clay loam and silty clay loam to sandy loam and loamy clay, characterized mainly by acidity originating from base cation leaching due to abundant precipitation and organic matter (*e.g.*, moder and mull humus forms); these characteristics are among the key soil features (Yener and Altun 2017). The study site's climate exhibits the typical humid conditions of the Eastern Black Sea subzone, characterized by mild winters, warm summers, and evenly distributed rainfall throughout the year.

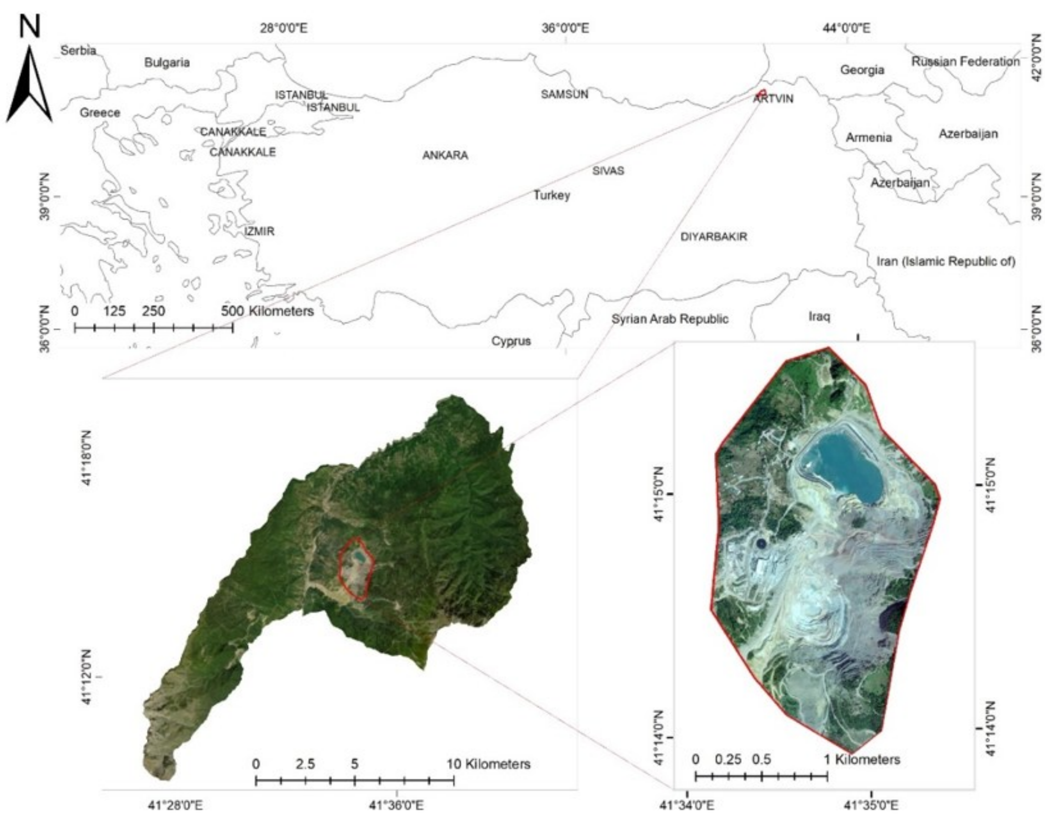


Fig. 1. Location map of the study area

The mean annual temperature is approximately 11.2 °C, and annual rainfall totals 1213 mm (Yener 2023), which extends the growing season from May to October. The climate is classified as AB'1rb'3 in the Thornthwaite system, indicating a perhumid, mesothermal regime with no seasonal moisture deficit.

The vegetation structure is ecologically rich – dominated by coniferous and broadleaf species, including *Picea orientalis*, *Fagus orientalis*, *Abies nordmanniana*, *Pinus sylvestris*, and *Alnus glutinosa*. The understory hosts a variety of woody shrubs and subshrubs, including *Sorbus aucuparia*, *Prunus officinalis*, *Ilex colchica*, *Sambucus nigra*, *Vaccinium myrtillus*, *Lonicera caucasica*, *L. xylosteum*, *Ribes biebersteinii*, *R. orientale*, *Rhododendron ponticum*, and *R. luteum* (Anşin 1980).

Soil Sampling and Analyses

Soil sampling was carried out in the summer of 2018 across 15 randomly distributed sample plots (on mine tailings). Topsoil (0 to 15 cm depth) was sampled in disturbed form (Fig. 2) because the acid-neutralizing effect of WA application is minimal at deeper soil layers but pronounced in the topsoil (Arvidsson and Lundkvist 2003; Hamidi *et al.* 2021; Baloch *et al.* 2024).

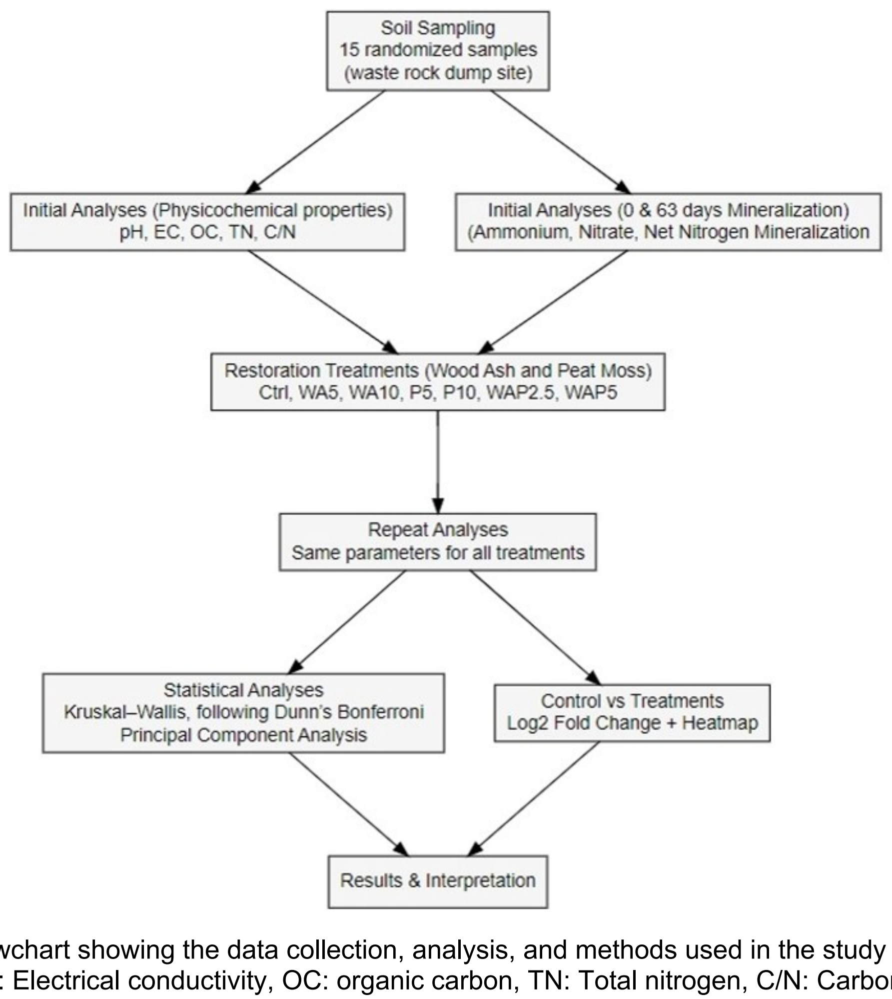


Fig. 2. Flowchart showing the data collection, analysis, and methods used in the study (pH: Soil acidity, EC: Electrical conductivity, OC: organic carbon, TN: Total nitrogen, C/N: Carbon / Nitrogen ratio; Ctrl: Control, WA5: 5% Wood Ash, WA10: 10% Wood Ash, P5: 5% Peat, P10: 10% Peat, WAP2.5: 2.5% Wood Ash+Peat, WAP5: 5% Wood Ash+Peat).

Before analysis, all soil samples were air-dried, hand-crushed in a porcelain mortar, and sieved through a 2-mm mesh. The pH and electrical conductivity (EC) were determined in 1:2.5 and 1:5 soil-water suspensions, respectively. Walkley-Black's wet digestion method was employed to quantify soil organic carbon, which was then converted to soil organic matter by multiplying it by 1.724 (Kalra and Maynard 1991). The Kjeldahl digestion technique was used to determine total nitrogen (TN), and the carbon-to-nitrogen (CN) ratio was calculated (Pansu and Gautheyrou 2007). The microdistillation technique, as described by Bremner and Keeney (1965), was used to determine the potentially mineralizable nitrogen (NO_3^-–N plus NH_4^+–N) at the beginning and on day 63 of incubation. Net mineral nitrogen on the 63rd day (Ammonium for 63 days: Ammonium 63; Nitrate for 63 days: Nitrate63; Net N mineralization for 63 days: TN63) was calculated as the difference between the beginning and the 63rd day (Guleryuz *et al.* 2007). The differences between days 0 and 63 reflect the dynamics of ammonification, nitrification, and net nitrogen mineralization. To optimize microbial activity for N mineralization analyses, soil moisture was adjusted to 60% of the water-holding capacity (WHC) and maintained at 25 °C throughout the incubation period, following the methods of Stanford and Smith (1972) and Bregliani *et al.* (2010).

Amendments and their Application

The wood ash used in this study originated from residential areas, such as households and bakeries, where wood from deciduous and coniferous trees was burned. The commercial horticultural Sphagnum peat (peat moss) used in this study was obtained from a licensed supplier and is widely used in greenhouse and nursery production systems.

A range of application doses, consistent with rates used in other similar studies (Beauchemin *et al.* 2015; Abad-Valle *et al.* 2017), was employed in laboratory experiments to assess the effects of amendments (*e.g.*, wood ash and peat moss) on the physicochemical properties and nitrogen mineralization of polluted soils. Two amendment rates (5% and 10% w/w)) were applied to wood ash and peat moss, respectively, based on the neutralization potential of wood ash and the enhanced adsorption capacity of peat moss (Beauchemin *et al.* 2015; Marques *et al.* 2020).

Additionally, the low combined amendment input levels of 2.5% and 5% (w/w) were used to evaluate their potential synergistic effect (Heiskanen *et al.* 2022). The treatments were abbreviated as follows: Ctrl (Control), WA5 (5% Wood Ash), WA10 (10% Wood Ash), P5 (5% Peat), P10 (10% Peat), WAP2.5 (2.5% Wood Ash + Peat), and WAP5 (5% Wood Ash + Peat)

Data Analysis

The physicochemical and nitrogen mineralization properties of soils from waste rock dump sites, along with those of amendments such as WA and peat moss, were summarized using statistical metrics, including means, standard errors, and ranges. The Kruskal-Wallis test was used to examine the effects of soil amendments on selected soil properties, followed by Dunn's Bonferroni post hoc test for pairwise comparisons (Dunn 1964; SPSS 2010), and principal component analysis (PCA) was used to determine the overall effects of the amendments on soil components. The log2-fold changes were calculated using Eq. 1, and heatmaps of selected properties and nitrogen mineralization in mine-affected soils (experimental *vs*. control) were generated. This technique is commonly used to analyze and visualize relatively high-dimensional data. Fold-change is the logarithmized (log2) ratio of the experimental value to the control value (Love *et al.* 2014).

$$log_2(\,fold\text{-}change\,) = log_2\left(\frac{Experimental}{Control}\right) \quad (1)$$

In Eq. 1, "experimental" denotes the measured value; "treated" for each treatment group is compared with the "control" value obtained from the control group. The heatmap is an essential tool for visualizing changes in data, typically using colors such as red and green to indicate up- and down-regulation. Nevertheless, alternative color scales and methods, such as the patch grid, have been utilized to enhance clarity and ensure precision (Müller *et al.* 2021). Log2 fold change calculations, heatmap visualizations, and PCA were performed in Python using the Jupyter Notebook environment (Kluyver *et al.* 2016).

RESULTS AND DISCUSSION

Within the scope of the present study, which investigated the effects of applying WA and peat moss on the properties of mine-affected soil and on nitrogen mineralization, the following results were obtained.

Characterization of the Amendments

Both WA and peat moss exhibited distinct characteristics, as presented in Table 1. Wood ash exhibited a strongly alkaline reaction and elevated salinity, as observed in numerous studies (Odlare and Pell 2009; Domes *et al.* 2018; Medaiyese *et al.* 2023). These properties were attributed to a high content of base cations (Ca, K, Mg, and Na) derived from the combustion of organic compounds (Demeyer *et al.* 2001). In contrast, peat moss was acidic and non-saline (Richard *et al.* 2021; Nawu *et al.* 2024), owing to its composition, mainly cellulose, lignin, and polar organic compounds, and its abundant organic matter content (up to 90%) and nitrogen (Nawab *et al.* 2019). By contrast, peat moss exhibited substantially higher organic matter content, total nitrogen, and C/N ratio than WA (Nawu *et al.* 2024; Richard *et al.* 2021).

Table 1. Average Values for Selected Properties of the Amendments

Amendment	Properties					
	pH	EC (µS/cm)	OM (%)	OC (%)	TN (%)	C/N Ratio
Wood Ash	13.16	41400.0	0.39	0.23	0.06	3.95
Peat Moss	5.87	313.5	69.30	40.19	1.13	35.51

Physicochemical Properties and Nitrogen Mineralization in the Waste Rock Dumpsite Soils

Table 2 summarizes the physicochemical characteristics and nitrogen mineralization of soils from waste rock dumpsites. Very strongly to strongly acidic soils prevail at the waste rock dump site (WRDS), with a mean pH of 4.81 ± 0.1 (strongly acid), and non-saline conditions (EC range 4-116 µS/cm; mean EC 49.6 ± 7.43 µS/cm). The organic matter content of the WRDS soils ranged from 0.58% (extremely low) to 2.49% (moderate), with an average of 1.64 ± 0.15%. The nitrogen content in the study area averaged 0.10 ± 0.01% (range 0.06-0.20%), in the low-to-medium range.

The carbon-to-nitrogen ratio (CN), on the other hand, ranged from 3 to 26 and averaged 11.47±1.76, indicating relatively good decomposition. Acidified soils commonly result from mining activities (*e.g.*, copper and gold mining), which trigger ore dissolution and increase heavy-metal concentrations.

Table 2. Some Descriptive Statistics of Selected Soil Properties and Nitrogen Mineralization

Variables	Statistic	Medium						
		Ctrl	WA5	WA10	P5	P10	WAP2.5	WAP5
pH	x̄±SE	4.81±0.1	8.99±0.26	10.4±0.16	5.23±0.09	5.6±0.06	7.85±0.25	9.01±0.17
	M	4.93	9.14	10.44	5.26	5.62	7.9	8.85
	Range	3.68-5.21	7.13-10.82	9.41-11.70	4.38-5.81	5.06-5.96	6.41-9.89	7.70-9.94
EC (µS/cm)	x̄±SE	49.6±7.43	1329.4±112.5	3336.67±293.9	243.27±30.3	328.8±19.1	833.4±61.1	1492±81.48
	M	40	1312	3360	212	335	718	1530
	Range	4-116	750-2270	1434-6060	152-640	114-418	562-1333	912.-2171
OM (%)	x̄±SE	1.64±0.15	0.86±0.06	0.71±0.05	4.77±0.21	9.05±0.22	2.88±0.14	4.61±0.17
	M	1.68	0.85	0.73	4.88	9.23	2.76	4.58
	Range	0.58-2.49	0.34-1.29	0.20-0.55	3.17-6.13	7.31-10.64	1.89-3.99	2.00-3.99
OC (%)	x̄±SE	0.95±0.09	0.5±0.04	0.41±0.03	2.77±0.12	5.25±0.13	1.67±0.08	2.67±0.1
	M	0.97	0.49	0.43	2.83	5.35	1.6	2.66
	Range	0.34-1.44	0.20-0.75	0.12-0.55	1.84-3.55	4.24-6.17	1.10-2.31	2.00-3.43
TN (%)	x̄±SE	0.1±0.01	0.11±0.01	0.1±0.01	0.15±0.01	0.21±0.01	0.12±0.01	0.14±0.01
	M	0.1	0.1	0.1	0.15	0.21	0.11	0.14
	Range	0.06-0.20	0.08-0.17	0.08-0.17	0.10-0.19	0.16-0.27	0.08-0.17	0.10-0.10
CN	x̄±SE	11.47±1.76	4.73±0.41	4.4±0.38	18.87±1.05	25.2±0.93	14.6±0.85	19±0.98
	M	9.0	4.0	5.0	18.0	25.0	14.0	19.0
	Range	3.00-26.00	2.00-8.00	1.00-7.00	13.00-26.00	20.00-34.00	10.00-22.00	13.00-
Ammon0 (kg/ha)	x̄±SE	8.48±0.63	10.25±0.35	9.22±0.47	11.12±0.6	14.07±0.38	10.15±0.51	11.63±0.47
	M	8.14	10.04	8.95	10.85	13.56	9.77	11.66
	Range	4.88-15.46	8.14-12.48	5.43-12.21	8.41-17.90	13.26-17.90	7.32-11.99	8.95-14.65
Nitrate0 (kg/ha)	x̄±SE	6.98±0.3	8.01±0.42	10.58±0.57	9.87±0.43	13.26±0.72	9.44±0.28	13.71±0.59
	M	6.78	8.14	10.85	9.77	13.83	9.49	13.29
	Range	4.88-8.95	4.61-10.85	4.88-13.56	7.32-12.48	6.24-17.09	7.32-11.99	10.85-
TN0 (kg/ha)	x̄±SE	15.46±0.69	18.26±0.44	19.8±0.76	21±0.69	27.33±0.94	19.58±0.61	25.33±0.79
	M	14.92	18.17	19.53	21.16	27.13	18.72	25.23
	Range	11.39-	15.46-21.43	14.65-24.68	16.82-27.67	19.26-34.99	17.09-25.50	19.80-
Ammo-nium63 (kg/ha)	x̄±SE	7.9±0.75	6.51±0.53	6.19±0.74	9.6±1.01	10.34±1.6	7.97±0.82	7.02±0.68
	M	8.68	6.51	6.51	10.85	9.22	8.14	7.05
	Range	0.81-12.21	3.53-10.58	1.36-12.21	2.44-15.46	1.36-21.43	8.30-15.19	3.26-13.56
Nitrate63 (kg/ha)	x̄±SE	7.49±0.45	14.4±1.8	6.75±0.7	12.75±1.65	16.51±1.69	16.04±1.77	13.29±1.59
	M	7.6	14.65	6.51	11.94	14.38	14.11	10.85
	Range	4.34-10.85	3.80-29.30	2.71-11.12	4.61-26.04	7.87-24.96	8.41-30.11	4.61-24.41
TN63 (kg/ha)	x̄±SE	15.39±0.98	20.9±2.03	12.93±0.98	22.35±1.4	26.85±1.85	24.02±1.78	20.31±1.85
	M	15.73	20.89	11.66	20.89	27.13	22.51	17.63
	Range	7.60-21.43	9.22-35.53	7.32-20.89	14.38-34.45	9.22-38.79	13.29-38.25	7.87-31.74

Note: x̄: Mean, SE: Standard error, M: Median, Range: Minimum and maximum values.
pH: Soil acidity, EC: Electrical conductivity, OC: organic carbon, TN: Total nitrogen, C/N: Carbon / Nitrogen ratio, ammonium.0-63, Nitrate.0-63, and TNMin.0-63 indicate ammonium, nitrate, and total mineralization levels at days 0 and 63. Mediums: Ctrl: Control, WA5: 5% Wood Ash, WA10: 10% Wood Ash, P5: 5% Peat, P10: 10% Peat, WAP2.5: 2.5% Wood Ash+Peat, WAP5: 5% Wood Ash+Peat

While Andráš *et al.* (2013) reported pH values ranging from 4.21 to 6.11 in Slovakian copper mining soils, Saglam *et al.* (2020) observed a narrower range of 3.52 to 3.81 in soils near the mining site in Artvin. Adamo *et al.* (2002) reported a relatively acidic soil, with an average pH of 4.5 (range 3.4 to 7.4) in the Sudbury Smelting area of Ontario, Canada, following mining operations. Hu *et al.* (2018) reported a pH of 4.7 in gold mine tailing soils inthe Greater Khingan Mountains, NE China. On the other hand, non-saline soils from copper mining areas in Artvin, Turkey, and metal mining sites (*e.g.*, Pb-Ag-Zn sulfide deposit) in Avila, Spain, were also reported to have ECs of 1020 µS/cm and 497 µS/cm, respectively (Abad-Valle *et al.* 2017; Aybar *et al.* 2023). Relatively low soil organic matter is also common in metal mine-polluted soils (Andráš *et al.* 2013; Cai *et al.* 2015); this may be attributed to metal toxicity from mining operations, which can lead to microbial depletion (Karn *et al.* 2021). However, relatively high levels were also reported (Abad-Valle *et al.* 2017).

Low soil organic matter content, combined with acidification due to oxidation of sulfide minerals (*e.g.*, pyrite), typically leads to reduced nitrogen levels, particularly in mining-affected areas, as observed in the current study (Banning *et al.* 2008; Feketeová *et al.* 2021; Guo *et al.* 2022; Kracmarova-Farren *et al.* 2023). Among them, Guo *et al.* (2022) reported low organic carbon content (0.3% to 3.5%) and limited total nitrogen levels (0.07% to 0.1%) at a pyrite-like mining site in Anhui, China.

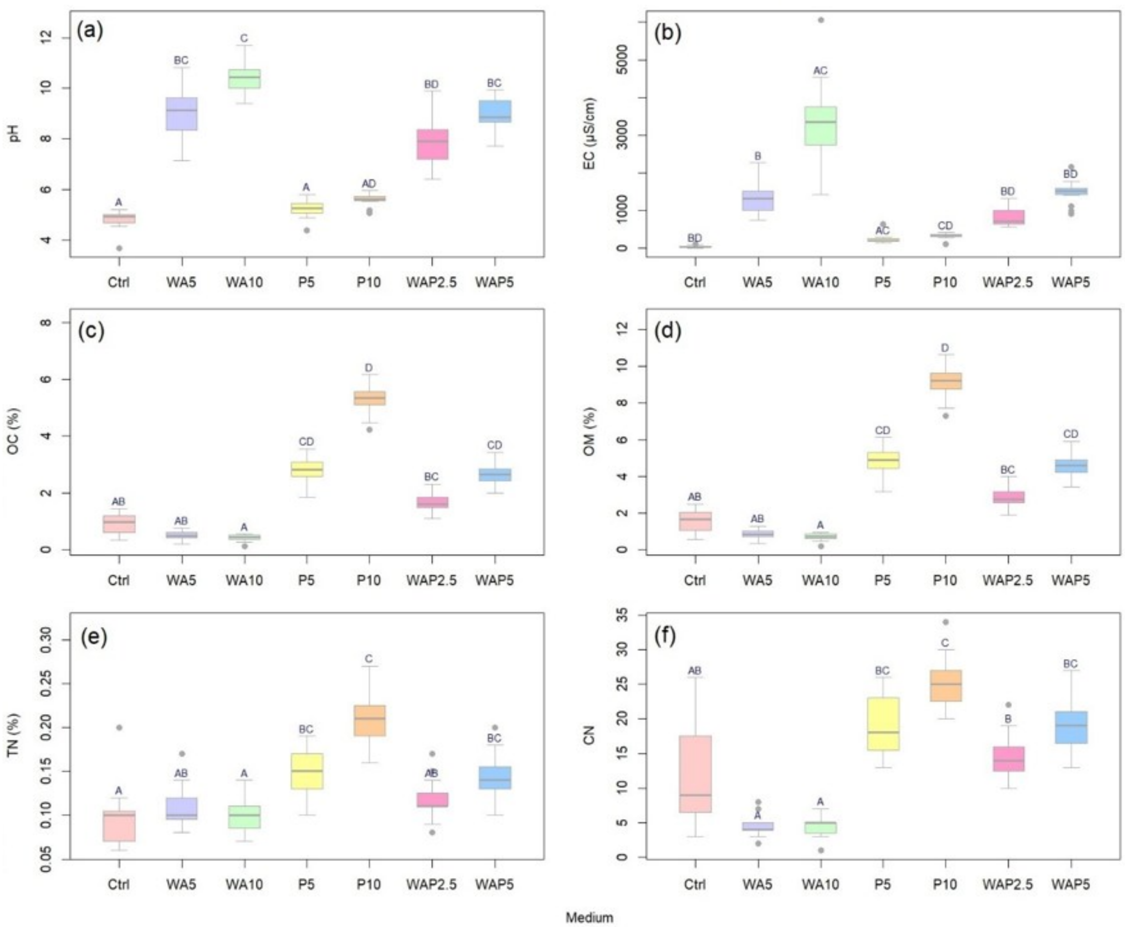
However, in some cases, a relatively high level of total nitrogen compared to control sites may be attributable to the use of explosives (*e.g.*, ANFO), which contain ammonium nitrate, for rock fragmentation, despite the limited organic matter (Hendry *et al.* 2018; Storb *et al.* 2023). Regarding nitrogen mineralization dynamics, NH_4^+–N (ammonium), NO_3^-–N (nitrate), and their sum (total nitrogen mineralization) were quantified and evaluated on day 0 and after 63 days of incubation. The ammonium content of WRDS soils averaged 8.48 ± 0.63 kg/ha on day 0 and 7.9 ± 0.75 kg/ha at day 63, while the nitrate content averaged 6.98 ± 0.30 kg/ha at day 0 and 7.49 ± 0.45 kg/ha at day 63. On the other hand, total N-mineralization varied between 15.46 ± 0.69 kg/ha and 15.39 ± 0.98 kg/ha over this time interval (Table 2). Over a 63-day incubation period, ammonium concentrations declined very slightly, and nitrate concentrations increased slightly, suggesting continued nitrification; however, net N-mineralization was minor. Typically, ammonium concentrations decrease, while the nitrate concentrations increase over time as mineralization and subsequent nitrification proceed. Long-term soil contamination from mining activities, *via* weathering and pH-driven heavy-metal release, adversely affects nitrogen mineralization by impairing microbial activity and function (Arslan *et al.* 2005; Banning *et al.* 2008; Rijk *et al.* 2024). Arslan *et al.* (2005) and Banning *et al.* (2008) reported similar findings (*e.g.*, diminished nitrogen mineralization) in soils impacted by wolfram mining in Bursa, Turkey, and bauxite mining in Western Australia; however, the former ascribed this phenomenon to heavy-metal-induced deterioration in microbial activity, while the latter attributed it to depletion of carbon and nitrogen contents. The latter reported similar improvements in organic matter, microbial biomass, and mineralization to those observed at control sites after 26 years of rehabilitation.

Effect of Wood Ash and Peat Moss

The impact of the amendments' application on soil properties and nitrogen forms was evaluated using three approaches. First, the Kruskal-Wallis test, followed by Dunn's post hoc test with a Bonferroni correction, was used to test for significant differences among treatments (Table 2, Figs. 3 and 5). Log_2FC was used to quantify differences in expression or abundance between the control and treatment groups (Fig. 4). This statistic indicates the magnitude and direction of change on a logarithmic scale. Heatmaps (Fig. 4) have recently been employed to visualize the effects of additives. The former identifies clustering or similarity patterns among variables (soil and nitrogen forms), whereas the latter combines log2FC and significance (-log10 *P*-values) to identify features that are both substantial and meaningful.

Effects on physicochemical properties of soils

The soil pH in the treatment groups differed significantly from the control ($P < 0.05$), except for P5 and P10 (Figs. 3a and 4). The most pronounced differences were observed under the WA10 treatment, followed by WA5 and WAP5. The WA10 and WA5 exhibited log2FC (L2FC) values of 1.11 and 0.90, respectively; the corresponding pH values for WA10, WA5, and WAP5 were 10.4 ± 0.16, 8.99 ± 0.26, and 9.01 ± 0.17, respectively, relative to the control (4.81 ± 0.1).



Note: Different uppercase letters above the boxplots indicate significant (p<0.05) differences across the applied amendments.
pH: Soil acidity, EC: Electrical conductivity, OC: organic carbon, TN: Total nitrogen, C/N: Carbon / Nitrogen ratio. Mediums: Ctrl: Control, WA5: 5% Wood Ash, WA10: 10% Wood Ash, P5: 5% Peat, P10: 10% Peat, WAP2.5: 2.5% Wood Ash+Peat, WAP5: 5% Wood Ash+Peat. Boxes represent the middle 50% of observations (interquartile range-IQR; 25th–75th percentiles), the central line indicates the median, and whiskers extend to 1.5 times the IQR; points beyond this range are shown as outliers.

Fig. 3. Changes in selected soil properties in response to applied amendments (a: pH, b: EC, c: OC, d: OM, e: TN, f: C/N).

The significant increases in pH resulting from applied WA and WAP can be attributed mainly to constituents of WA: Combustion mineralizes organic compounds and produces base cations (*e.g.*, Ca, K, Mg), which alkalinize the soil solution (Odlare and Pell 2009; Domes *et al*. 2018; Medaiyese *et al*. 2023; Rolka *et al*. 2023). Blonska *et al*. (2023) explained these significant pH elevations as reductions in exchangeable and hydrolytic acidity.

Peat moss applied alone did not significantly affect soil pH (P > 0.05), but it did so when combined with WA, likely owing to the alkaline properties of WA. Results for pH changes following WA application varied. Beauchemin *et al*. (2015) reported an increase in pH from 8.3 to 9.4 at a Canadian gold mine. Chan *et al*. (2008) reported a small change (from 4.9 to 6.8) in Australia, whereas Heviánková *et al*. (2014) from the Czech Republic reported substantially larger pH differences (2.19 to 7.19). However, significant decreases in pH were also reported after the peat application (Hu *et al*. 2018).

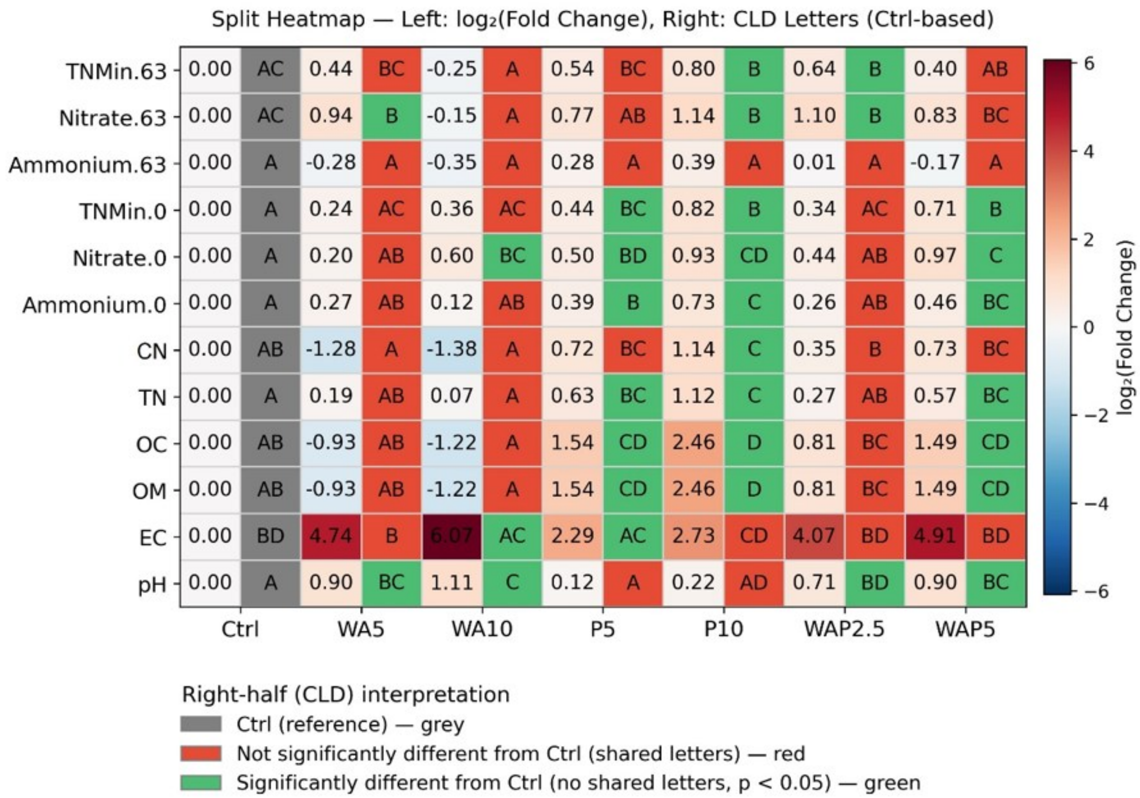
Soil EC also differed significantly in response to applications of WA10 and P5. The increases were log2FC = 6.07 and 2.29, meaning EC increased from 49.6 ± 7.43 µS/cm to 3336.67 ± 293.94 µS/cm and to 243.27 ± 30.31 µS/cm, respectively (Figs. 3b and 4). The increases in EC were more pronounced with WA10 than with P5. The elevated EC from additives may result from the release of weakly bound cations, anions, and soluble salts following application (Chan *et al*. 2008; Maljanen *et al*. 2015; Fernández-Delgado Juárez *et al*. 2020). An and Park (2021), for example, found that the EC of control soils significantly increased from 350 µS/cm to 1530 µS/cm ($P < 0.001$), suggesting the release of soluble salts. Peat moss also significantly ($P < 0.05$) increased the EC owing to higher soluble ion content and calcium concentration (Kwak *et al*. 2016; Marques *et al*. 2020; Kim *et al*. 2022). For example, Marques *et al*. (2020) reported a significant increase in EC from 35.3 µS/cm to 448 µS/cm after applying peat at 5%-10% in a clayey tropical soil in Brazil.

While peat moss at 10% (P10) significantly increased TN content from 0.1 ± 0.01% to 0.21 ± 0.01%, peat moss at 5% (P5), 10% (P10) and peat moss combined with WA at 5% (WAP5) also enhanced the OC content, from 0.95 ± 0.09% to 2.77 ± 0.12%, 5.25 ± 0.13%, and 2.67 ± 0.1%, respectively (Table 2, Figs. 3d-e). Figure 4 further indicates that P5, P10, and WAP5 altered TN and OC contents in soil to varying degrees. The treatment P10 was the most influential for both OC and TN, with log2-fold changes of 2.46 (~5.50) and 1.12 (~2.17), respectively (Fig. 4).

As shown in Table 2 and Figs. 3d–e, TN and OC were influenced by peat moss and by peat moss combined with wood ash. However, the most pronounced effect was observed under the P10 treatment. An increase in organic matter due to the addition of organic amendments either enhances TN content or reduces the availability of heavy metals, a common problem in mine-affected soils, by enhancing their immobilization, creating stable complexes, and facilitating processes such as ion exchange, chelation, coagulation, and peptization (Mortensen 1963; Kabata-Pendias 2000; Weng *et al*. 2002).

Enhancement of organic carbon through organic amendments–primarily peat moss, owing to its recalcitrance to microbial decomposition (Nawu *et al*. 2024) –the associated improvement in total nitrogen was also documented in other studies (Dietrich *et al.* 2017; Hu *et al.* 2018; Nawu *et al.* 2024). While Wang *et al.* (2024) attributed this improvement in TN (15.75 mg kg^{-1} to 189.583 mg kg^{-1}) to an enhanced bacterial community, Nawu *et al.* (2024) attributed this improvement (from 1755 mg kg^{-1} to 3290 mg kg^{-1}) to the higher nitrogen content of peat.

The P10 application also improved the C/N ratio (Figs. 3f and 4) by 1.14 L2FC (~2.2), which may be attributed to increased OC and TN in the peat (Nawu *et al.* 2024). Rijk *et al.* (2024) also reported similar results.



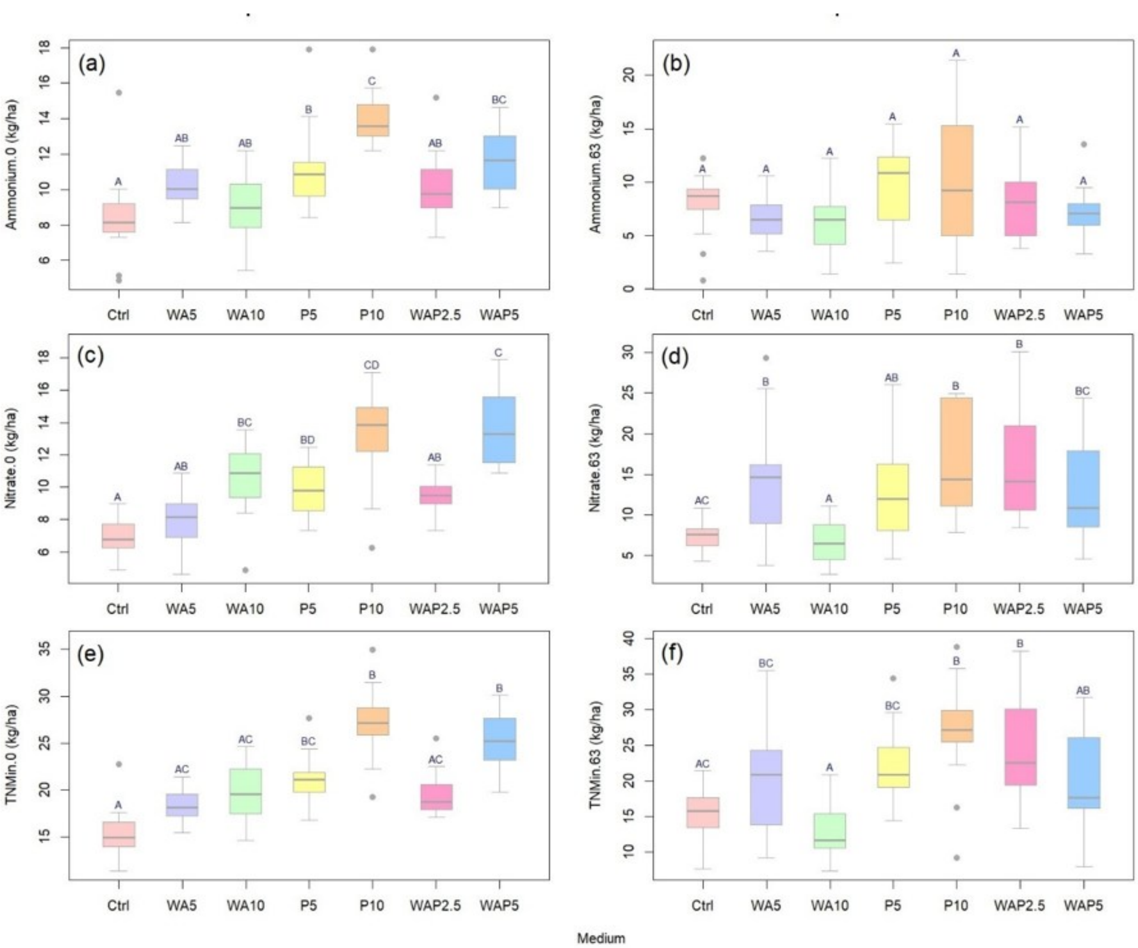
Note: Ctrl: Control, WA5: 5% Wood Ash, WA10: 10% Wood Ash, P5: 5% Peat, P10: 10% Peat, WAP2.5: 2.5% Wood Ash+Peat, WAP5: 5% Wood Ash+Peat
pH: Soil acidity, EC: Electrical conductivity, OC: organic carbon, TN: Total nitrogen, C/N: Carbon / Nitrogen ratio; Ammonium.0-63, Nitrate.0-63, and TNMin.0-63 indicate ammonium, nitrate and total mineralization levels at day 0 and 63, respectively

Fig. 4. Log_2 fold change and heatmap visualization of soil properties and nitrogen mineralization, showing significant differences relative to the control group (upper case letters indicate significant difference by experimental groups according to Dunn-Bonferroni test following Kruskal-Wallis)

Effects on nitrogen mineralization

At the initial stage of incubation, peat– and peat-WA -based amendments markedly improved soil mineral-N relative to the control (Figs. 5a-f). Improvements in the initial mineral N pool are consistent with previous studies, indicating that peat-based organic amendments increase the supply of labile organic matter and thereby stimulate N-mineralization, while WA-based materials raise soil pH and base cation availability, thereby improving microbial activity in acidic soils (Pitman 2006; Gómez-Rey *et al.* 2012; Anisimova *et al.* 2019).

Figures 4 and 5a indicate that initial ammonium concentrations increased from 8.48 ± 0.63 kg ha^{-1} to 11.12 ± 0.60, 14.07 ± 0.38, and 11.63 ± 0.47 kg ha^{-1}, respectively, corresponding to log2FCs of 0.39, 0.73, and 0.46 (≈ 31%–66% increases over the control). Likewise, nitrate at day 0 increased from 6.98 ± 0.30 kg ha^{-1} in the control to 10.58 ± 0.57 kg ha^{-1} in WA10, 9.87 ± 0.43 kg ha^{-1} in P5, 13.26 ± 0.72 kg ha^{-1} in P10, and 13.71 ± 0.59 kg ha^{-1} in WAP5 (log2FC = 0.60, 0.50, 0.93 and 0.97, respectively; Fig. 5c), indicating up to nearly twofold increase of the nitrate pool. Such short-term increases in nitrate and N mineralization following the application of organic amendments such as WA and peat have been reported in both incubation and pot studies (Gómez-Rey *et al.* 2012; Abbasi *et al.* 2013; Anisimova *et al.* 2019), and are attributed to increased nitrification potential, microbial activity, and biomass, thereby improving N-dynamics. An opposite trend in nitrate after organic amendments (*e.g.*, WA), unlike that observed in the present study, was documented by Maljanen *et al.* (2015) and Ibeto *et al.* (2023), suggesting that higher concentrations of extractable ions promote nitrification *via* WA (Klemedtsson *et al.* 2010). However, there are also instances, such as in the studies by Saarsalmi *et al.* (2014) and Maljanen *et al.* (2014), which reported no significant changes in soil nitrate and ammonium levels following wood ash treatments.



Note: Different uppercase letters above the boxplots indicate significant differences across the applied amendments. Ammonium.0-63, Nitrate.0-63, and TNMin.0-63 indicate ammonium, nitrate and total mineralization levels at day 0 and 63, respectively. Mediums: Ctrl: Control, WA5: 5% Wood Ash, WA10: 10% Wood Ash, P5: 5% Peat, P10: 10% Peat, WAP2.5: 2.5% Wood Ash+Peat, WAP5: 5% Wood Ash+Peat. Boxes represent the middle 50% of observations (interquartile range-IQR; 25th–75th percentiles), the central line indicates the median, and whiskers extend to 1.5 times the IQR; points beyond this range are shown as outliers.

Fig. 5. Changes in nitrogen mineralization in response to applied amendments (a: Ammonium.0, b: Ammonium.63, c: Nitrate.0, d: Nitrate.63, e: TNMin.0, f: TNMin.63).

As a result, total mineral-N content at day 0 (TNMin.0) increased from 15.46 ± 0.69 kg ha^{-1} in the control to 21 ± 0.69 kg ha^{-1}, 27.33 ± 0.94 kg ha^{-1}, and 25.33 ± 0.79 kg ha^{-1} under P5, P10, and WAP5 (log2FC = 0.44, 0.82, and 0.71, *i.e.*, ~36%–77% higher than the control). This pattern (Fig. 5e) matches previous studies, indicating that combined WA-peat enhances N supply more than ash alone, especially in acidic or nutrient-depleted mine-affected soils. This improvement is attributed to increased nutrient availability and enhanced plant growth (Gómez-Rey *et al.* 2012; Heiskanen *et al.* 2022), as well as to changes in N forms resulting from elevated pH and heavy-metal immobilization (Ibeto *et al.* 2023).

After 63 days, ammonium concentrations converged across treatments (6.19–10.34 kg ha^{-1}) and did not differ significantly from the control (Fig. 5b). In contrast, nitrate (Fig. 5d) and total mineral N (Fig. 5f) remained elevated in specific treatments: nitrate nearly doubled under WA5, P10, and WAP2.5 (7.49 ± 0.45 kg ha^{-1} in the control *vs*. 14.4 ± 1.8, 16.51 ± 1.69 and 16.04 ± 1.77 kg ha^{-1}; log2FC = 0.94, 1.14 and 1.10, respectively), and TNMin.63 increased from 15.39 ± 0.98 kg ha^{-1} to 26.85 ± 1.85 kg ha^{-1} in P10 and 24.02 ± 1.78 kg ha^{-1} in WAP2.5 (log2FC = 0.80 and 0.64, respectively). Taken together, these patterns indicate that the 10% peat amendment (P10) and its mixtures with wood ash (particularly WAP5 at day 0 and WAP2.5 at day 63) not only increased the initial mineral N pool but also sustained net nitrification over time. In contrast, wood ash alone at 5% (WA5) mainly promoted nitrate accumulation during the later phase of incubation. On the other hand, responses of ammonium and nitrate concentrations to WA application vary widely depending on site characteristics. For example, on a site with a relatively low C/N ratio, WA increased N mineralization without affecting net nitrification or net ammonification (Rosenberg *et al.* 2010).

This behavior is consistent with numerous studies demonstrating that wood ash-based amendments, owing to their high acid-neutralizing capacity and substantial base-cation content (*e.g.*, Ca, Mg, K), effectively alleviate soil acidity. This elevation in soil pH creates an optimal environment for bacterial proliferation, stimulating microbial activity and favoring fast-growing copiotrophic bacteria. Consequently, this enhanced bacterial activity accelerates net N mineralization and strongly promotes nitrification, the biological oxidation of NH_4^+ to NO_3^-. Ultimately, these combined physicochemical and biological shifts significantly increase N mineralization and inorganic N availability in acidic organic soils, particularly when the initial nitrogen supply is not limiting (Pitman 2006; Gómez-Rey *et al.* 2012; Abbasi *et al.* 2013; Brais *et al.* 2015; Bang-Andreasen *et al.* 2017; An and Park 2021). However, in some cases (*e.g.*, in N-limited ecosystems), the stimulated microbial biomass rapidly immobilizes available inorganic N. Coupled with reduced ammonification, this biotic immobilization offsets anticipated increases in net N mineralization, ultimately restricting its release to the soil (Gómez-Rey *et al.* 2012).

Unlike WA, peat moss has a high C:N ratio, functioning as a biologically mediated slow-release amendment that improves microbial N immobilization and reduces initial nitrate accumulation (Bossolani *et al.* 2023; Li 2021; N'Dayegamiye *et al.* 1997). The present results (Fig. 4 and Fig 5) confirm this. P10 application significantly increased OC, TN, and the C:N ratio, while P10 and WAP5 initially supplied higher mineral N due to inherent soluble N pools (Lazicki *et al.* 2020). Peat's biological buffering capacity emerged over time. By Day 63, P10 and WAP2.5 exhibited significantly higher mineral N than the control, suggesting that soil microbial biomass effectively acted as a temporary sink—sequestering early-available N to prevent leaching before gradually remineralizing it, thereby ensuring long-term nutrient availability.

Overall Soil Physicochemical Properties and Nitrogen Mineralization Responses to WA and Peat Treatments Using Principal Component Analysis

The principal component analysis (PCA) biplot shows positive effects of WA and peat additives on soil properties and nitrogen mineralization dynamics, relative to control samples that are acidified and have low plant nutrient levels. The principal components PC1, PC2, and PC3 accounted for 48.3%, 19.2%, and 11.8%, respectively, of the total variation (79.3%) (Table 3, Fig. 6).

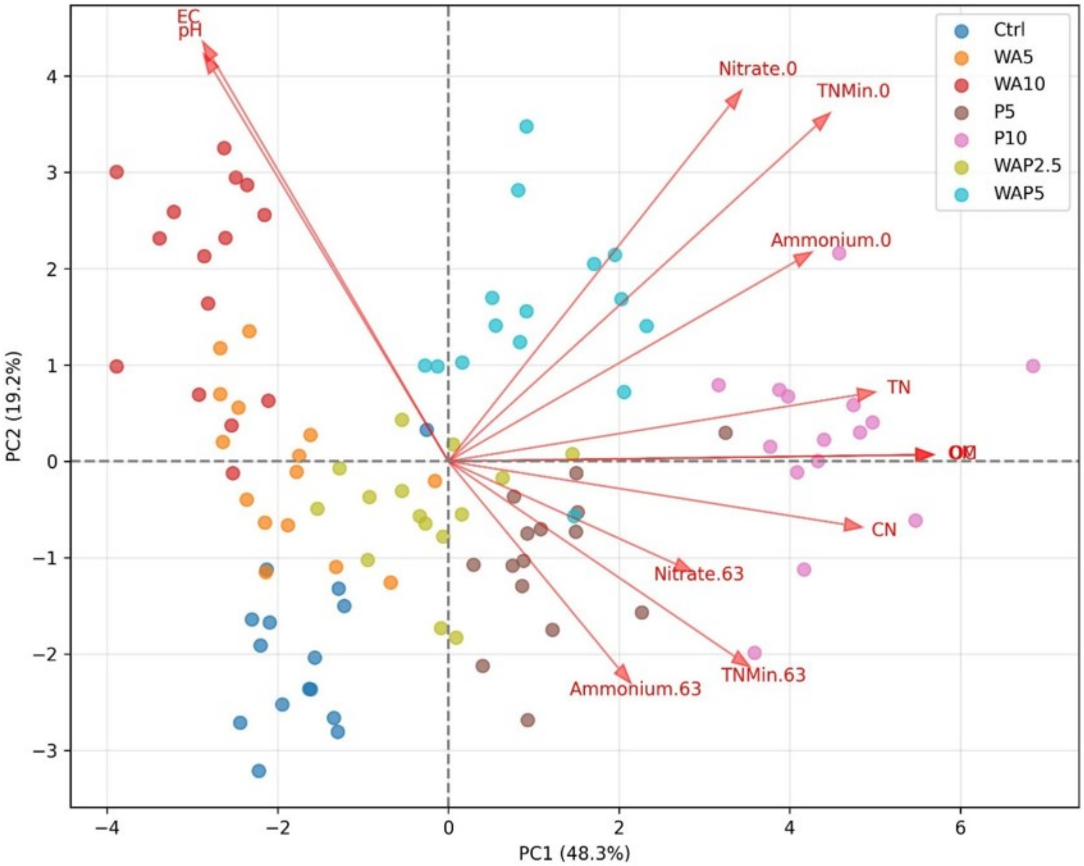
Table 3. Principal Component Analysis: Variables, Eigenvalues, and Explained Variances

Variables	PC1	PC2	PC3
pH	-0.48	**0.72**	0.35
EC	-0.49	**0.74**	0.21
OM	**0.97**	0.01	-0.15
OC	**0.97**	0.01	-0.15
TN	**0.85**	0.12	0.01
C/N Ratio	**0.82**	-0.12	-0.24
Ammonium.0	**0.72**	0.37	-0.08
Nitrate.0	**0.58**	**0.65**	0.03
TNMin.0	**0.76**	**0.61**	-0.03
Ammonium.63	0.35	-0.38	0.01
Nitrate.63	0.47	-0.19	**0.81**
TNMin.63	**0.59**	-0.36	**0.71**
Eigen Value	5.85	2.33	1.43
Variance (%)	48.3	19.2	11.8
Cumulative Variance (%)	48.3	67.5	79.3

* PC1, PC2, and PC3 denote the principal components.

The first eigenvector exhibited strong positive loadings on OM (0.97), TN (0.85), C/N ratio (0.82), initial TNMin0 (0.76), Ammonium.0 (0.72), Nitrate.0 (0.58), and total TNMin.63 (0.59), and negative loadings on pH (-0.48) and EC (-0.49). This pattern could be due to the peat additive, particularly P10, supplying the soil with a relatively high proportion of organic matter and nitrogen, both of which are strongly correlated with nitrogen dynamics (*e.g.*, nitrogen mineralization) (Nawab *et al.* 2019; Richard *et al.* 2021). Rijk *et al.* (2024) reported similar findings, explaining the strong effect of peat through the first component, which accounted for 40.3% of the variation in their study *vs*. 48.3% in this study; this component was positively correlated with organic carbon and cation exchange capacity. By contrast, the second component unlike the first, showed strong positive loadings for pH (0.72), EC (0.74), Nitrate.0 (0.65), and initial TNMin.0 (0.61), all of which are controlled by wood ash, especially WA10, suggesting that WA, particularly WA10, promotes nitrifying bacteria, explained by increases in soil pH (Bang-Andreasen *et al.* 2017; An and Park 2021; Bang-Andreasen *et al.* 2021). Bang-Andreasen *et al.* (2017), for example, reported similar results from PCA analysis, showing that WA application was positively correlated with pH and negatively correlated with organic matter and nitrogen. Pukalchik *et al.* (2017) also documented the acid-reducing effects of wood ash using PCA. The third component accounted for the smallest proportion of variance, was primarily associated with Nitrate.63 and TNMin.63, and had positive loadings of 0.81 and 0.71, respectively.

Each amendment, when applied alone, affected soil components. However, the combined effects (*e.g.*, WAP5) are also evident from the positive loadings in PC1 and PC2 (Fig. 6), which suggest that organic substrates derived from peat and the alkaline medium were attributable to base cations originating from wood ash.



Mediums: Ctrl: Control, WA5: 5% Wood Ash, WA10: 10% Wood Ash, P5: 5% Peat, P10: 10% Peat, WAP2.5: 2.5% Wood Ash+Peat, WAP5: 5% Wood Ash+Peat

Fig. 6. Principal component analysis biplot based on the correlation matrix of soil physicochemical properties and nitrogen mineralization across different application rates of soil amendments.

The PCA also shows the pronounced effects of relatively high peat and wood ash combined peat (*e.g.*, P10 and WAP5) on nitrogen mineralization at the initial stage of incubation (at day 0), and a smaller portion of them (*e.g.,* P5 and WAP2.5) on it at the final stage of incubation (at day 63). The initial promoting effects of relatively large amounts of organic amendments may be due to the rapid incorporation of organic compounds and base cations into mine-polluted soils, which enhances microbial activity (Lazicki *et al*. 2020). The pronouncedly small portion of the organic amendments in the final stages of mineralization may be due to system saturation or nitrogen immobilization. For example, Rijk *et al*. (2024) reported an insignificant change following a further increase in biochar (wood ash in our case) in peat-amended soil, suggesting that its positive effect is more pronounced in soil with low organic carbon.

CONCLUSIONS

1. The results highlighted that the amendments, alone or in combination, can cause significant changes in both soil physicochemical properties and nitrogen dynamics except for Ammonium.63.
2. Findings from the analyses suggest that variation in soil components is driven by two factors: first, wood ash's neutralization potential, which promotes decomposer microorganisms and base cations; and second, the organic matter from peat moss application, which dominates nitrogen availability and mineralization.
3. More specifically, the mixture of amendments (*e.g.*, WAP2.5 and WAP5) created environments that were more conducive to improved physicochemical properties and nitrogen mineralization than the amendments alone, owing to slightly to moderately alkaline conditions, moderate to high levels of organic matter, and moderate total nitrogen levels.
4. These amendments could be used as artificial topsoil for the reclamation of slate dumps. However, long-term investigations are needed to support such lab-based experimental studies.

ACKNOWLEDGMENTS

Conflict of Interest

The authors declare no competing interests.

REFERENCES CITED

Abad-Valle, P., Iglesias-Jiménez, E., and Alvarez-Ayuso, E. (2017). "A comparative study on the influence of different organic amendments on trace element mobility and microbial functionality of a polluted mine soil," *Journal of Environmental Management* 188, 287-296. https://doi.org/10.1016/j.jenvman.2016.12.017

Abbasi, M. K., Afsar, N., and Rahim, N. (2013). "Effect of wood ash and compost application on nitrogen transformations and availability in soil-plant systems," *Soil Science Society of America Journal* 77(2), 558-567. https://doi.org/10.2136/sssaj2012.0365

Acatay, A. (1968). "Smoke damages from copper smelter factory in Murgul (in Turkish)," *İstanbul Üniversitesi Orman Fakültesi Dergisi A* 18(1).

Adamo, P., Dudka, S., Wilson, M. J., and McHardy, W. J. (2002). "Distribution of trace elements in soils from the Sudbury smelting area (Ontario, Canada)," *Water Air and Soil Pollution* 137(1-4), 95-116. https://doi.org/10.1023/A:1015587030426

Aide, M. (2022). "Aluminum soil chemistry: Influence on soil health and forest ecosystem productivity," *Agricultural Sciences* 13, 917-935. doi: 10.4236/as.2022.138057. https://doi.org/10.4236/as.2022.138057

Allgaier, F. (1997). "Environmental effects of mining," in: *Mining Environmental Handbook: Effects of Mining on The Environment and American Environmental Controls on Mining*, World Scientific, pp. 132-189. https://doi.org/10.1142/9781860943768_0005

An, J. Y., and Park, B. B. (2021). "Effects of wood ash and N fertilization on soil chemical properties and growth of *Zelkova serrata* across soil types," *Scientific Reports* 11(1). https://doi.org/10.1038/s41598-021-93805-5

Andráš, P., Turisová, I., Lacková, E., Kharbish, S., Krnác, J., and Cmielová, L. (2013). "Environmental risk due to heavy metal contamination caused by old copper mining activity at Lubietová deposit, Slovakia," *Energy and Environment Research* 3(2), article 182. https://doi.org/10.5539/eer.v3n2p182

Anisimova, T. Y., Naliukhin, A. N., Hamitowa, S. M., Avdeev, Y. M., and Belozerov, D. A. (2019). "Responses of soil properties and crop productivity to peat-fertilizers in Russia," *International Journal of Pharmaceutical Research and Allied Sciences* 8(2), 180-189.

Anonymous. (2002). "Maden Tetkik ve Araştırma Genel Müdürlüğü, 1/500.000 Ölçekli Trabzon ve Samsun Paftaları (General Directorate of Mineral Exploration and Research, Trabzon and Samsun Map Sheets at a Scale of 1/500,000)," Maden Tetkik ve Araştırma Enstitüsü, Ankara.

Anşin, R. (1980). "Doğu Karadeniz Bölgesi Florası ve Asal Vejetasyon Tiplerinin Floristik İçerikleri (Flora of the Eastern Black Sea Region and Floristic Contents of its Main Vegetation Types)," Doçentlik Tezi, Karadeniz Teknik Üniversitesi, Trabzon.

Antonelli, P. M., Coghill, M. G., Gardner, W. C., and Fraser, L. H. (2021). "Semiarid bunchgrasses accumulate molybdenum on alkaline copper mine tailings: Assessing phytostabilization in the greenhouse," *SN Applied Sciences* 3(747). https://doi.org/10.1007/s42452-021-04732-z

Arslan, H., Güleryüz, G., Kirmizi, S., and Güçer, S. (2005). "Nitrogen mineralization in mine waste-contaminated soils," *Fresenius Environmental Bulletin* 14(10), 900-906.

Arvidsson, H., and Lundkvist, H. (2003). "Effects of crushed wood ash on soil chemistry in young Norway spruce stands," *Forest Ecology and Management* 176(1), 121-132. https://doi.org/10.1016/S0378-1127(02)00278-5

Aybar, M., Saglam, B., Daghan, H., Tüfekçioglu, A., Köleli, N., and Yilmaz, F. N. (2023). "Phytoextraction of heavy metal (Cu, Zn, Pb) from mining area by sunflower (*Helianthus annuus*)," *Kastamonu University Journal of Forestry Faculty* 23(1), 75-85. https://doi.org/10.17475/kastorman.1269527

Baloch, S. B., Ali, S., Bernas, J., Moudrý, J., Konvalina, P., Mushtaq, Z., Murindangabo, Y. T., Onyebuchi, E. F., Baloch, F. B., Ahmad, M., Saeed, Q., and Mustafa, A. (2024). "Wood ash application for crop production, amelioration of soil acidity and contaminated environments," *Chemosphere* 357, article 141865. https://doi.org/10.1016/j.chemosphere.2024.141865

Bang-Andreasen, T., Nielsen, J. T., Voriskova, J., Heise, J., Ronn, R., Kjoller, R., Hansen, H. C. B., and Jacobsen, C. S. (2017). "Wood ash ınduced pH changes strongly affect soil bacterial numbers and community composition," *Frontiers in Microbiology* 8. https://doi.org/10.3389/fmicb.2017.01400

Bang-Andreasen, T., Peltre, M., Ellegaard-Jensen, L., Hansen, L. H., Ingerslev, M., Ronn, R., Jacobsen, C. S., and Kjoller, R. (2021). "Application of wood ash leads to strong vertical gradients in soil pH changing prokaryotic community structure in forest top soil," *Scientific Reports* 11(1). https://doi.org/10.1038/s41598-020-80732-0

Banning, N. C., Grant, C. D., Jones, D. L., and Murphy, D. V. (2008). "Recovery of soil organic matter, organic matter turnover and nitrogen cycling in a post-mining forest rehabilitation chronosequence," *Soil Biology and Biochemistry* 40(8), 2021-2031.

https://doi.org/10.1016/j.soilbio.2008.04.010
Barbu, C. H., Pavel, P. B., Moise, C. M., Sand, C., and Pop, M. R. (2017). "Neutralization of acid mine drainage with wood ash," *Revista De Chimie* 68(12), 2768-2770. https://doi.org/10.37358/RC.17.12.5975
Beauchemin, S., Clemente, J. S., MacKinnon, T., Tisch, B., Lastra, R., Smith, D., and Kwong, J. (2015). "Metal leaching in mine tailings: Short-term ımpact of biochar and wood ash amendments," *Journal of Environmental Quality* 44(1), 275-285. https://doi.org/10.2134/jeq2014.04.0195
Benidire, L., Pereira, S., Aboudrar, W., Hafidi, M., Castro, P., and Boularbah, A. (2022). "Remediation of metal-contaminated mine tailings by the application of organic and mineral amendments," *Journal of Soils and Sediments* 22, 482-495. https://doi.org/10.1007/s11368-021-03081-z
Blonska, E., Prazuch, W., Boron, P., and Lasota, J. (2023). "Effects of wood ash on the soil properties and fungal community structure in a beech forest in Poland," *Geoderma Regional* 34, article e00676. https://doi.org/10.1016/j.geodrs.2023.e00676
Bossolani, J. W., Leite, M. F., Momesso, L., Ten Berge, H., Bloem, J. and Kuramae, E. E., 2023. "Nitrogen input on organic amendments alters the pattern of soil-microbe-plant co-dependence," *Science of the Total Environment* 890, article 164347. https://doi.org/10.1016/j.scitotenv.2023.164347
Brais, S., Bélanger, N., and Guillemette, T. (2015). "Wood ash and N fertilization in the Canadian boreal forest: Soil properties and response of jack pine and black spruce," *Forest Ecology and Management* 348, 1-14. https://doi.org/10.1016/j.foreco.2015.03.021
Bregliani, M. M., Ros, G. H., Temminghoff, E. J. M., and van Riemsdijk, W. H. (2010). "Nitrogen mineralization in soils related to ınitial extractable organic nitrogen: Effect of temperature and time," *Communications in Soil Science and Plant Analysis* 41(11), 1383-1398. https://doi.org/10.1080/00103621003759387
Bremner, J., and Keeney, D. R. (1965). "Steam distillation methods for determination of ammonium, nitrate and nitrite," *Analytica Chimica Acta* 32, 485-495. https://doi.org/10.1016/S0003-2670(00)88973-4
Cai, L. M., Xu, Z. C., Qi, J. Y., Feng, Z. Z., and Xiang, T. S. (2015). "Assessment of exposure to heavy metals and health risks among residents near Tonglushan mine in Hubei, China," *Chemosphere* 127, 127-135. https://doi.org/10.1016/j.chemosphere.2015.01.027
Campillo-Cora, C., Rodríguez-Seijo, A., Pérez-Rodríguez, P., Fernández-Calviño, D., and Santás-Miguel, V. (2025). "Effect of heavy metal pollution on soil microorganisms: Influence of soil physicochemical properties. A systematic review," *European Journal of Soil Biology* 124, article 103706. https://doi.org/10.1016/j.ejsobi.2024.103706
Chan, K. Y., Van Zwieten, L., Meszaros, I., Downie, A., and Joseph, S. (2008). "Using poultry litter biochars as soil amendments," *Australian Journal of Soil Research* 46(5), 437-444. https://doi.org/10.1071/SR08036
Demeyer, A., Nkana, J. C. V., and Verloo, M. G. (2001). "Characteristics of wood ash and influence on soil properties and nutrient uptake: An overview," *Bioresource Technology* 77(3), 287-295. https://doi.org/10.1016/S0960-8524(00)00043-2
Deng, X. Z., Zhao, C. H., and Yan, H. M. (2013). "Systematic modeling of ımpacts of land use and land cover changes on regional climate: A review," *Advances in Meteorology* 2013, article 317678. https://doi.org/10.1155/2013/317678

Dietrich, S. T., MacKenzie, M. D., Battigelli, J. P., and Enterina, J. R. (2017). "Building a better soil for upland surface mine reclamation in northern Alberta: Admixing peat, subsoil, and peat biochar in a greenhouse study with aspen," *Canadian Journal of Soil Science* 97(4), 592-605. https://doi.org/10.1139/CJSS-2017-0021

Dold, B. (2008). "Sustainability in metal mining: from exploration, over processing to mine waste management," *Reviews in Environmental Science and Bio/Technology* 7(4), 275-285. https://doi.org/10.1007/s11157-008-9142-y

Domes, K. A., de Zeeuw, T., Massicotte, H. B., Elkin, C., McGill, W. B., Jull, M. J., Chisholm, C. E., and Rutherford, P. M. (2018). "Short-term changes in spruce foliar nutrients and soil properties in response to wood ash application in the sub-boreal climate zone of British Columbia," *Canadian Journal of Soil Science* 98(2), 246-263. https://doi.org/10.1139/cjss-2017-0115

Dourado, L. G. A., Bonfim-Silva, E. M., da Silva, T. J. A., Pinheiro, E. A. R., and Fenner, W. (2021). "Effects of wood ash and soil water potential on vegetative development of mung bean (*Vigna radiata* L.)," *Australian Journal of Crop Science* 15(3), 354-361. https://doi.org/10.21475/ajcs.21.15.03.p2710

Dunn, O. J. J. T. (1964). "Multiple comparisons using rank sums," *Technometrics* 6(3), 241-252. https://doi.org/10.1080/00401706.1964.10490181

Feketeová, Z., Hrabovský, A., and Šimkovic, I. (2021). "Microbial features ındicating the recovery of soil ecosystem strongly affected by mining and ore processing," *Int. J. Environ. Res. Public Health* 18(6), article 3240. https://doi.org/10.3390/ijerph18063240

Fernández-Delgado Juárez, M., Fabiani, G., Mazzier, T., Schönegger, D., Pietramellara, G., Gómez-Brandón, M., Insam, H. J. W., and Valorization, B. (2020). "Reclamation of acid soils with biomass ashes from pyrolytic wood liquefaction," *Waste Biomass Valor* 11, 5067-5078. https://doi.org/10.1007/s12649-019-00789-5

Forsberg, L. S., and Ledin, S. (2003). "Effects of iron precipitation and organic amendments on porosity and penetrability in sulphide mine tailings," *Water Air and Soil Pollution* 142(1-4), 395-408. https://doi.org/10.1023/A:1022036317408

Gómez-Rey, M. X., Madeira, M., and Coutinho, J. (2012). "Wood ash effects on nutrient dynamics and soil properties under Mediterranean climate," *Annals of Forest Science* 69(5), 569-579. https://doi.org/10.1007/s13595-011-0175-y

Guleryuz, G., Kirmizi, S., and Arslan, H. (2007). "Nitrogen mineralisation in the soils of alpine mat communities: an incubation experiment under laboratory conditions," *Turkish Journal of Botany* 31(4), 277-286.

Guo, J., Xuan, F., Li, D., Wang, J., and Zhang, B. (2022). "Variations of soil chemical properties and microbial community around the acid reservoir in the mining area," *Sustainability* 14(17), article 10746. https://doi.org/10.3390/su141710746

Haghighizadeh, A., Rajabi, O., Nezarat, A., Hajyani, Z., Haghmohammadi, M., Hedayatikhah, S., Asl, S. D., and Beni, A. A. (2024). "Comprehensive analysis of heavy metal soil contamination in mining Environments: Impacts, monitoring techniques, and remediation strategies," *Arabian Journal of Chemistry* 17(6), article 105777. https://doi.org/10.1016/j.arabjc.2024.105777

Hamidi, N. H., Ahmed, O. H., Omar, L., and Ch'ng, H. Y. (2021). "Soil nitrogen sorption using charcoal and wood ash," *Agronomy-Basel* 11(9), article 1801. https://doi.org/10.3390/agronomy11091801

Heiskanen, J., Ruhanen, H., and Hagner, M. (2022). "Effects of compost, biochar and ash mixed in till soil cover of mine tailings on plant growth and bioaccumulation of elements: A growing test in a greenhouse," *Heliyon* 8(2), article e08838. https://doi.org/10.1016/j.heliyon.2022.e08838

Hendry, M. J., Wassenaar, L. I., Barbour, S. L., Schabert, M. S., Birkham, T. K., Fedec, T., and Schmeling, E. E. (2018). "Assessing the fate of explosives derived nitrate in mine waste rock dumps using the stable isotopes of oxygen and nitrogen," *Science of The Total Environment* 640-641, 127-137. https://doi.org/10.1016/j.scitotenv.2018.05.275

Heviánková, S., Bestová, I., and Kyncl, M. (2014). "The application of wood ash as a reagent in acid mine drainage treatment," *Minerals Engineering* 56, 109-111. https://doi.org/10.1016/j.mineng.2013.10.032

Hu, Y. L., Mgelwa, A. S., Singh, A. N., and Zeng, D. H. (2018). "Differential responses of the soil nutrient status, biomass production, and nutrient uptake for three plant species to organic amendments of placer gold mine-tailing soils," *Land Degradation and Development* 29(9), 2836-2845. https://doi.org/10.1002/ldr.3002

Hytönen, J. (2003). "Effects of wood, peat and coal ash fertilization on Scots pine foliar nutrient concentrations and growth on afforested former agricultural peat soils," *Silva Fennica* 37(2), 219-234. https://doi.org/10.14214/sf.503

Ibeto, C. N., Lag-Brotons, A. J., Marshall, R., and Semple, K. T. (2023). "Wood ash effects on soil properties and *Lactuca sativa* growth in soils amended with digestate and poultry litter," *Journal of Plant Nutrition* 46(7), 1231-1245. https://doi.org/10.1080/01904167.2022.2067065

Jansone, B., Samariks, V., Okmanis, M., Klavina, D., and Lazdina, D. (2020). "Effect of high concentrations of wood ash on soil properties and development of young norway spruce (*Picea abies* (L.) Karst) and Scots pine (*Pinus sylvestris* L.)," *Sustainability* 12(22), article 9479. https://doi.org/10.3390/su12229479

Kabata-Pendias, A. (2000). *Trace Elements in Soils and Plants*, CRC press. https://doi.org/10.1201/9781420039900

Kalra, Y. P., and Maynard, D. G. (1991). *Methods Manual for Forest Soil and Plant Analysis*, Forestry Canada, Northwest Region, Northern Forestry Centre.

Karn, R., Ojha, N., Abbas, S., and Bhugra, S. (2021). "A review on heavy metal contamination at mining sites and remedial techniques," IOP Conference Series: *Earth and Environmental Science* 796(1), article 012013. https://doi.org/10.1088/1755-1315/796/1/012013

Kim, Y.-N., Lee, K.-A., Lee, M., and Kim, K.-R. (2022). "Synergetic effect of complex soil amendments to improve soil quality and alleviate toxicity of heavy metal(loid)s in contaminated arable soil: toward securing crop food safety and productivity," *Environmental Science and Pollution Research* 29(58), 87555-87567. https://doi.org/10.1007/s11356-022-21752-3

Klemedtsson, L., Ernfors, M., Björk, R., Weslien, P., Rütting, T., Crill, P., and Sikström, U. J. E. J. o. S. S. (2010). "Reduction of greenhouse gas emissions by wood ash application to a *Picea abies* (L.) Karst. forest on a drained organic soil," *European Journal of Soil Science* 61, 734-744. https://doi.org/10.1111/j.1365-2389.2010.01279.x

Kluyver, T., Ragan-Kelley, B., Pérez, F., Granger, B., Bussonnier, M., Frederic, J., Kelley, K., Hamrick, J., Grout, J., Corlay, S., Ivanov, P., Avila, D., Abdalla, S., Willing, C., and Jupyter Development Team. (2016). "Jupyter Notebooks – A publishing format for reproducible computational workflows," in: F. Loizides and B. Schmidt (Eds.), *Positioning and Power in Academic Publishing: Players, agents and Agendas* (pp. 87-90), IOS Press. https://doi.org/10.3233/978-1-61499-649-1-87

Kracmarova-Farren, M., Papik, J., Uhlik, O., Freeman, J., Foster, A., Leewis, M.-C., and Creamer, C. (2023). "Compost, plants and endophytes *versus* metal contamination: choice of a restoration strategy steers the microbiome in polymetallic mine waste," *Environmental Microbiome* 18(1), article 74. https://doi.org/10.1186/s40793-023-00528-3

Kwak, J. H., Chang, S. X., Naeth, M. A., and Schaaf, W. (2016). "Nitrogen transformation rates are affected by cover soil type but not coarse woody debris application in reclaimed oil sands soils," *Restoration Ecology* 24(4), 506-516. https://doi.org/10.1111/rec.12344

Lazicki, P., Geisseler, D., and Lloyd, M. (2020). "Nitrogen mineralization from organic amendments is variable but predictable," *Journal of Environmental Quality* 49(2), 483-495. https://doi.org/10.1002/jeq2.20030

Li, X., You, F., Huang, L., Strounina, E., and Edraki, M. (2013). "Dynamics in leachate chemistry of Cu-Au tailings in response to biochar and woodchip amendments: A column leaching study," *Environmental Sciences Europe* 25(32). https://doi.org/10.1186/2190-4715-25-32

Li, Z. (2023). "Effect of organic soil amendments on increasing soil N retention and reducing N losses from agricultural soils," Doctoral dissertation, Universitäts-und Landesbibliothek, Bonn).

Love, M. I., Huber, W., and Anders, S. J. G. b. (2014). "Moderated estimation of fold change and dispersion for RNA-seq data with DESeq2," *Genome Biol.* 15(12), article 550. https://doi.org/10.1186/s13059-014-0550-8

Mahmood, R., Pielke Sr, R. A., Hubbard, K. G., Niyogi, D., Bonan, G., Lawrence, P., McNider, R., McAlpine, C., Etter, A., and Gameda, S. (2010). "Impacts of land use/land cover change on climate and future research priorities," *Bulletin of the American Meteorological Society* 91(1), 37-46. https://doi.org/10.1175/2009BAMS2769.1

Maljanen, M., Liimatainen, M., Hytönen, J., and Martikainen, P. J. (2014). "The effect of granulated wood-ash fertilization on soil properties and greenhouse gas (GHG) emissions in boreal peatland forests," *Boreal Environment Research* 19(4), 295-309. https://doi.org/10.60910/tn5a-y2y5

Maljanen, M., Liimatainen, M., and Sigurdsson, B. D. (2015). "Effect of volcanic ash on GHG production rates and soil properties in a drained peat soil compared to wood ash," *Icelandic Agricultural Sciences* 28, 25-28. https://doi.org/10.16886/IAS.2015.03

Marques, J. P., Rodrigues, V. G. S., Raimondi, I. M., and Lima, J. Z. (2020). "Increase in Pb and Cd adsorption by the application of peat in a tropical soil," *Water Air and Soil Pollution* 231(3). https://doi.org/10.1007/s11270-020-04507-z

Medaiyese, A. O., Wu, J., and Unc, A. (2023). "Utility of wood ash, paper sludge and biochar for the mitigation of greenhouse gases emissions from acid boreal soils," *J. Environ. Manag.* 330, article 117202. https://doi.org/10.1016/j.jenvman.2022.117202

Mkpuma, R. O., Okeke, O., and Abraham, E. J. I. J. E. S. (2015). "Environmental problems of surface and underground mining: A review," *The International Journal of Engineering and Science (IJES)* 4, 12-20.

Mortensen, J. (1963). "Complexing of metals by soil organic matter," *Wiley Online Library*. https://doi.org/10.2136/sssaj1963.03615995002700020027x

Müller, A., Lausser, L., Wilhelm, A., Ropinski, T., Platzer, M., Neumann, H., and Kestler, H. A. (2021). "A perceptually optimised bivariate visualisation scheme for high-dimensional fold-change data," *Advances in Data Analysis and Classification* 15(2), 463-480. https://doi.org/10.1007/s11634-020-00416-5

Naghoum, I., Edahbi, M., Melián, J. A. H., Doña Rodriguez, J. M., Durães, N., Pascual, B. A., and Salmoun, F. (2025). "Passive treatment of acid mine drainage effluents using constructed wetlands: Case of an abandoned ıron mine, Morocco," *Water* 17(5), article 687. https://doi.org/10.3390/w17050687

Nawab, J., Khan, N., Ahmed, R., Khan, S., Ghani, J., Rahman, Z., Khan, F., Wang, X. P., Muhammad, J., and Sher, H. (2019). "Influence of different organic geo-sorbents on *Spinacia oleracea* grown in chromite mine-degraded soil: A greenhouse study," *Journal of Soils and Sediments* 19(5), 2417-2432. https://doi.org/10.1007/s11368-019-02260-3

Nawu, T., Zvomuya, F., Adesanya, T., Amarakoon, I., and Bekele, A. (2024). "Soil properties following borrow pit reclamation with insufficient topsoil amended with peat and biochar," *Land Degradation and Development* 35(3), 1061-1073. https://doi.org/10.1002/ldr.4970

N'Dayegamiye, A., R. Royer and P. Audesse, 1997. "Nitrogen mineralization and availability in manure composts from Québec biological farms," *Can. J. Soil Sci*. 77, 345-350. https://doi.org/10.4141/S96-004

Nieminen, M., Piirainen, S., and Moilanen, M. (2005). "Release of mineral nutrients and heavy metals from wood and peat ash fertilizers: Field studies in Finnish forest soils," *Scandinavian Journal of Forest Research* 20(2), 146-153. https://doi.org/10.1080/02827580510008293

Nkana, J. V., Demeyer, A., and Verloo, M. G. (2002). "Effect of wood ash application on soil solution chemistry of tropical acid soils: Incubation study," *Bioresource Technology* 85(3), 323-325. https://doi.org/10.1016/S0960-8524(02)00140-2

Odlare, M., and Pell, M. (2009). "Effect of wood fly ash and compost on nitrification and denitrification in agricultural soil," *Applied Energy* 86(1), 74-80. https://doi.org/10.1016/j.apenergy.2008.04.004

Pansu, M., and Gautheyrou, J. (2007). *Handbook of Soil Analysis: Mineralogical, Organic and Inorganic Methods*, Springer Berlin Heidelberg.

Pitman, R. M. (2006). "Wood ash use in forestry – A review of the environmental impacts," *Forestry: An International Journal of Forest Research* 79(5), 563-588. https://doi.org/10.1093/forestry/cpl041

Pukalchik, M., Mercl, F., Panova, M., Brendová, K., Terekhova, V. A., and Tlustos, P. (2017). "The improvement of multi-contaminated sandy loam soil chemical and biological properties by the biochar, wood ash, and humic substances amendments," *Environmental Pollution* 229, 516-524. https://doi.org/10.1016/j.envpol.2017.06.021

Reid, N. B., and Naeth, M. A. (2005). "Establishment of a vegetation cover on Tundra Kimberlite mine tailings: 1. A greenhouse study," *Restoration Ecology* 13(4), 594-601. https://doi.org/10.1111/j.1526-100X.2005.00076.x

Richard, D., Neculita, C. M., and Zagury, G. J. (2021). "Removal of nickel from neutral mine drainage using peat-calcite, compost, and wood ash in column reactors," *Environmental Science and Pollution Research* 28(12), 14854-14866. https://doi.org/10.1007/s11356-020-11623-0

Rijk, I., Ekblad, A., Dahlin, A. S., Enell, A., Larsson, M., Leroy, P., Kleja, D. B., Tiberg, C., Hallin, S., and Jones, C. (2024). "Biochar and peat amendments affect nitrogen retention, microbial capacity and nitrogen cycling microbial communities in a metal and polycyclic aromatic hydrocarbon contaminated urban soil," *Science of the Total Environment* 936, article 173454. https://doi.org/10.1016/j.scitotenv.2024.173454

Rolka, E., Zolnowski, A. C., Wyszkowski, M., Zych, W., and Skorwider-Namiotko, A. (2023). "Wood biomass ash (WBA) from the heat production process as a mineral amendment for ımproving selected soil properties," *Energies* 16(13), article 5110. https://doi.org/10.3390/en16135110

Rosenberg, O., Persson, T., Högbom, L., and Jacobson, S. (2010). "Effects of wood-ash application on potential carbon and nitrogen mineralisation at two forest sites with different tree species, climate and N status," *Forest Ecology and Management* 260(4), 511-518. https://doi.org/10.1016/j.foreco.2010.05.006

Saarsalmi, A., Smolander, A., Moilanen, M., and Kukkola, M. (2014). "Wood ash in boreal, low-productive pine stands on upland and peatland sites: Long-term effects on stand growth and soil properties," *Forest Ecology and Management* 327, 86-95. https://doi.org/10.1016/j.foreco.2014.04.031

Saglam, B., Bilgin, A., and Aybar, M. (2020). "Assessment of heavy metal pollution in soil and sediments of murgul copper mine and ıts surroundings," *Kastamonu University Journal of Forestry Faculty* 20(1), 25-37. https://doi.org/10.17475/kastorman.705816

SPSS, I. (2010). "IBM SPSS statistics 19 core system user's guide.© ," *Copyright SPSS Inc*.

Stanford, G., and Smith, S. J. (1972). "Nitrogen mineralization potentials of soils," *Soil Science Society of America Journal* 36(3), 465-472. https://doi.org/10.2136/sssaj1972.03615995003600030029x

Storb, M. B., Bussell, A. M., Caldwell Eldridge, S. L., Hirsch, R. M., and Schmidt, T. S. (2023). "Growth of coal mining operations in the Elk River Valley (Canada) linked to ıncreasing solute transport of Se, NO_3^-, and SO_4^{2-} into the Transboundary Koocanusa Reservoir (USA-Canada)," *Environmental Science and Technology* 57(45), 17465-17480. https://doi.org/10.1021/acs.est.3c05090

Wang, X. Z., Zhou, Z., Lu, Z. J., Xia, L., Song, S. X., Meza, J. V. G., Montes, M. L., and Li, J. B. (2024). "Surge of native rare taxa in tailings soil induced by peat bacterial invasion," *Science of the Total Environment* 908, article 168596. https://doi.org/10.1016/j.scitotenv.2023.168596

Weng, L., Temminghoff, E. J., Lofts, S., Tipping, E., and Van Riemsdijk, W. H. J. E. s, (2002). "Complexation with dissolved organic matter and solubility control of heavy metals in a sandy soil," *Environ Sci Technol*. 36(22), 4804-4810. https://doi.org/10.1021/es0200084

Westcott, P. (1998). "Surface coal mining management (in Chapter: Mining and Quarrying)," *Encyclopedia of Occupational Health and Safety*, J. R. Armstrong and R. Menon (eds.), ILO, Geneva, 972-978.

Williams, J. M., and Thomas, S. C. (2023). "High-carbon wood ash biochar for mine tailings restoration: A field assessment of planted tree performance and metals uptake," *Science of the Total Environment* 901, article 165861. https://doi.org/10.1016/j.scitotenv.2023.165861

Wuana, R. A., and Okieimen, F. E. (2011). "Heavy metals in contaminated soils: A review of sources, chemistry, risks and best available strategies for remediation," *ISRN Ecology* 2011, article 402647. https://doi.org/10.5402/2011/402647
Yener, I. (2023). "Development of high-resolution annual climate surfaces for Turkey using ANUSPLIN and comparison with other methods," *Atmosfera* 37, 425-444. https://doi.org/10.20937/ATM.53189
Yener, I., and Altun, L. (2017). "Effect of climatic factors on the growth of oriental spruce stands in mountainous ecoregion of NE Turkey," *International Journal of Ecosystems and Ecology Science (IJEES)* 7(3), 597-602.
You, F., Dalal, R., and Huang, L. (2018). "Initiation of soil formation in weathered sulfidic Cu-Pb-Zn tailings under subtropical and semi-arid climatic conditions," *Chemosphere* 204, 318-326. https://doi.org/10.1016/j.chemosphere.2018.04.037

Article submitted: February 24,2026; Peer review completed: May 11, 2026; Revised version received: May 17, 2026; Accepted: June 20, 2026; Published: July 2, 2026.
DOI: 10.15376/biores.21.3.7703-7727