Journal of Environmental Science and Engineering B 15 (2026) 159-170
doi:10.17265/2162-5263/2026.04.002

Pyrolysis Optimization of Biochars for Remediating Acidic Polymetallic Mining Soils in Haut-Katanga, Democratic Republic of Congo: Fertility Restoration, and Immobilization of Trace Metals

Clarice Zoza Kunyonga[1, 2], Bamba Bukengu Muhaya[2], Martin Mutala Kabimbi[1], Raissa Kiansosa Diya[1], Georges Kabongo Ntambwe[1] and Jean-Baptiste Simbi Lumbu[2]

1. Department of Chemical and Materials Process Engineering, School of Industrial Engineers, University of Lubumbashi, P.O. Box 1825 Lubumbashi, Democratic Republic of Congo

2. Department of Chemistry and Industry, Faculty of Science and Technology, University of Lubumbashi, P.O. Box 1825 Lubumbashi, Democratic Republic of Congo

Abstract: This study optimized the pyrolysis of two local biomasses: coconut shells (*Cocos nucifera*) and the seed husks of *Acacia ataxacantha*, to produce biochars that can help restore soil fertility and reduce the bioavailability of trace metals. The biochars were produced at 300, 450, and 600 °C for 60 to 120 minutes during the pyrolysis heating period. After production, the obtained biochars were characterized for yield, pH, EC (electrical conductivity), moisture, volatile matter, ash, fixed carbon, CEC (cation exchange capacity), specific surface area, and carbon-sulfur/mineral elemental analysis (XRF (X-ray fluorescence)). A multi-response optimization (Taguchi design combined with ANOVA identified 450 °C and 120 minutes as the best compromise between yield and agronomic quality. The biochars produced at 300, 450, and 600 °C (for 120 min) were then applied to the mining soil at rates of 1, 5, and 10% (w/w) and incubated for 30 days. Acacia biochar pyrolyzed at 450 °C and applied at 10% turned out to be the most effective treatment: it increased the soil's CEC from 26.3 to 30.61 cmol/kg (+16%) by day 30, raised the pH from 6.65 to around 8.9, enriched the soil in total carbon (up to 8.94% for the 600 °C treatment) and calcium, and reduced EDTA (Ethylenediaminetetraacetic Acid)-extractable copper, cobalt, lead, and cadmium below detection limits in just 15 days. Bioavailable aluminum and manganese, which are toxic to plants in acidic soil, were also greatly reduced. On the other hand, electrical conductivity and bioavailable sodium increased significantly, especially with coconut biochar and at the highest acacia dose, which means the doses need to be managed carefully. These results confirm the potential of pyrolyzed *Acacia ataxacantha* biochar at 450-600 °C and applied at 10% as a low-cost and promising amendment to restore the acidic and polluted mining soils of Haut-Katanga.

Key words: Biochar, pyrolysis optimization, remediation of mining soils, bioavailability of trace metal elements, cation exchange capacity.

1. Introduction

The Katanga Copperbelt, which runs through Haut-Katanga Province in the DRC (Democratic Republic of Congo), is home to some of the world's largest copper and cobalt deposits and has been under intense mining pressure for decades. Mining and metallurgical activities around Lubumbashi have led to widespread polymetallic contamination (Cu, Co, Pb, Cd, Zn) and significant soil acidification, harming farmland and posing risks to food security and public health for local communities [1]. The Ruashi Mining site, an open-pit mine that has been operating for about twenty years near Lubumbashi, illustrates this issue: the surrounding soils have high

Corresponding author: Clarice Zoza Kunyonga, Master of Science, Senior Lecturer, research field: environmental pollution and remediation.

levels of bioavailable trace metals, low organic matter, and acidity that promotes phytotoxicity [2, 3].

Among remediation strategies, soil amendment with biochar, a carbon-rich material produced by pyrolyzing biomass in a low-oxygen environment, is generating increasing interest. Biochar can improve soil fertility by increasing CEC (cation exchange capacity), pH, and water retention, while also immobilizing heavy metals through mechanisms like complexation, precipitation, and ion exchange [4]. Its effectiveness, however, strongly depends on the type of biomass and pyrolysis conditions, particularly temperature [5, 6]: moderate temperatures (300-450 °C) preserve oxygen-containing functional groups that complex metals, while higher temperatures (≈ 600 °C) increase surface area and aromaticity, promoting physical adsorption and long-term stability.

In the context of Haut-Katanga, abundant local residues like coconut shells and *Acacia ataxacantha* seed coats could be an economical and sustainable source of biochar. To our knowledge, no study has yet optimized the pyrolysis of these two biomasses specifically for the remediation of an acidic mining soil in this region. This work therefore aimed to (i) produce and optimize biochars from coconut shells and acacia seed coats at 300, 450, and 600 °C; (ii) apply them to a soil near the Ruashi Mining company at doses of 1, 5, and 10% (w/w); and (iii) evaluate their effects on pH, EC (electrical conductivity), CEC, total carbon, sulfur, major elements, and available trace metals after 15 and 30 days of incubation. Our hypothesis was that acacia biochar pyrolyzed at 450 °C and applied at 10% would be the most effective treatment for restoring fertility and immobilizing heavy metals.

2. Materials and Methods

2.1 Study Area and Soil Sampling

The mining company Ruashi Mining is located near the city of Lubumbashi, in the Haut-Katanga Province, in the southeast of the DRC, right in the heart of the Katanga Copperbelt. The open-pit mining, which has been active for about twenty years, generates large volumes of waste rock, processing residues, and dust emissions. Soil samples were taken from the neighborhoods surrounding the site (Fig. 1) using a field GPS (Global Positioning System) (Garmin GPSMAP 64). After removing surface litter and large stones, thirteen subsamples were collected in a star pattern around a central point to create a representative composite sample; the samples were then transported to the lab in sealed plastic bags. The pretreatment involved air-drying for 7 to 10 days, manually sorting out stones, roots, and debris, grinding, sieving at 1.1 mm, and storing the <2 mm fraction in airtight polyethylene bags, away from light and moisture.

2.2 Initial Soil Characterization

- Moisture: weight loss by drying at 105 °C for 24 hours (AFNOR standard NF X31-102).
- pH and EC (electrical conductivity): soil/distilled water suspensions at a 1:5 ratio (10 g of soil, 50 mL of water), stirred for 30 min, settled for 1 h, pH measured (AFNOR NF X31-103) and conductivity measured at 22 ± 1 °C; potential acidity was additionally measured in 1 M KCl.
- CEC (cation exchange capacity): method using 0.1 M BaCl2 [7], based on saturating the exchange sites with Ba^{2+}, rinsing, re-exchanging with Mg^{2+} ($MgSO_4$), and measuring the magnesium consumed by AAS (atomic absorption spectrometry).
- Bioavailable MTEs (metallic trace elements): extraction with 0.05 M EDTA (Ethylenediaminetetraacetic Acid) (5 g of soil, 50 mL of extractant, 2 hours of stirring; standard NF X31-120), filtration with Whatman No. 5 paper, measurement by AAS.
- Pseudo-total contents: portable XRF (X-ray fluorescence) on 13 field soil samples (12 individual plots and one reference composite sample), targeting Cu, Co, Pb, Zn, and Cd.

2.3 Biomass and Pyrolysis

Two lignocellulosic residues were selected: coconut shells (Cocos nucifera), a dense, highly lignified, and

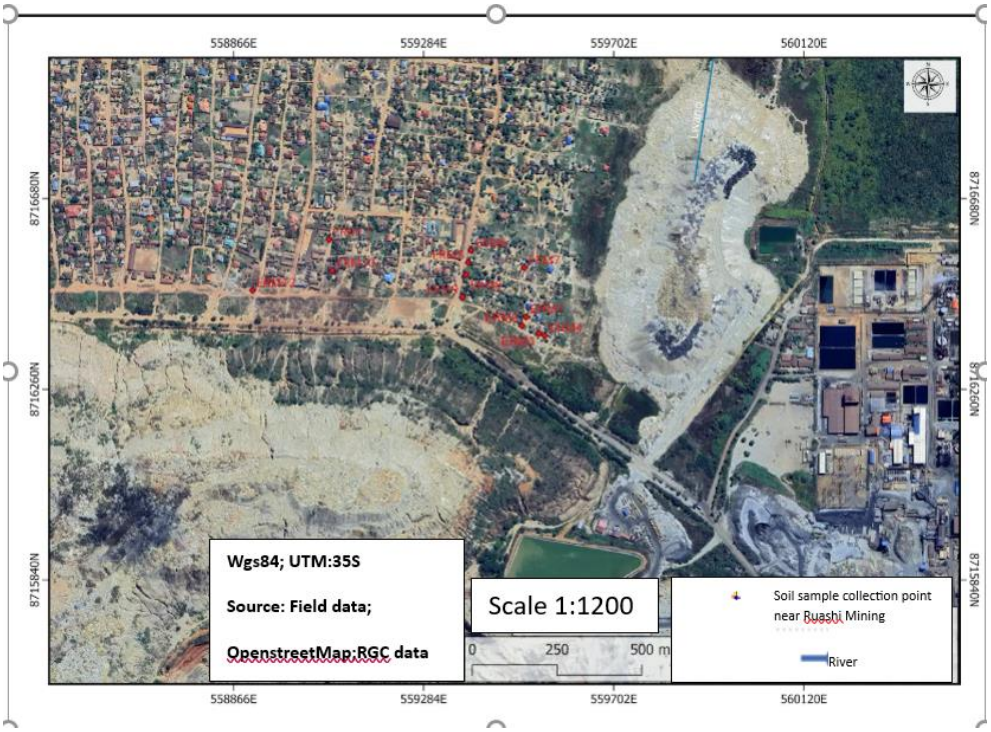

Fig. 1 Mapping of soil sampling sites around the Ruashi Mining company.

Fig. 2 Coconut shells-biochar-*Acacia ataxacantha* seed coats.

naturally porous material, and the seed coats of *Acacia ataxacantha*, a thinner but tough protective covering (Fig. 2). Pyrolysis was carried out in a muffle furnace under a flow of inert nitrogen (1 L/min), with a heating rate of 10 °C/min [8]. Three carbonization temperatures (300, 450, and 600 °C) were tested alongside three residence times (60, 90, and 120 min), with a constant load of 360 g of dry biomass per trial for both types of biomass. At the end of each trial, the furnace was turned off and the biochars were allowed to cool passively under an inert atmosphere to prevent oxidation, then they were ground, sieved at 1.1 mm, and stored in airtight polyethylene containers.

2.4 Characterization of Biochars

- Yield: mass ratio between recovered biochar and introduced dry biomass.
- pH and EC: biochar/water extracts at a 1:10 ratio, according to ISO 10390: 2021 (pH) [9] and a protocol inspired by ISO 11265 (EC) [10].
- Moisture and volatile matter: mass loss at 105 °C, then at 950 °C for 7 min in a closed crucible, respectively.
- TC (total carbon), organic matter, and ash: TC was determined by elemental analysis/wet oxidation; organic matter was estimated by TC × 1.724 (Van Bemmelen factor) and ash content by difference to 100%.
- Total porosity: water displacement method on 10 g of dry biochar immersed in 30 mL of water, from the saturated mass and displaced volume.
- Specific surface area: stain test with methylene blue, using a conversion factor of 2.54 m² per mg of adsorbed methylene blue.

- Cation exchange capacity: saturation with 0.1 N $BaCl_2$, displacement with 0.01 N $MgSO_4$, and titration with 0.1 N EDTA in the presence of Eriochrome Black T.
- Elemental content of carbon and sulfur, and mineral composition (K, Ca, Fe, Cu, Zn, Cd, W), by XRF.

2.5 Multi-response Optimization

A multi-response optimization (using Minitab software, a Taguchi design combined with an analysis of variance) was carried out on the pyrolysis yield, pH, EC, CEC, and specific surface area of the two biochars, based on the selected optimization limits and targets. The approach converged to a temperature of 450 °C and a residence time of 120 minutes as the operating point that best balances yield and the target agronomic properties for both biomasses.

2.6 Soil Incubation Test

The mine soil was air-dried, ground, and sieved to 1.1 mm (100 g of dry matter per experimental unit) and then manually mixed for 10 minutes with coconut or acacia biochar (produced with a 120-minute residence time at 300, 450, or 600 °C) at doses of 0 (control), 1, 5, or 10% (w/w), making 18 soil × biochar combinations. The coconut treatments pyrolyzed at 300, 450, and 600 °C were coded 1, 2, and 3, and the acacia ones at the same temperatures were coded 4, 5, and 6. Although process optimization indicated 450 °C as optimal, all three pyrolysis temperatures were kept for the incubation test because temperature, rather than residence time, turned out to be the key factor affecting the agronomic properties of the biochar. The mixtures were placed in boxes covered with perforated plastic film and incubated at 25 ± 2 °C for 30 days, with humidity kept at 70% of field capacity by regularly adding distilled water. Subsamples (≈ 50 g) were taken on day 15 and day 30, dried in an oven at 40 °C for 48 hours, ground and sieved before analyzing pH, EC, total carbon, CEC, and bioavailable (EDTA) contents of Cr, Cu, Ni, Pb, Cd, Co, and Na, as well as the levels of Al, Ca, Fe, Zn, Mg, and Mn determined by XRF.

2.7 Statistical Analysis

The effects of pyrolysis temperature (300, 450, 600 °C) and residence time (60, 90, 120 min) on the properties of biochars were evaluated separately for each biomass using a two-way ANOVA (Analysis of Variance). When the ANOVA showed a significant effect ($p < 0.05$), a Tukey post-hoc test was done for pairwise comparisons; the significance threshold was set at $p = 0.05$.

3. Results

3.1 Pyrolysis Yield

Eighteen pyrolysis trials were carried out for each type of biomass, combining three temperatures and three residence times (Table 1). The yield systematically decreases as the temperature increases for both types of biomass: from 47.75% (300 °C, 60 min) to 25.15% (600 °C, 120 min) for coconut shell (a relative drop of 47%), and from 52.32% to 11.72% for acacia husk (a 78% drop), showing a much more pronounced

Table 1 Pyrolysis yield of biochars from coconut shells (*Cocos nucifera*) and *Acacia ataxacantha* husks depending on temperature and residence time.

Temperature (°C)	Residence time (min)	Pyrolysis yield—coconut shells (%)	Pyrolysis yield—acacia husks (%)
300	60	47.75	52.32
300	90	44.87	50.04
300	120	41.97	44.12
450	60	42.13	31.14
450	90	37.05	26.82
450	120	33.06	24.21
600	60	28.04	16.98
600	90	26.26	14.28
600	120	25.15	11.72

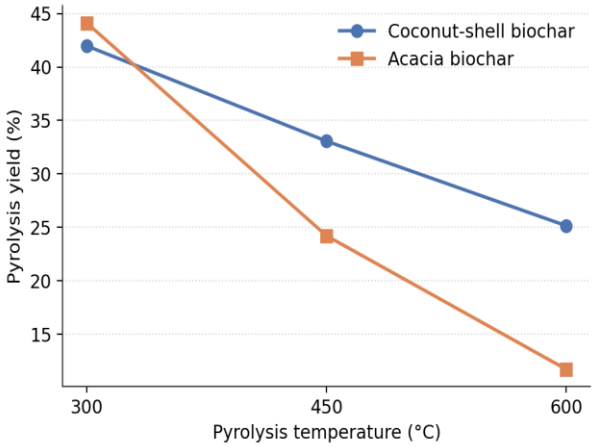

Fig. 3 Pyrolysis yield of coconut and acacia biochars depending on the temperature (120 minutes residence time).

devolatilization of acacia biomass at high temperatures (Fig. 3). The analysis of coded coefficients shows that temperature is the dominant factor, with about twice the sensitivity for acacia compared to coconut, and a more moderate but still significant effect of residence time between 60 and 120 minutes. The quadratic yield models show excellent accuracy, with adjusted R^2 of 98.3% (coconut) and 99.7% (acacia).

3.2 Physico-Chemical Properties of Biochars

The pH and EC of both biochars increase significantly with the pyrolysis temperature (Table 2, Fig. 4), going from moderately alkaline values at 300 °C (pH 7.2-8.3) to strongly alkaline values at 600 °C (pH 10.0-10.6), which reflects the gradual breakdown of acidic surface functional groups (-COOH, phenolic -OH) and the concentration of alkaline ashes (oxides, hydroxides, carbonates, and silicates of Ca, Mg, K, and Na). EC rises alongside it, from 233-387 µS/cm at 300 °C to 800-1,017 µS/cm at 600 °C, showing the concentration of soluble mineral salts as the organic fraction volatilizes; overall, acacia biochar has a higher EC than coconut biochar, especially at 450 and 600 °C.

The volatile matter drops sharply with temperature —from 64.6-74.9% at 300 °C to 12.7-26.1% at 600 °C —while the moisture stays low across the whole range (0.1-3.1%). The specific surface area rises sharply with temperature, from 11.7-19.4 m^2/g at 300 °C to 373.9-541.7 m^2/g at 600 °C, consistent with the gradual development of microporosity during carbonization (Fig. 5). In contrast, the CEC of the biochars shows a bell-shaped trend with temperature, reaching a maximum at 450 °C (17.5-21.6 cmol/kg) before dropping at 600 °C (13.3-17.9 cmol/kg), due to the thermal breakdown of oxygen-containing functional groups at high temperatures (Fig. 5). The ash content steadily increases with temperature (19-63% for coconut, 8.5-31% for acacia), while fixed carbon peaks around 450 °C (up to 43.7% for coconut at 120 minutes), marking the formation of stable polyaromatic carbon structures, which are relevant for long-term carbon sequestration

3.3 Multi-response Optimization Result

The multi-response optimization converges to a pyrolysis temperature of 450 °C and a residence time of 120 minutes as the operating point that best balances yield and the target ranges for pH, EC, CEC, and specific surface area for both biomasses.

Table 2 Selected physicochemical properties of coconut and acacia biochars at 120 minutes residence time, according to pyrolysis temperature.

Property	300 °C Coco	300 °C Acacia	450 °C Coco	450 °C Acacia	600 °C Coco	600 °C Acacia
pH	7.34	8.28	9.46	9.33	9.99	10.60
EC (µS/cm)	233.6	239.8	470.0	606.3	875.6	796.7
Humidity (%)	2.0	1.60	2.0	1.70	0.1	0.20
Volatile matter (%)	64.6	74.9	14.3	52.0	12.7	26.1
Specific surface area (m^2/g)	19.0	19.4	188.7	140.7	411.3	508.5
CEC (cmol/kg)	15.7	13.0	19.8	17.5	15.0	13.3
Ash content (%)	23.0	11.7	40.0	19.2	63.0	31.0
Fixed carbon (%)	10.4	11.8	43.7	27.1	24.2	42.0

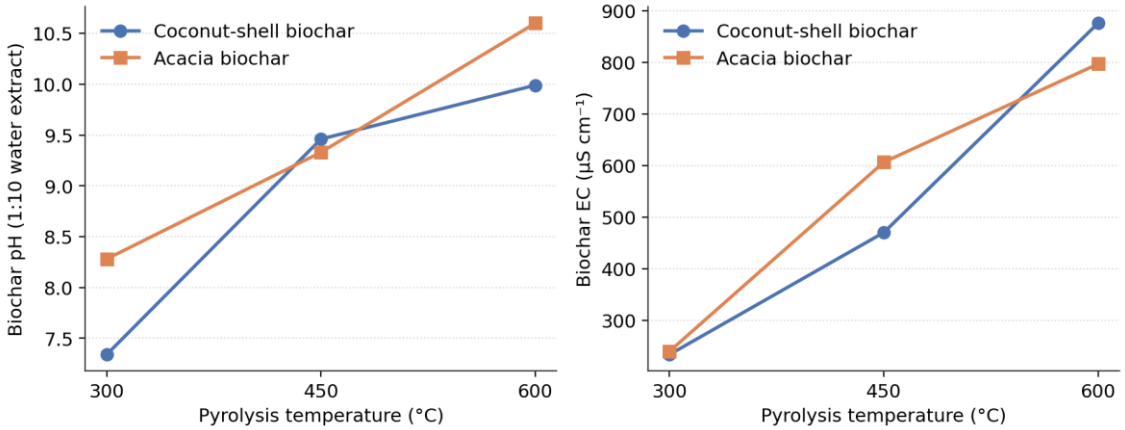

Fig. 4 Effect of pyrolysis temperature on the pH (left) and electrical conductivity (right) of biochar.

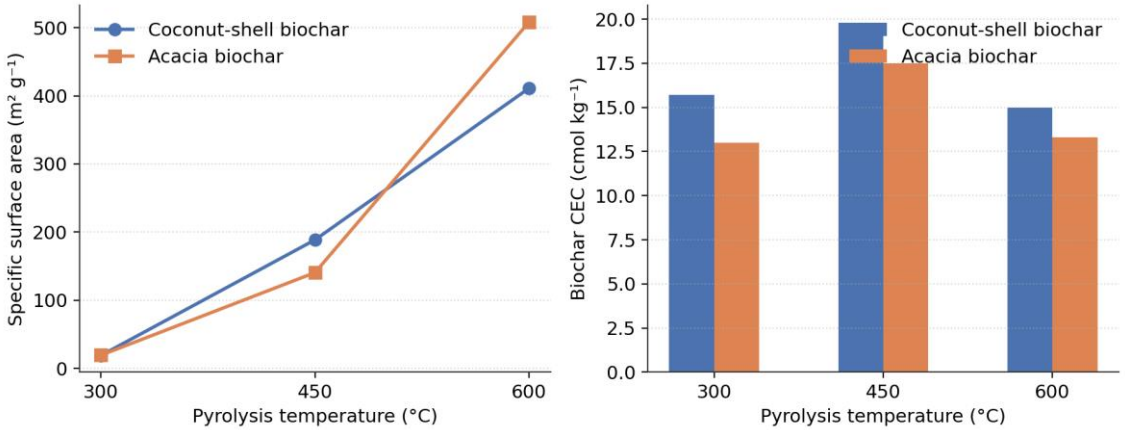

Fig. 5 Effect of pyrolysis temperature on the specific surface area (left) and cation exchange capacity (right) of biochar.

Table 3 Total carbon (C) and sulfur (S) content of coconut and acacia husk biochars.

Biomass	Temperature (°C)	Total carbon (%)	Sulfur (%)
Coconut	300	70.5	0.0541
Coconut	450	65.8	0.0746
Coconut	600	64.1	0.153
Acacia husk	300	78.2	0.0667
Acacia husk	450	64.8	0.081
Acacia husk	600	60.7	0.107

Table 4 Mineral composition (XRF) of coconut and acacia husk biochars (450 °C, mg/kg).

Biochar	K	Ca	Fe	Cu	Zn	Cd	W
Acacia husk	10,500	1,910	380	150	60	20	1,410
Coconut	10,600	1,200	240	110	26	15	1,320

3.4 Basic and Mineral Composition of Biochars

The total carbon content decreases moderately with the pyrolysis temperature, from 70.5% to 64.1% for coconut and from 78.2% to 60.7% for acacia (300 to 600 °C), while the sulfur content increases over the same range (0.054% to 0.153% for coconut; 0.067% to 0.107% for acacia husk), reflecting the gradual concentration of mineral sulfur as the organic carbon volatilizes (Table 3). The XRF analysis of both biochars (Table 4) shows a common richness in potassium (≈ 10,500-10,600 mg/kg) and a moderate richness in calcium (1,200-1,910

mg/kg), with low concentrations of copper, zinc, and notably cadmium (15-20 mg/kg), which is an important indicator supporting safe agronomic use.

3.5 Initial Soil Characteristics

The unamended Ruashi soil is slightly acidic (pH 6.65), moderately saline (EC 192.2 µS/cm), and has moderate cation exchange capacity (26.3 cmol/kg) [11], low in total carbon (1.27%) and sulfur (0.023%). Field XRF analysis of 13 samples confirms severe contamination with copper (600-1,000 mg/kg, which is 6 to 10 times the agricultural reference threshold of ≈100 mg/kg) and cobalt (220-490 mg/kg, up to ≈45 times the threshold of ≈11 mg/kg), with a contamination hierarchy of Cu ≫ Co ≫ Zn ≈ Cd > Pb; lead, zinc, and most cadmium values remain below or close to the agricultural reference thresholds. Available contents (EDTA-extractable) of chromium, copper, nickel, lead, cadmium, and cobalt before amendment were 0.079, 65.19, 0.323, 5.14, 0.282, and 4.42 mg/kg, respectively, and available sodium was 904.8 mg/kg.

3.6 Effect of Biochar on Soil pH and Electrical Conductivity

Coconut biochar has only a mild buffering effect on soil pH, which stays close to its initial value (6.36-6.89) regardless of the dose or incubation time. Acacia biochar, on the other hand, causes a clear, dose-dependent alkalinization: by day 30, the pH reaches 7.34-7.65 for the 300 °C biochar (1 to 10%) and 8.92-9.17 for the 450 and 600 °C biochars at 10% (Fig. 6). Electrical conductivity behaves differently depending on the biomass: it drops sharply with coconut biochar, down to 19-65 µS/cm by day 30 for all doses, but increases with acacia biochar, especially at 10% (EC by day 30 of 144.6 µS/cm for the 450 °C biochar and 230.2 µS/cm for the 600 °C one, the latter exceeding the soil's initial EC of 192.2 µS/cm) (Fig. 7).

3.7 Effect on Cation Exchange Capacity

CEC increases with the biochar dose for all treatments, more noticeably for acacia biochars pyrolyzed at 300 and 450 °C. The best-performing treatment is acacia biochar pyrolyzed at 450 °C and applied at 10%—it raises the soil CEC from 26.3 to 30.01 cmol/kg at day 15 and then to 30.61 cmol/kg at day 30, a 16% increase compared to unamended soil (Fig. 8). Biochars pyrolyzed at 600 °C give the smallest CEC gains, with one of them (coconut, 10%) barely exceeding the initial value, consistent with their lower intrinsic CEC (§3.2).

3.8 Effect on Total Soil Carbon and Sulfur

Soil total carbon consistently increases with the biochar dose and the pyrolysis temperature, from 1.78% (coconut, 300 °C, 1%) to 8.94% (acacia, 600 °C, 10%) at day 30 (Fig. 9). Sulfur follows a similar upward trend, reaching maximum values of 0.107-0.114% for the 10% treatments at 600 °C, with acacia biochar generally contributing more sulfur than coconut biochar at the same dose.

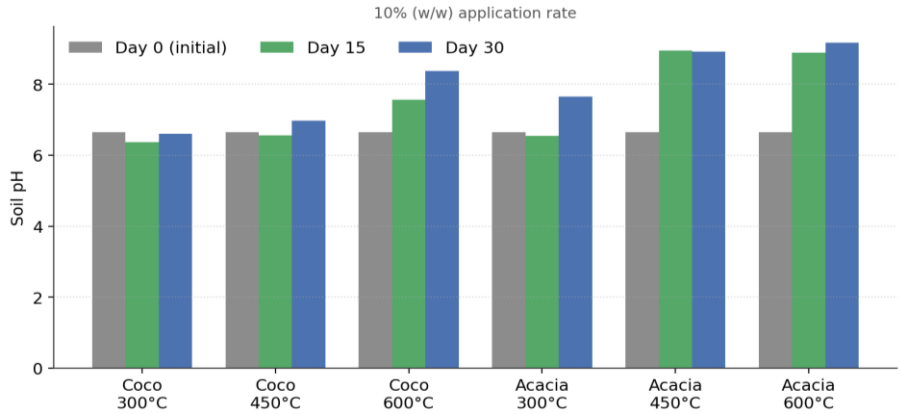

Fig. 6 Soil pH before amendment (D0) and after 15 and 30 days of incubation, for coconut and acacia biochars (300-600 °C) applied at 10% (w/w).

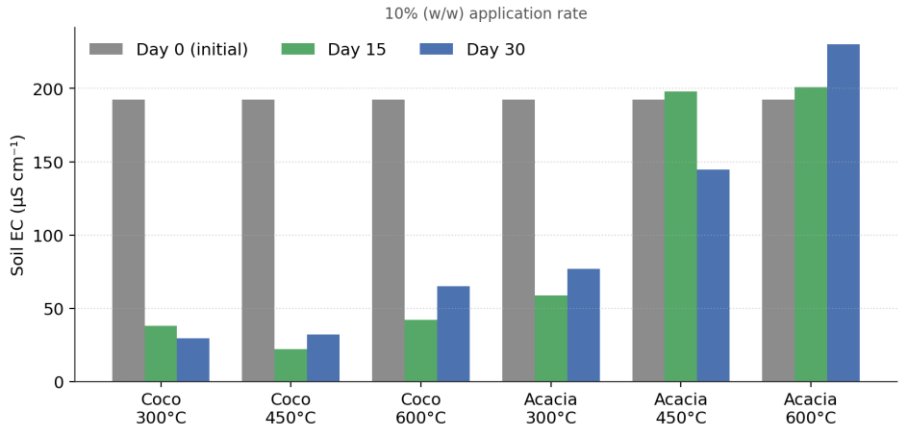

Fig. 7 Soil electrical conductivity (µS/cm) before amendment (J0) and after 15 and 30 days of incubation, for coconut and acacia biochars (300-600 °C) applied at 10% (w/w).

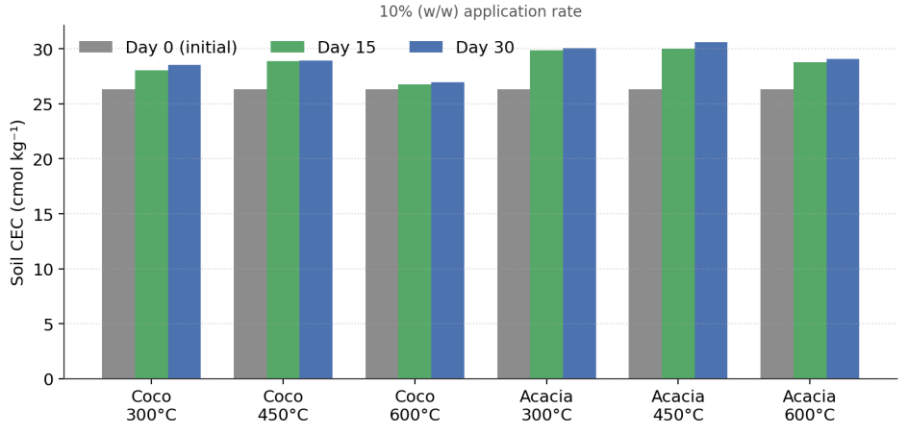

Fig. 8 Soil cation exchange capacity (cmol/kg) before amendment (D0) and after 15 and 30 days of incubation, for coconut and acacia biochars (300-600 °C) applied at 10% (w/w).

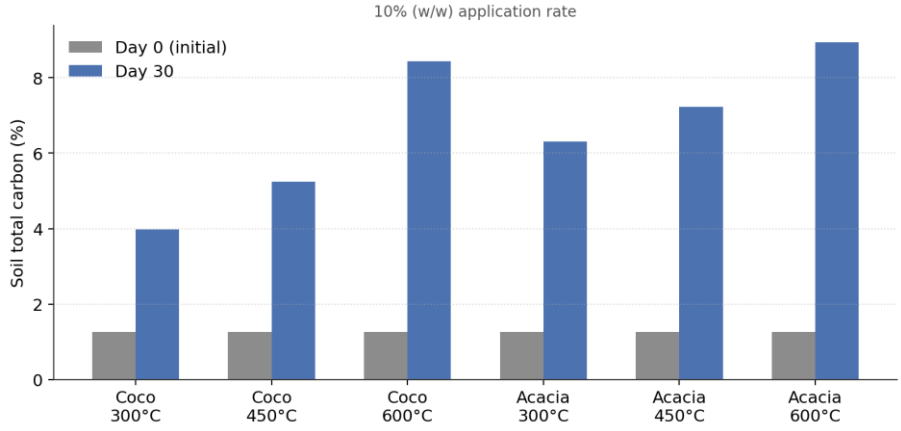

Fig. 9 Total soil carbon before amendment (D0) and after 30 days of incubation, for coconut and acacia biochars (300-600 °C) applied at 10% (w/w).

3.9 Effect on Bioavailable Trace Metal Elements

The copper and cobalt extractable with EDTA go from 65.19 and 4.42 mg/kg (Day 0) to values below the analytical detection limit for most treatments by Day 15, and they stay low at Day 30. Lead, cadmium, nickel, and chromium show the same downward trend, becoming largely undetectable across all treatments

(Table 5, Fig. 10). Bioavailable sodium, on the other hand, increases sharply, exceeding 2,758 mg/kg by Day 30 (compared to 904.8 mg/kg initially), confirming that soluble sodium salts are being released by the amended soil (Fig. 11).

3.10 Effect on Major Elements and Trace Elements

Bioavailable aluminum, iron, and manganese—which are toxic to plants in acidic soil—drop significantly after amendment, especially by day 30 and at the 5 and 10% doses. Calcium and magnesium generally go up by day 15 compared to untreated soil, particularly with acacia biochar, before dropping by day 30 for most treatments. This suggests gradual reprecipitation or fixation as the pH rises during incubation. Zinc tends to stabilize or slightly decrease depending on the treatment, limiting the risk of induced deficiency.

Table 5 Bioavailable metallic trace elements (extractable with EDTA) and sodium in mining soil before amendment (Day 0) and after 15 and 30 days of incubation, values combined for all treatments (mg/kg; "<" indicates a value below the analytical detection limit; ">" indicates a value above the stated number).

Deadline	Cr	Cu	Ni	Pb	Cd	Co	Na
Day 0	0.079	65.19	0.323	5.144	0.282	4.42	904.8
Day 15	< 0.057	< 0.231	< 0.356	< 0.052	< 0.07	< 0.153	> 1,429.06
Day 30	< 0.011	< 0.046	< 0.071	< 0.010	< 0.014	< 0.031	> 2,758.7

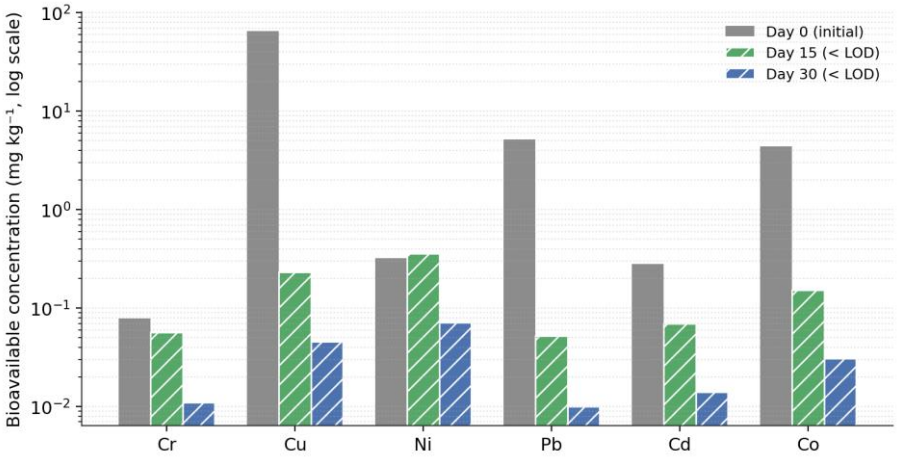

Fig. 10 Bioavailable chrome, copper, nickel, lead, cadmium, and cobalt (extractable with EDTA) before amendment (Day 0) and after 15 and 30 days of incubation, values combined for all treatments (log scale; hatched bars indicate values below the analytical detection limit, LOD).

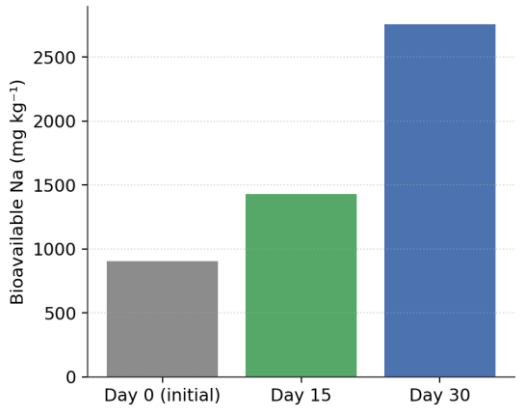

Fig. 11 Bioavailable sodium before amendment (Day 0) and after 15 and 30 days of incubation, values grouped for all treatments.

4. Discussion

Amending the soil around the Ruashi Mining company with biochars made from coconut shells and acacia leads to deep and interconnected changes in its physicochemical properties, fertility, and the dynamics of trace metals. Changes in pH and electrical conductivity form the basis of these transformations: adding biochar, especially at 10%, makes the soil more alkaline, an effect due to its richness in ash and carbonates. This alkalinization is crucial in the context of acidic mining soil because it affects nutrient availability and metal solubility. At the same time, EC

increases with the amendment dose, reflecting the release of soluble ions (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) from the biochar [12]. Moderate at 1-5%, this increase deserves closer monitoring at 10%, as excessive salinity can inhibit microbial activity and disrupt the roots' absorption of water and nutrients [13].

The soil CEC, initially at 26.3 cmol/kg, improves significantly and in a dose-dependent way, with acacia biochars proving more effective than coconut ones. The optimal treatment—acacia biochar pyrolyzed at 450 °C and applied at 10%—reaches 30.61 cmol/kg at day 30 (+16%), consistent with the additional negative charges provided by the oxygen-containing functional groups of the biochar (carboxyls, phenolics) and the increase in organic matter [4]. Biochars pyrolyzed at 600 °C have inherently lower CEC due to decarboxylation and loss of functional groups at high temperatures [14], which limits their short-term contribution to CEC despite higher structural stability.

The dynamics of total carbon and sulfur illustrate the dual role of biochar, acting both as a carbon sink and as a source of additional elements. Total carbon rises sharply with the dose and pyrolysis temperature, going from 1.27% in the control soil to 8.94% for the acacia treatment at 600 °C and 10%, representing an accumulation of recalcitrant carbon that benefits soil structure and long-term atmospheric carbon sequestration [15]. Sulfur shows a similar trend, peaking at 0.107-0.114% for high-temperature, high-dose treatments. This sulfur enrichment deserves some monitoring, as part of it could oxidize into sulfates over time, generating acidity and partially offsetting the alkalinizing effect of the biochar [16]; however, this risk is buffered here by the high intrinsic alkalinity of acacia biochar.

The immobilization of bioavailable ETMs is probably the most striking result of this study. Extractable copper and cobalt with EDTA drop from 65.19 and 4.42 mg/kg to values below detection limits for most treatments after just 15 days, with lead, cadmium, nickel, and chromium showing the same trend. This efficiency can be explained by three synergistic mechanisms: (i) alkalinization induced by biochar, which promotes the precipitation of metals as insoluble hydroxides [17]; (ii) surface complexation of metal cations by biochar functional groups [18]; and (iii) ion exchange, where metal cations (Cu^{2+}, Co^{2+}, Pb^{2+}) are displaced from the exchange complex by alkali and alkaline earth cations (Ca^{2+}, Mg^{2+}) released by the biochar [19]. Acacia biochars pyrolyzed at 450 and 600 °C turn out to be particularly effective, consistent with their higher specific surface area and aromaticity, which promote physical adsorption and long-term sequestration. These results are in line with previous studies on the sorption of Cu, Cd, and Pb by biochar in acidic soil [20], a 55% reduction of available copper in Chinese acidic mining soils amended with bamboo biochar combined with compost [21], and the conversion of mobile fractions of lead and cadmium into stable residual forms after amending a contaminated rice paddy soil [22].

Regarding the major elements, the significant decrease in bioavailable aluminum, iron, and manganese is particularly beneficial, since Al and Mn toxicity is a major limiting factor for plant growth in acidic soils; their immobilization through precipitation at higher pH and complexation removes an important barrier to fertility [23]. On the other hand, exchangeable calcium and magnesium tend to increase, especially with acacia biochar, improving the Ca/Mg ratio and the soil's cation nutrition potential [4], while zinc remains generally stable, preventing deficiencies that could result from excessive immobilization of other metals [24].

Finally, the significant increase in bioavailable sodium from 904.8 to over 2758 mg/kg is a critical point to watch out for. While biochar improves CEC, the release of sodium can lead to soil sodification, which harms its structure and reduces its permeability; this risk is more pronounced with coconut biochar. Moderate doses (5%) or using biochars lower in sodium, like acacia pyrolyzed at 600 °C, are

recommended to limit this risk. It has also been shown that acidified or washed biochar can reduce the percentage of exchangeable sodium and the sodium adsorption ratio in amended soils [20].

Ultimately, amending the soil around the Ruashi Mining site with acacia biochar pyrolyzed at 450-600 °C and applied at 10% is an effective strategy to immobilize copper, cobalt, lead, and cadmium, and to reduce the toxicity of aluminum and manganese, while improving chemical fertility (Ca, Mg, CEC) and carbon sequestration. However, this benefit should be balanced with the need to monitor electrical conductivity and sodium dynamics. Since this was a lab study, in pots, on a single soil type, and lasted only 30 days without any crops, it doesn't capture the long-term aging effects on metal remobilization or the actual response of plants. Agronomic tests (germination, biomass, tissue absorption of metals), field trials, and an economic assessment of local biochar production from coconut shells and *Acacia ataxacantha* residues are needed to confirm the sustainability and practical feasibility of this soil remediation strategy in Haut-Katanga province.

5. Conclusion

This work optimized the pyrolysis of coconut shells and *Acacia ataxacantha* husks and evaluated the resulting biochars as amendments for an acidic mining soil polluted with copper and cobalt from the Ruashi Mining site in the Haut-Katanga province. A temperature of 450 °C and a residence time of 120 minutes turned out to be the optimal pyrolysis conditions, balancing yield and targets for pH, EC (electrical conductivity), CEC (cation exchange capacity), and specific surface area. When applied to the mining soil, the acacia biochar pyrolyzed at 450 °C and applied at 10% (w/w) proved to be the most effective treatment: it increases the CEC by 16% (up to 30.61 cmol/kg), raises the pH from 6.65 to about 8.9, enriches the soil in carbon, calcium, and magnesium, and reduces the bioavailability of copper, cobalt, lead, and cadmium below detectable limits within 15 days, while strongly mitigating aluminum and manganese toxicity. Two points of concern have been identified: an increase in electrical conductivity and bioavailable sodium, which was more pronounced with coconut biochar and at the highest dose of acacia biochar. A moderate dose (5%), or the use of acacia biochar pyrolyzed at 600 °C, where sodium release is more limited, could help mitigate these risks. Overall, amending with *Acacia ataxacantha* biochar pyrolyzed at 450-600 °C and applied at 10% is a promising strategy, based on local resources, to restore the fertility of acidic mining soils in Haut-Katanga Province and reduce the risk of heavy metal transfer to the food chain. Long-term agronomic trials (germination, yield) and an economic feasibility assessment are needed to validate this approach at the field scale.

Statements & Declarations

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Clarisse Zoza Kunyonga. The first draft of the manuscript was written by Clarisse Zoza Kunyonga and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Acknowledgments

The authors thank the staff of the General and Physical Chemistry laboratory at the Polytechnic Faculty of the University of Lubumbashi for their

technical support during the experimental part of the present work.

References

[1] Banza, C. L. N., Nawrot, T. S., Haufroid, V., Decrée, S., De Putter, T., Smolders, E., Kabyla, B. I., Luboya, O. N., Ilunga, A. N., Mutombo, A. M., and Nemery, B. 2009. "High Human Exposure to Cobalt and Other Metals in Katanga, a Mining Area of the Democratic Republic of Congo." *Environmental Research* 109 (6): 745-52.

[2] Muhaya, B. B., Bukas, A., Lubala, F. T., Kaseti, P. K., and Mugisho, J. B. 2016. "Assessment of Trace Metals in Soils of North-Eastern Lubumbashi (Upper-Katanga Province, Democratic Republic of Congo)." *Journal of Environmental Science and Engineering A* 5 (9): 452-62.

[3] Ilonga, B. M., Kongolo, M., Kisimba, T., Kiteba, M. S., and Mputu, K. J.-N. 2023. "Assessment of Soil Pollution by Metallic Trace Elements (MTE): Case of Environment of Ruashi Mining/Haut-Katanga (DR Congo)." *European Journal of Environment and Earth Sciences* 4 (1): 69-72.

[4] Lehmann, J., and Joseph, S. (Eds.). 2015. *Biochar for Environmental Management: Science, Technology and Implementation* (2nd ed.). London: Routledge.

[5] Tomczyk, A., Sokołowska, Z., and Boguta, P. 2020. "Biochar Physicochemical Properties: Pyrolysis Temperature and Feedstock Kind Effects." *Reviews in Environmental Science and Bio/Technology* 19 (1): 191-215.

[6] Kloss, S., Zehetner, F., Dellantonio, A., Hamid, R., Ottner, F., Liedtke, V., Schwanninger, M., Gerzabek, M. H., and Soja, G. 2012. "Characterization of Slow Pyrolysis Biochars: Effect of Feedstocks and Pyrolysis Temperature on Biochar Properties." *Journal of Environmental Quality* 41 (4): 990-1000.

[7] ISO 11260. 2018. Qualité du sol—Détermination de la capacité d'échange cationique effective et du taux de saturation en bases à l'aide d'une solution de chlorure de baryum. Organisation internationale de normalisation.

[8] Manyà, J. J. 2012. "Pyrolysis for Biochar Purposes: A Review to Establish Current Knowledge Gaps and Research Needs." *Environmental Science & Technology* 46 (15): 7939-54.

[9] ISO 10390. 2021. Sols, biodéchets traités et boues—Détermination du pH. Organisation internationale de normalisation.

[10] ISO 11265. 1994. Qualité du sol-Détermination de la conductivité électrique spécifique. Organisation internationale de normalisation.

[11] Zgorelec, Z., Bilandzija, N., Knez, K., Galic, M., and Percin, A. 2013. "Cation Exchange Capacity of Dominant Soil Types in the Republic of Croatia." *Journal of Central European Agriculture* 14 (3): 84-98.

[12] Ding, Y., Liu, Y., Liu, S., Li, Z., Tan, X., Huang, X., Zeng, G., Zhou, L., and Zheng, B. 2016. "Biochar to Improve Soil Fertility. A Review." *Agronomy for Sustainable Development* 36 (2): 36.

[13] Munns, R., and Tester, M. 2008. "Mechanisms of Salinity Tolerance." *Annual Review of Plant Biology* 59: 651-81.

[14] Gaskin, J. W., Steiner, C., Harris, K., Das, K. C., and Bibens, B. 2008. "Effect of Low-Temperature Pyrolysis Conditions on Biochar for Agricultural Use." *Transactions of the ASABE* 51 (6): 2061-9.

[15] Lehmann, J. 2007. "Bio-energy in the Black." *Frontiers in Ecology and the Environment* 5 (7): 381-7.

[16] Dold, B. 2010. "Basic Concepts in Environmental Geochemistry of Sulfidic Mine-Waste Management." *Waste Management* 30 (4): 173-98.

[17] Yuan, J.-H., Xu, R.-K., and Zhang, H. 2011. "The Forms of Alkalis in the Biochar Produced from Crop Residues at Different Temperatures." *Bioresource Technology* 102 (3): 3488-97.

[18] Uchimiya, M., Chang, S., and Klasson, K. T. 2011. "Screening Biochars for Heavy Metal Retention in Soil: Role of Oxygen Functional Groups." *Journal of Hazardous Materials* 190 (1-3): 432-41.

[19] El-Naggar, A., Lee, S. S., Rinklebe, J., Farooq, M., Song, H., Sarmah, A. K., Zimmerman, A. R., Ahmad, M., Shaheen, S. M., and Ok, Y. S. 2019. "Biochar Application to Low Fertility Soils: A Review of Current Status and Future Prospects." *Geoderma* 337: 536-54.

[20] Li, H., Dong, X., da Silva, E. B., de Oliveira, L. M., Chen, Y., and Ma, L. Q. 2017. "Mechanisms of Metal Sorption by Biochars: Biochar Characteristics and Modifications." *Chemosphere* 178: 466-78.

[21] Ali, A., Guo, D., Mahar, A., Wang, P., Ma, F., Li, R., and Zhang, Z. 2017. "Using Bamboo Biochar with Compost for the Stabilisation and Phytotoxicity Reduction of Heavy Metals in Mine-Contaminated Soils of China." *Scientific Reports* 7 (1): 2690.

[22] Cui, L., Li, L., Zhang, A., Pan, G., Bao, D., and Chang, A. 2011. "Biochar Amendment Greatly Reduces Rice Cd Uptake in a Contaminated Paddy Soil: A Two-Year Field Experiment." *BioResources* 6 (3): 2605-18.

[23] Dai, Z., Zhang, X., Tang, C., Muhammad, N., Wu, J., Brookes, P. C., and Xu, J. 2017. "Potential Role of Biochars in Decreasing Soil Acidification—A Critical Review." *Science of the Total Environment* 581-582: 601-11.

[24] Zeng, F., Ali, S., Zhang, H., Ouyang, Y., Qiu, B., Wu, F., and Zhang, G. 2011. "The Influence of pH and Organic Matter Content in Paddy Soil on Heavy Metal Availability and Their Uptake by Rice Plants." *Environmental Pollution* 159 (1): 84-91.