# BASELINE CHARACTERISATION AND MULTI-YEAR ELEMENTAL MONITORING OF BIOMASS CROPS ON POST-MINING LAND IN PETRILA, ROMANIA
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# *CARACTERIZAREA INIȚIALĂ ȘI MONITORIZAREA MULTIANUALĂ A COMPOZIȚIEI ELEMENTARE A CULTURILOR DE BIOMASĂ PE TEREN POST-MINIER DIN PETRILA, ROMÂNIA*

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## ABSTRACT
*Post-mining substrates are spatially heterogeneous and require site-specific diagnosis before biomass cultivation. This study documents the establishment and three-year monitoring of a 4,500 m² field platform on a coal-mining waste dump in Petrila, Romania. Nine 500 m² plots were used: three fixed-crop reference plots (designated as controls in the original project records) and six plots under a balanced cyclic rotation of maize (Zea mays), soybean (Glycine max) and sweet sorghum (Sorghum bicolor). Amendment treatments formed part of the wider experimental layout but are not evaluated in the present manuscript. Baseline measurements at eight points in June 2023 included instrument-reported volumetric water content (VWC), temperature, penetration resistance, field pH and semi-quantitative N-P-K screening, complemented by preliminary potentially toxic element screening. Mean VWC was 26.6 ± 4.2% at 5 cm and 20.0 ± 4.3% at 15 cm; mean temperatures were 18.2 ± 1.3 and 16.7 ± 1.1°C. Mean penetration resistance across seven complete profiles was 1.05 ± 0.28 MPa and increased with depth. Field pH averaged 7.1 ± 0.1, and the available laboratory summary prioritised Cu and Ni for follow-up. All crops reached reproductive development. Preliminary operational harvest totals were 85, 263 and 487 kg in 2023, 2024 and 2025, respectively; these values are reported descriptively only and are not interpreted as crop yield because harvested area, crop-specific contributions and moisture basis were not documented consistently. The nine crop-year elemental records are likewise treated as single descriptive observations displaying apparent crop-year differences in the reported Cu, Ni, Zn and Pb values; no inferential comparison among crops or years and no conclusion on soil-to-plant transfer or bioaccumulation is made.*

## REZUMAT
*Substraturile post-miniere sunt eterogene spațial și necesită diagnoză specifică înaintea cultivării biomasei. Studiul documentează înființarea și monitorizarea pe trei ani a unei platforme de 4.500 m² pe halda Petrila. Au fost utilizate nouă parcele de 500 m²: trei parcele de referință cu cultură fixă (desemnate drept martor în documentația inițială a proiectului) și șase cu rotație echilibrată de porumb (Zea mays), soia (Glycine max) și sorg zaharat (Sorghum bicolor). Tratamentele cu amendamente au făcut parte din configurația experimentală extinsă, dar nu sunt evaluate în prezentul manuscris. Caracterizarea inițială din iunie 2023, în opt puncte, a inclus umiditatea volumetrică raportată de instrument, temperatura, rezistența la penetrare, pH-ul de teren și screeningul N-P-K, completate de screeningul preliminar al elementelor potențial toxice. Umiditatea medie a fost 26,6 ± 4,2% la 5 cm și 20,0 ± 4,3% la 15 cm, iar temperaturile 18,2 ± 1,3 și 16,7 ± 1,1°C. Rezistența medie la penetrare pentru șapte profile complete a fost 1,05 ± 0,28 MPa și a crescut cu adâncimea. pH-ul mediu a fost 7,1 ± 0,1, iar sinteza de laborator a prioritizat Cu și Ni pentru monitorizare. Toate culturile au ajuns la dezvoltare reproductivă. Totalurile operaționale preliminare ale biomasei recoltate au fost de 85, 263 și 487 kg în 2023, 2024 și, respectiv, 2025; aceste valori sunt raportate exclusiv descriptiv și nu sunt interpretate ca producții agricole, deoarece suprafața recoltată, contribuțiile specifice fiecărei culturi și baza de umiditate nu au fost documentate consecvent. Cele nouă înregistrări cultură-an privind compoziția elementală sunt, de asemenea, tratate ca observații descriptive individuale, evidențiind diferențe aparente între combinațiile cultură-an în valorile raportate pentru Cu, Ni, Zn și Pb; nu se realizează comparații inferențiale între culturi sau ani și nu se formulează concluzii privind transferul sol-plantă ori bioacumularea.*

## INTRODUCTION

Post-mining substrates are radically different from agricultural soils in that the excavation, transportation and deposition of the substrate disturb natural horizons and produce combinations of coarse fragments, poorly aggregated fine material and low organic matter matrices. These conditions can limit water retention, nutritional availability and root penetration, and metal(loid)s may add further limitations (*Agbeshie et al., 2024; Castellanos-Barliza and León-Peláez, 2023; Ghosh et al., 2020; Ruiz et al., 2023; Uzarowicz et al., 2025*). Thus, revegetation at field scale should be based on site-specific baseline data to distinguish between initial physical and chemical constraints and later changes during vegetation development (*Miguel et al., 2023; Yuan et al., 2023*).

However, total concentrations of potentially toxic elements (PTEs) alone do not allow proving mobility, bioavailability or ecological risk. Phytomanagement, which integrates monitoring of contaminants and the establishment of vegetation and functional indicators of soil, is increasingly proposed for the production of non-food biomass on degraded land (*Borbón-Palomares et al., 2024; Ceacero-Moreno et al., 2026; Conesa et al., 2026; Paniagua-López et al., 2024*). Maize, soybean and sweet sorghum differ in architecture, nutritional demand and environmental tolerance; sorghum is particularly relevant as a high-biomass crop under marginal conditions (*Kharytonov et al., 2019; Osman et al., 2023*). Mining-derived substrates can also be explored for non-food conversion routes, however feedstock origin can influence product composition and consequently needs elemental supervision before valorisation (*Roman et al., 2025*). Results from conventional maize-soybean systems cannot be easily extrapolated to post-mining substrates without field validation (*Hou et al., 2025*).

Recent geochemical investigations from the broader Petrila mining-waste setting provide important context for the present study. *Dunca et al. (2025)* documented pronounced spatial heterogeneity in heavy-metal burdens and used the geoaccumulation index (Igeo) and contamination factor (Cf) to identify Ni as a main contaminant requiring priority monitoring. *Ioniță (2026)* reported, based on a 2022-2024 dataset covering Ramura 1-4, a gradual decrease in mean pH (from 6.72 to 6.31), an increase in Eh (from 312 to 342 mV), and an annual increases of approximately 3-7% in total Cr, Cu and Ni. A separate redox-focused investigation *(Ioniță et al., 2026)* demonstrated marked intra-dump heterogeneity, including oxidising alkaline upper sectors, wetter near-neutral to slightly acidic/reducing lower sectors, and local extractable Cr(VI) hotspots. Together, these studies show that geochemical conditions across the broader Petrila mining-waste setting are spatially and temporally heterogeneous and strengthen the need for temporally resolved, paired substrate-plant monitoring; they are used here as contextual evidence and are not merged with the present biomass-monitoring dataset.

From an agricultural-engineering perspective, crop establishment on reconstructed or post-mining land is controlled by coupled soil-machine-crop interactions. Heavy machinery traffic can increase soil strength and penetration resistance and can reduce hydraulic functioning, while restored mine soils are particularly vulnerable to recompaction *(Schäffer et al., 2007; Obour and Ugarte, 2021)*. Mechanical reconstruction and surface/subsurface tillage can improve mine-soil physical conditions and vegetation establishment *(Fulton and Wells, 2005; Angel et al., 2018)*. In soils with a high coarse skeletal fraction, stone content directly affects planter workability, admissible forward speed and sowing quality *(Toscano et al., 2022)*. For perennial and other energy crops, georeferenced UAV and multispectral monitoring can complement ground observations with spatially explicit information on canopy development and biomass *(Impollonia et al., 2022)*.

A practical knowledge gap exists between laboratory-scale remediation studies and the engineering steps to convert an untreated heterogeneous mining surface into a repeatable field platform. The site-specific baseline method is in agreement with European and FAO soil-management frameworks (*European Commission, 2021; FAO, 2017*). This study fills that gap using the Petrila platform, and views the 2023-2025 record as a descriptive baseline, not as a demonstration of remediation efficacy. The originality of this work is documentation of field-scale platform establishment, balanced crop rotation and multi-year elemental surveillance under clearly controlled inferential settings. We asked four questions: (Q1) what was the spatial and depth-related variability of VWC, temperature, penetration resistance, and pH characteristic of the baseline campaign; (Q2) which PTEs were prioritised for follow-up by preliminary laboratory screening; (Q3) could maize, soybean and sweet sorghum be repeatedly established under the operational constraints of a coarse post-mining substrate; and (Q4) what interannual patterns were observed in harvested biomass and elemental composition during 2023-2025 in the absence of plot-level analytical replication?

Previous studies have generally addressed individual components of this chain - mine-soil reconstruction/tillage, traffic-induced compaction, planter performance on stony soils, or remote crop monitoring - rather than documenting the end-to-end conversion of an untreated coarse post-mining surface into a repeatable field platform. The specific contribution of the Petrila study is therefore the integrated engineering workflow linking baseline diagnosis, adaptation of mechanical preparation to site constraints, operational crop establishment and multi-year surveillance on the same 4,500 m² field platform. The novelty lies in this field-scale integration and traceable workflow, not in demonstrating amendment efficacy or statistically confirmed yield improvement.

## MATERIALS AND METHODS

### *Study site and environmental context*

The field study was conducted on Branch IV of the Petrila coal-mining waste-dump complex, Valea Jiului, Hunedoara County, Romania (locality-level reference ≈45.450° N, 23.419° E; central elevation ≈708 m a.s.l.). Waste deposition in the wider sector ceased in 2015. The mining-derived substrate contains weathered marl and sandstone fragments, a clay-rich matrix, coal fragments and abundant coarse material; before preparation, vegetation consisted of discontinuous herbs, shrubs and birch regrowth. No previous agricultural use or systematic soil-amendment programme was documented (*Sorică et al., 2024*).

Baseline measurements and soil sampling were performed in June 2023 and sowing was completed in late June. Petroșani station data for May-June 2023 (13.3°C/77 mm and 19.8°C/113 mm, respectively) are reported only as campaign context. Comparable seasonal meteorological series for 2024-2025 were not retained in the manuscript dataset; therefore, climate-year effects were not modelled and cannot be separated from interannual crop responses.

Official annual and seasonal climatological characterisations published by the Romanian National Meteorological Administration for 2023-2025 were consulted *(ANM, 2023-2025)*. They confirm substantial interannual thermal and pluviometric differences, but a complete Petroșani station-level growing-season series directly comparable with the archived May-June 2023 station values could not be reconstructed for all three years. To avoid mixing local station observations with non-equivalent national or seasonal summaries, meteorology is retained as contextual information only and is not used as an explanatory covariate for year-to-year biomass differences.

### *Experimental design and inferential scope*

A 5,000 m$^2$ perimeter was delimited, with approximately 4,500 m$^2$ used as nine 500 m$^2$ main plots. Three plots were designated as fixed-crop controls in the original project records and are treated here as fixed-crop reference plots (L1-1 maize, L2-1 soybean and L3-1 sweet sorghum). Six plots followed a balanced three-year cyclic rotation: L1-2/L1-3 maize→sorghum→soybean; L2-2/L2-3 soybean→maize→sorghum; and L3-2/L3-3 sorghum→soybean→maize. The wider project layout also contained amendment subplots. However, treatment identity, application rate, composition and application metadata are not available in the archived dataset used for this manuscript. Accordingly, amendment treatments are excluded from analysis and interpretation; no comparison of biochar versus digestate and no causal amendment effect is estimated.

**Fig. 1 - Field establishment workflow for the Petrila biomass-crop platform**

***Baseline in situ measurements and traceability***

Eight operationally selected points (P11-P14 and P21-P24) provided spatial coverage while avoiding plot margins, traffic tracks and conspicuous stone accumulations, consistent with the sampling-strategy principles of ISO 18400-104:2018 but not with a probability-based survey. Instrument-reported VWC and soil temperature were measured at 5 and 15 cm. The equipment inventory lists a FieldScout TDR 300 and an ML2x probe, but the archived field table does not identify which probe generated the reported VWC values; the readings are therefore not interpreted as substrate-calibrated absolute water contents. Penetration resistance was measured with a FieldScout SC 900 at 2.5 cm increments from 2.5 to 15 cm, with one profile per point; P11 showed refusal below 5 cm. Cone geometry, insertion speed and repeated insertions were not retained. Field pH and N-P-K were screened once per point with an electronic tester; N-P-K outputs are used only as semi-quantitative screening.

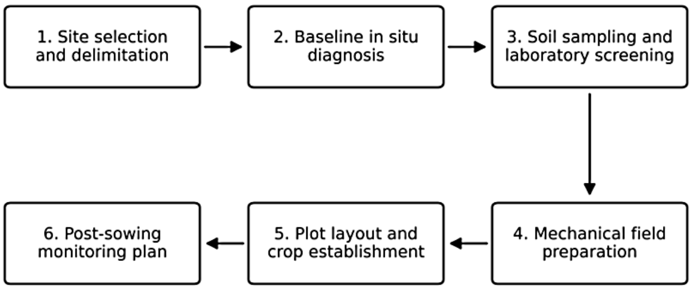


**Fig. 2 - Baseline measurement, sampling and crop-establishment workflow**

***Soil sampling and laboratory screening***

Soil samples associated with the in situ network were dried, homogenised and prepared according to the project laboratory workflow and the pretreatment principles of ISO 11464:2006. The available project summary was compared with Romanian reference values from Order no. 756/1997 and identified Cu and Ni as elements requiring follow-up. Sample-level concentrations, digestion details, calibration records, blanks, duplicates, certified reference materials, recoveries and LOD/LOQ were not available in the manuscript dataset. Accordingly, the soil laboratory evidence is used only for qualitative prioritisation, not for contamination classification, bioavailability assessment or risk calculation.

***Mechanical preparation and crop establishment***

Coarse stones and spontaneous vegetation were removed, the perimeter was staked, and shallow surface mobilisation was performed with a tracked hydraulic excavator because coarse fragments and irregular microrelief obstructed small conventional equipment. Maize hybrid Oituz, soybean variety Eugen and sweet sorghum variety SAȘM 2 were established at crop-appropriate depths using a common 50 × 20 cm geometry (100,000 planting positions $ha^{-1}$) to standardise field operations (Jităreanu et al., 2020). A one-row manual seeder was abandoned after repeated clogging, and planting positions were opened and covered manually. The common geometry is an operational standardisation, not an agronomic optimum for all three species. Detailed annual records of re-sowing, irrigation, supplementary fertilisation, soybean inoculation, plant-protection interventions and harvest stage were not retained in the manuscript dataset.

The maize, soybean and sweet sorghum crops were used here as experimental biomass crops on degraded post-mining land. Harvested material from the trial was not intended for human food or animal feed, and the present dataset is not used to support any food-chain safety claim.

***Biomass elemental-composition monitoring***

Above-ground biomass (stems and leaves) of maize, soybean and sorghum was monitored annually from 2023 to 2025. The archived analytical workflow records grinding, homogenisation, acid digestion with $HNO_3/H_2O_2$ and measurement by ICP-MS (PerkinElmer NexION 1000) for Cu, Pb, Co, Ni, Cr, Zn, Ba, Cd, B, Mo, As and Hg, reported in mg/kg. The supplied dataset contains one reported value for each crop-year combination and does not retain biological replication, plot/subplot identity, detailed sample-drying and aliquot procedures, instrument-calibration parameters, internal standards, blanks, certified reference materials, recoveries or element-specific LOD/LOQ. Therefore, values are reproduced as reported and interpreted descriptively. A dash in the 2023 file for Ba, As or Hg denotes absence of a reported value, not non-detection.

The original laboratory certificates/reports and the missing calibration/QA-QC records were not available in the archived dataset. Consequently, the elemental entries in Tables 2a-2b are retained as archived project-reported values for transparency only. Repeated exact entries such as 1.00 and 0.25 mg/kg are not treated as confirmed quantified concentrations, reporting limits or non-detects, and no regulatory, threshold-based or accumulation interpretation is assigned to them.

### *Statistical analysis*

Analyses were descriptive because point selection was operational, the baseline comprised one campaign and the biomass file lacked plot-linked replication. VWC, temperature and pH were summarised by mean, SD, coefficient of variation and range across eight points; 5- versus 15-cm differences were summarised descriptively. For penetration resistance, site summaries used seven complete profiles, while the valid P11 readings were retained graphically. Biomass elemental values were tabulated by crop-year only. Reported annual harvested-biomass totals (85, 263 and 487 kg) were retained as operational totals only because harvested area, crop-specific mass and moisture basis were not documented consistently. No hypothesis tests, treatment-effect estimates, bioaccumulation factors or soil-to-plant transfer factors were calculated.

Table 1 and Figures 3-4 therefore present descriptive summary statistics only (mean, SD, CV, range and depth-wise summaries), not inferential hypothesis tests. For biomass elemental composition, each crop-year entry is a single reported analytical record; crop species or years cannot be treated as statistical replicates without pseudoreplication. Consequently, additional inferential tests on the archived biomass values would not be statistically valid.

## RESULTS AND DISCUSSION

### *Operational establishment*

The 4,500 m² platform was established despite stoniness, irregular microrelief and local slope. Tracked-excavator surface mobilisation followed by manual seed placement provided a workable field solution after the one-row seeder repeatedly clogged. This demonstrates operational feasibility, not superiority of the preparation method or agronomic optimality. Similar constraints from coarse fragments and reconstructed structure are widely reported for post-mining substrates (*Agbeshie et al., 2024; Ruiz et al., 2023; Uzarowicz et al., 2025*).

The field sequence also illustrates the engineering constraint imposed by the coarse skeletal fraction: equipment capable of shallow surface mobilisation remained workable, whereas the one-row seeder repeatedly clogged and could not maintain reliable seed placement. This is consistent with planter-workability studies showing that stoniness reduces admissible operating speed and increases dynamic loads at the soil-planter interface *(Toscano et al., 2022)*.

### *Crop rotation, reproductive development and harvested biomass*

Maize, soybean and sweet sorghum reached reproductive development in all three years. The field notes describe ears in maize, panicles in sorghum and pods in soybean; because these observations were not quantified at plot level, they are treated only as evidence of reproductive establishment. The reported annual harvested-biomass totals were 85 kg in 2023, 263 kg in 2024 and 487 kg in 2025. These values are not interpreted as yield improvement because harvested area, crop-specific contributions and fresh-/dry-mass basis were not retained consistently. The balanced rotation reduced persistent association of a crop with a single field position, but the non-randomised layout and missing plot-level harvest data prevent causal partitioning of crop, rotation, amendment and year effects.

Accordingly, the manuscript uses these masses only as operational harvest totals and not as statistically validated crop-yield estimates.

### *Baseline water, temperature, pH and N-P-K response*

During the June 2023 campaign, instrument-reported VWC ranged from 19.0-30.9% at 5 cm (26.6 ± 4.2%; CV 16.0%) and 12.2-25.3% at 15 cm (20.0 ± 4.3%; CV 21.5%). All eight points were wetter at 5 cm, with a paired depth difference of 6.6 ± 1.9 percentage points. Mean temperature was 18.2 ± 1.3°C at 5 cm and 16.7 ± 1.1°C at 15 cm. Field pH ranged from 7.0 to 7.3 (7.1 ± 0.1), whereas the semi-quantitative N-P-K response was 'very low' at all points. These observations describe one campaign only; near-neutral pH does not imply adequate fertility or low PTE pressure (*Haghighizadeh et al., 2024; Ceacero-Moreno et al., 2026*). Standardised laboratory pH and nutrient analyses are required for agronomic interpretation.

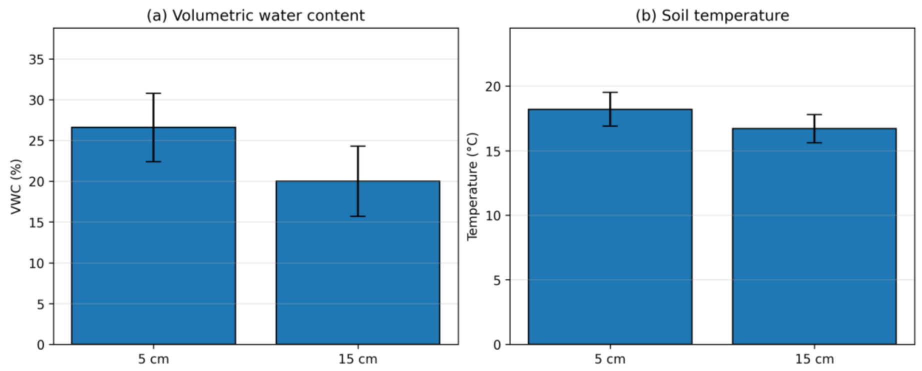


**Fig. 3 - Mean VWC and soil temperature at 5 and 15 cm in June 2023 (mean ± SD; n = 8)**

**Table 1**

**Baseline observations from the June 2023 campaign**

| Point | VWC 5 cm (%) | VWC 15 cm (%) | T 5 cm (°C) | T 15 cm (°C) | Field pH | Mean PR 2.5-15 cm (MPa) |
|---|---|---|---|---|---|---|
| P11 | 19.0 | 12.2 | 18.2 | 17.5 | 7.0 | NA* |
| P12 | 27.3 | 18.0 | 18.0 | 16.7 | 7.3 | 1.13 |
| P13 | 21.6 | 16.3 | 20.5 | 17.0 | 7.3 | 0.79 |
| P14 | 29.9 | 22.0 | 17.7 | 15.9 | 7.0 | 0.87 |
| P21 | 29.4 | 20.7 | 18.4 | 18.7 | 7.2 | 0.76 |
| P22 | 25.7 | 21.6 | 17.5 | 16.1 | 7.0 | 1.51 |
| P23 | 30.9 | 25.3 | 16.0 | 15.2 | 7.2 | 0.98 |
| P24 | 28.8 | 23.9 | 19.5 | 16.7 | 7.1 | 1.29 |
| Mean ± SD | 26.6 ± 4.2 | 20.0 ± 4.3 | 18.2 ± 1.3 | 16.7 ± 1.1 | 7.1 ± 0.1 | 1.05 ± 0.28† |

** P11 had valid penetration readings only at 2.5 and 5.0 cm and was excluded from the complete-profile mean. † n = 7 complete profiles. N-P-K response was „very low" at all eight points.*

### *Penetration resistance*

Across the seven complete profiles, mean penetration resistance was 1.05 ± 0.28 MPa (CV 26.5%), with point means from 0.76 to 1.51 MPa. The depth-specific mean increased from 0.49 MPa at 2.5 cm to 1.52 MPa at 15 cm; P11 was incomplete because of local refusal below 5 cm. The profile demonstrates small-scale mechanical heterogeneity and greater resistance to root penetration in the deeper measured layer under the moisture conditions of the baseline campaign. It does not justify a universal compacted/not-compacted classification because penetration resistance also depends on water content, particle-size distribution, bulk density, coarse fragments and measurement protocol (*Miguel et al., 2023; Ruiz et al., 2023*).

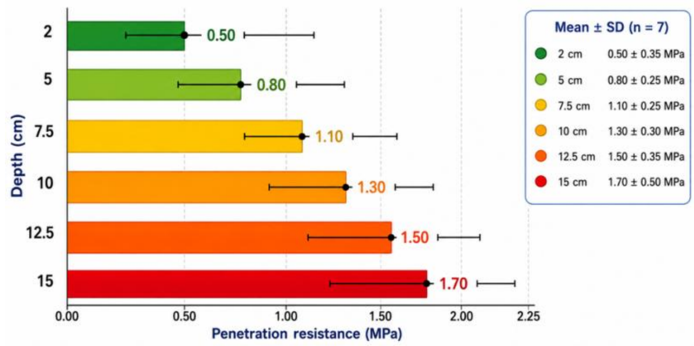


**Fig. 4 - Mean penetration-resistance profile for seven complete baseline profiles.**

Penetration resistance increased with depth, indicating greater mechanical resistance to root penetration in the deeper measured layer under the moisture conditions of the baseline campaign.

In agricultural-engineering terms, the observed profile links substrate mechanics with crop establishment. Increasing penetration resistance implies a progressively less favourable mechanical environment for root elongation, while machinery traffic can further increase soil strength; therefore, preparation should create a workable rooting layer while limiting unnecessary traffic and recompaction

*(Schäffer et al., 2007; Obour and Ugarte, 2021)*. On reclaimed mine soils, ripping and combined surface/subsurface tillage have been shown to reduce soil strength and improve vegetation establishment *(Angel et al., 2018)*. At Petrila, increasing penetration resistance indicated a root-zone mechanical constraint that motivated site-adapted surface preparation and low-traffic operations; the coarse skeletal fraction subsequently limited seeder operation, necessitating manual seed placement, after which all three crops reached reproductive development. Root growth itself was not measured, so this sequence is interpreted mechanistically rather than as a measured root-response pathway.

***Preliminary Potentially Toxic Elements screening***

The available laboratory summary prioritised Cu and Ni for follow-up: Cu was described as above the Romanian normal value but below the sensitive-use alert threshold, while some Ni results were described as near or locally above that alert threshold. Pb and Cd were not identified as relevant exceedances in the summary. Because sample-level concentrations and analytical QA/QC were unavailable, Order no. 756/1997 (*Ministry of Waters, Forests and Environmental Protection, 1997*) is used only as a historical screening reference, and no site-wide contamination, mobility or ecological-risk class is assigned. This distinction is important because total concentration does not directly represent bioavailability or plant exposure (*Borbón-Palomares et al., 2024; Ceacero-Moreno et al., 2026; Paniagua-López et al., 2024*).

This qualitative prioritisation is consistent with recent dump-scale studies, which identified Ni as a major contamination priority and showed that pH/Eh conditions and metal concentrations vary in both space and time across the Petrila complex *(Dunca et al., 2025; Ioniță, 2026; Ioniță et al., 2026)*. These external geochemical results support the need for continued monitoring but do not substitute for paired, plot-linked substrate and plant measurements in the present experiment.

***Archived biomass elemental records, 2023-2025***

The archived biomass file comprised nine crop-year elemental records, reproduced in Tables 2a-2b for transparency. Because the corresponding analytical certificates, full calibration/QA-QC documentation, LOD/LOQ information and plot-linked replication were unavailable, these entries are treated as nominal project-reported values rather than analytically validated concentrations for quantitative comparison. The manuscript therefore does not rank crops or years by elemental concentration, calculate annual concentration means for inference, compare the values with regulatory thresholds, or infer species-specific accumulation capacity.

Because these are single crop-year records rather than replicated plot-level observations, no statistical test of differences among crops or years is performed, and the apparent differences are treated as preliminary, hypothesis-generating patterns only.

The apparent differences among the archived crop-year records may plausibly reflect crop identity, seasonal conditions, growth dilution, substrate mineralogy, pH/redox status and changes in element availability, but these mechanisms were not tested here. Without verified analytical reporting metadata and paired plot-level substrate-plant data, the elemental records cannot be interpreted quantitatively as temporal trends, bioaccumulation or soil-to-plant transfer. Cu and Ni remain priorities for future replicated monitoring because they were also identified as relevant in the separate soil-screening and site-geochemistry datasets. Exact repeated values (1.00 and 0.25 mg/kg) and missing Ba/As/Hg entries must be resolved from laboratory certificates before any quantitative use.

**Table 2a**

**Archived reported biomass elemental values, 2023-2025 (units as supplied: mg/kg): Cu, Pb, Co, Ni, Cr and Zn**

| Sample | Crop | Year | Cu | Pb | Co | Ni | Cr | Zn |
|---|---|---|---|---|---|---|---|---|
| L1_porumb2023 | Maize | 2023 | 20.57 | 1.60 | 0.97 | 10.18 | 6.11 | 36.18 |
| L2_soia2023 | Soybean | 2023 | 41.37 | 3.67 | 3.09 | 26.50 | 17.27 | 87.01 |
| L3_sorg2023 | Sorghum | 2023 | 23.80 | 0.95 | 1.15 | 12.11 | 5.75 | 30.17 |
| L1_porumb2024 | Maize | 2024 | 4.51 | 1.00 | 1.00 | 2.54 | 7.63 | 35.28 |
| L2_soia2024 | Soybean | 2024 | 3.31 | 1.08 | 1.00 | 2.78 | 6.37 | 35.25 |
| L3_sorg2024 | Sorghum | 2024 | 8.52 | 2.15 | 1.89 | 12.85 | 6.39 | 27.21 |
| L1_porumb2025 | Maize | 2025 | 8.77 | 4.75 | 1.00 | 10.96 | 6.21 | 38.01 |
| L2_soia2025 | Soybean | 2025 | 10.64 | 6.46 | 1.00 | 12.92 | 7.75 | 47.11 |
| L3_sorg2025 | Sorghum | 2025 | 9.14 | 4.32 | 1.00 | 7.48 | 8.06 | 42.36 |

**Table 2b**
**Archived reported biomass elemental values, 2023-2025 (units as supplied: mg/kg): Ba, Cd, B, Mo, As and Hg**

| Sample | Ba | Cd | B | Mo | As | Hg |
|---|---|---|---|---|---|---|
| L1_porumb2023 | - | 0.04 | 12.93 | 0.99 | - | - |
| L2_soia2023 | - | 0.02 | 83.33 | 1.35 | - | - |
| L3_sorg2023 | - | 0.19 | 7.87 | 0.67 | - | - |
| L1_porumb2024 | 3.17 | 1.00 | 8.12 | 1.00 | 1.03 | 0.25 |
| L2_soia2024 | 3.28 | 1.00 | 8.05 | 1.00 | 1.10 | 0.25 |
| L3_sorg2024 | 36.85 | 1.00 | 28.25 | 1.00 | 1.27 | 0.25 |
| L1_porumb2025 | 5.85 | 1.00 | 16.81 | 1.00 | 1.00 | 1.00 |
| L2_soia2025 | 6.00 | 1.00 | 22.80 | 1.00 | 1.00 | 1.00 |
| L3_sorg2025 | 9.30 | 1.00 | 19.93 | 1.00 | 1.00 | 1.00 |

**Note:**„-” *indicates that no value was present in the supplied dataset and does not mean zero or <LOD. Exact values of 1.00 and 0.25 mg/kg are reproduced as reported and require confirmation against laboratory certificates before interpretation as quantified values or reporting limits*.

***Implications for subsequent biomass monitoring***

The current record establishes an initial elemental-surveillance baseline but does not demonstrate biomass safety. If non-food thermochemical conversion is pursued, PTEs should be quantified in replicated harvested tissues and conversion products because feedstock origin and process conditions can influence product composition (*Roman et al., 2025*). Future work should preserve plot/subplot identity, use replicated paired substrate-plant sampling, document full QA/QC and LOD/LOQ, and report crop-specific dry-matter yield per unit area.

Future monitoring can also be strengthened by georeferenced UAV/multispectral surveys synchronized with field observations. Vegetation indices, canopy height and repeated spatial imagery can provide non-destructive information on crop development and biomass heterogeneity and can guide plot-level sampling; such approaches have been demonstrated for high-throughput phenotyping and biomass/yield prediction in Miscanthus *(Impollonia et al., 2022)*.

In addition, perennial non-food energy crops such as Miscanthus should be evaluated in future field trials as complementary candidates under the evolving pH and redox conditions documented at the Petrila dump.

***Study limitations***

Two limitation groups constrain inference. Design limitations include one operationally selected baseline network, one baseline campaign and systematic rather than randomised crop/treatment allocation. Data-retention limitations include missing amendment dose/composition metadata, incomplete annual crop-management and meteorological records, non-normalised harvest totals, crop-year aggregation of elemental data, absence of plot-linked biological/analytical replication, and incomplete laboratory QA/QC and LOD/LOQ documentation. The absence of plot-linked analytical replication is a design/data-retention limitation, not evidence of treatment equivalence. Consequently, treatment effects, statistically confirmed temporal trends, bioaccumulation factors, soil-plant transfer factors and safe-valorisation thresholds cannot be inferred from the present dataset.

The present results should therefore be considered preliminary and hypothesis-generating; confirmatory conclusions require additional seasons with replicated, plot-linked measurements and complete analytical QA/QC.

## CONCLUSIONS

- A 4,500 m² field platform with nine 500 m² plots was operationally established on a heterogeneous mining-derived substrate in Petrila; maize, soybean and sweet sorghum reached reproductive development under the adopted field preparation and crop-rotation scheme.

- The reported 2023-2025 harvested masses are operational totals only; because harvested area, crop-specific contributions and fresh-/dry-mass basis were not documented consistently, they are not comparable agricultural yields and no year-to-year yield increase is inferred.

- The June 2023 baseline showed clear spatial and depth-related heterogeneity: the 5-cm layer was wetter and warmer than the 15-cm layer, field pH was near neutral, N-P-K screening was very low, and penetration resistance increased with depth under the measured moisture conditions.

- Preliminary laboratory screening prioritised Cu and Ni for follow-up, while the archived 2023-2025 biomass records displayed apparent crop-year differences in the reported Cu, Ni, Zn and Pb values. No conclusion is drawn regarding either the presence or the absence of soil-to-plant transfer or bioaccumulation, because paired substrate-plant data and plot-level replication were unavailable; treatment effects likewise cannot be inferred.

- Subsequent monitoring should retain plot/subplot identity, quantify crop-specific dry-matter yield, pair substrate and plant samples, document amendment properties and seasonal conditions, and apply full analytical QA/QC with explicit LOD/LOQ before evaluating remediation performance or biomass valorisation safety.

- The findings are preliminary and should be used to design confirmatory monitoring rather than to support causal, food-chain-safety or remediation-efficacy claims.

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