Environmental and Climate Technologies
2025, vol. 29, no. 1, pp. 710–724
https://doi.org/10.2478/rtuect-2025-0047
https://content.sciendo.com

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Assessment of Biofuel Ash Impact on Soil Quality Changes

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Received 11.04.2025; accepted 17.06.2025

***Abstract* – The degradation of urban soil quality is an emerging issue caused by rapid urbanisation, poor land management practices and pollution. These factors lead to reduced soil fertility and diminished vegetation in certain areas. Biomass ash, a byproduct of the biomass combustion process, proved to be an effective soil amendment due to the high levels of major soil nutrients, most notably calcium, potassium, and phosphorus. However, managing the fine particle size of biomass ash is problematic because wind could disperse particles into the air and migrate them to unwanted places, possibly causing wastewater pollution or even respiratory health hazards. To address these challenges and produce effective urban soil fertilisation techniques, this study explores pelletisation of biomass ash with gypsum as a stabilisation technique and its application on degraded soil using various application rates ranging from 1 t/ha to 7 t/ha. A series of controlled experiments were conducted to determine the ash pellets impacts on soil pH, nutrient availability, and plant biomass growth. The findings show that pellets of biomass ash to gypsum of ratio 5:1 with 12 % water addition were the most optimal to minimise binder usage and produce pellets durable enough for transportation and field distribution. Biomass ash considerably improves soil quality by increasing nutrient content in soil with a potassium increase in soil from an initial 1.2450 ± 0.00225 % concentration up to 1.4889 ± 0.0268 % and a calcium increase from an initial 1.8016 ± 0.0213 % concentration up to 2.3438 ± 0.0230 % depending on the fertilisation rate. Research has revealed that soil fertilisation using ash pellets with a rate of 1 t/ha showed no significant increase in biomass yield; however, higher fertilisation rates can increase ryegrass biomass yield by 9–38 % with the highest increase in biomass yield with biomass ash addition of 7 t/ha. The study underlines the potential of biomass ash pellets as an environmentally sound and sustainable solution to urban soil remediation as well as the reduction of waste.**

***Keywords* – Ash pelletization; biomass ash waste; soil quality improvement.**

1. INTRODUCTION

Global energy consumption has been increasing rapidly and is expected to continue growing. From 2000 to 2024, energy consumption has increased by more than half [1]. Biomass energy accounts for roughly 10–14 % of the world's total energy demand [2]. By 2050, biomass is projected to provide 23 % of global primary energy to help reduce greenhouse gas emissions by up to 50 % [3]. However, biomass energy production generates a significant amount of ash, which is managed as waste. Globally, approximately 170 million tonnes per year of biomass ash

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is produced [4]. Due to its high Ca, K, P and Mg nutrient content, biomass ash has high potential in circular usage and can be used as a fertiliser or soil amendment in areas with depleted soil quality [5]. These macronutrients are the most important for plant growth stimulation and soil fertility conservation [6]. The amount of these elements in biomass ash is dependent on the type of biomass; for instance, hardwood ashes are rich in calcium, potassium, and phosphorus, while softwood ashes contain higher levels of calcium, silicon, and potassium. Herbaceous feedstocks produce significantly more ash (typically 5–9 %) than woody feedstocks (typically 1–2 %) [7].

Biomass ash has significant potential to address urban soil degradation. This issue is especially important to prevent nutrient loss and enhance soil structure. Biomass ash has been successfully used in phytoremediation practices, aiding in the growth of plants like Ricinus communis and vetiver grass, which help in overall soil quality improvement [8].

In addition to simply replenishing nutrients, application of biomass ash can also play an important role in improving physical properties of urban soils. Biomass ash improves the stability of soil aggregates, reducing the percentage of aggregate destruction by up to 60 % and enhancing soil structural stability [9]. the presence of fine particles in a soil matrix can lead to a more uniform distribution of pore sizes, enhancing the soil's ability to retain water [10]. Biomass ash could also contribute to restoring useful microorganisms to urban soils. Biomass ash can promote the population of these microorganisms to grow by providing nutrients and enhancing the aeration of the soil [6].

Even though biomass ash has the potential to be used as urban soil fertiliser, potentially high heavy metal concentrations in ash might raise public concern. Heavy metals that are most common in biomass ash are lead (Pb), cadmium (Cd), zinc (Zn) and copper (Cu). The presence of these heavy metals in biomass ash raises discussions about their potential to contaminate soil and threaten soil macro- and microorganisms and public health by entering the food chain [11].

To enhance the performance and safety of biomass ash in soil applications, this study utilises ash-gypsum pellets a novel composite formed by combining biomass ash with gypsum. Gypsum provides Ca^{2+} and SO_4^{2-} ions that interact with other components in the ash to form C-S-H gels and ettringite, which enhance the mechanical properties and strength of the pellets. This interaction helps in achieving a reticular structure that improves the overall strength [12].

Gypsum acts as a binder and pH buffer, helping to stabilise heavy metals and reduce their mobility in the soil. Pelletising the mixture not only improves handling and application but also allows for a more controlled nutrient release, reduces dust, and enhances soil conditioning properties.

The main aim of the study is to assess soil quality changes in urban areas by implementing biomass ash as a remediation for nutrient depletion. The study aims to reduce biomass ash waste by producing ash-gypsum pellets used for vegetation improvement in nutrient-depleted urban soils.

2. METHODOLOGY

2.2. Analysis of Soil and Ash Elemental Composition

For the elemental analysis of soil and ash, the XRF analysis method was chosen. Numerous analytical methods, including atomic absorption spectrometry (AAS), inductively coupled plasma-optical emission spectrometry (ICP-OES), and X-ray fluorescence (XRF), can be used to determine the total metal contents in different materials. Regarding XRF, the method offers the following benefits [13]: elemental concentrations are directly obtainable from the sample's surface; minimal preparation and analytical work are needed; measurements are quick; up to 34 elements can be measured at once; and the analytical method is non-destructible, allowing the sample to be saved for additional analyses.

Measurements for soil and ash samples compositions were done with the SciAps X-200 XRF analyser (Fig. 1).

Fig. 1 SciAps X-200 XRF analyser.

All analyses were performed on dry and powdered samples. Soil samples were dried at 110 °C for 90 minutes before taking measurements. The sample cup preparation step is illustrated in Fig. 2. The sample cup was loaded with 5 grams of soil or ash powder in a 32-mm X-ray cup and covered with 6-micron (µrn) polypropylene X-ray film. The sample is gently compressed and tapped.

Fig. 2. XRF sample cup preparation.

A soil sample was retrieved from an area with reduced vegetation in Vilnius city, and ash samples were retrieved from the 'Vilniaus šilumos tinklai' heating plant.

2.2. Soil pH Measurement

The pH of ash and soil samples was measured according to the ISO 10390:2021 standard. According to the standard, three different types of media can be used to measure pH in soil: distilled water (pH in H_2O), potassium chloride solution (pH in KCl), and calcium chloride solution (pH in $CaCl_2$). In this case distilled water was used as a medium. First, a sample of at least 5 mL of soil or ash was taken with a spoon. Then this sample was placed into a bottle, and five times as much water was added – a ratio of 1:5. Then, the suspension was shaken for roughly 60 minutes using a mechanical shaker. Once the mixture was made, the suspension sat for an hour before measuring pH.

2.3. Biomass Ash and Gypsum Pellets Production

For the production of the pellets, the 'Wiesenfield WIE-PM-1500' pellet machine was used. The 'Wiesenfield' pellet production machine WIE-PM-1500 allows the production of up to 100 kg of pellets per hour. The pellet press machine heats the material to a temperature of 60–80 °C. Then, the solid cast iron construction presses the material through a 120 mm diameter disc. The result is firmly compressed, durable pellets with a diameter of 8 mm.

The mixture of the gypsum and biomass ash is mixed to achieve uniformity in texture. The pelletising machine receives the mixture, heats it, and compresses it under high pressure. The heat in the process activates the gypsum, thus allowing the ash particles to bind properly. The pressure forms the mixture into pellets of uniform shape. These pellets are then dried to take out extra moisture and solidify into durable material that could be used in various applications, including as a soil amendment. This process uses not only waste materials but also furthers sustainability by reusing industrial byproducts for purposes that create value.

In the experiment, different mixture proportions of biomass ash and gypsum were tested to achieve pellets durable enough for transportation and distribution. The main problem is determining how much gypsum one needs to incorporate into the ash biomass, mainly because too much gypsum makes pellets very hard. When the pellets are too hard, they are likely not to break down in soil properly and therefore may not spread the potentially available nutrients: potassium, phosphorus, and calcium.

The experiment started with a mixture of 15 parts of biomass ash and 1 part of gypsum. From there forward, the ratio of gypsum to biomass ash was increased by 5 (10:1, 5:1). The produced sample was taken for each concentration. The experiment was continued; the resulting pellets were able to withstand all rigours likely encountered in shipment and spreading in the field. In each trial, the durability of the pellets over time was observed.

2.4. ***Ryegrass Sowing and Fertilizer Pellets Implementation***

Plastic 1-litre volume pots were filled with 1 kg of homogenised soil, then 0.5 grams of ryegrass seeds were spread on the soil and covered with a 2 cm layer of soil as seen in Fig. 3.

Fig. 3. Control pots (bottom) and Ryegrass pots (top).

For the study five different ash pellet fertiliser quantities were chosen: 0 tonnes/ha, 1 tonnes/ha, 3 tonnes/ha, 5 tonnes/ha and 7 tonnes/ha. Control pot with no pellets added corresponds to 0 tonnes/ha quantity. The area of the pot is 200 cm², so the biomass ash pellets mass for each pot is calculated using the formula (1) and presented in Table 1.

$$m = \frac{q}{10} \cdot A \cdot 1000, \tag{1}$$

where

q fertilizer quantity, tons/ha;

A area of pot, cm^2;

10 conversion factor from t/ha to kg/m^2.

TABLE 1. BIOMASS ASH FERTILIZER QUANTITY FOR 200 CM^2 AREA POTS

Ash quantity, t/ha	Biomass ash quantity in 200 cm^2, g	Pellets, quantity, g
0.00	0.0	0.0
1.00	2.00	2.40
3.00	6.00	7.20
5.00	10.0	12.0
7.00	14.0	16.8

Ash/gypsum pellets were added to the soil to achieve these fertilizer concentrations.

2.5. Soil Moisture Control

There was a uniform watering schedule using water to maintain field capacity in all pots, representing field conditions naturally. According to data collected by the Lithuanian Hydrometeorological Service, the average annual precipitation in Lithuania is 695 mm in the years 1991–2020. The best time for sowing lawn seeds is in late March or early April, when the ground has warmed enough for seed germination [14]. Taking that into account, the average amount of precipitation in April (37 mm or 37 L/m²) was used for calculations of the watering schedule. The surface area of the soil in the pot is 200 cm² or 0.02 m². Then the daily water feed to pots is calculated using the formula (2).

$$V = \frac{P \cdot A \cdot 1000}{t}, \tag{2}$$

where

P monthly rain precipitation, L;

A area of the soil, m^2;

1000 conversion factor from litres to millilitres;

t length of month, days.

According to the calculations, a daily amount of 25 mL (rounded for easier measurement in the laboratory) of distilled water was fed into the pots to imitate natural precipitation volume. Distilled water was used in order to prevent any mineral addition from water.

2.6. Experiment Duration

The whole experiment was conducted for four weeks. Measurements were done with a control pot and each pot with different concentrations of fertiliser. Soil samples were taken every two days to observe nutrient dynamics, with samples drawn in the centre part of the pot to minimise edge effects.

Soil samples collected every four days were analysed with a handheld X-ray fluorescence (XRF) analyser to monitor over-time variations in nutrient composition. The XRF analyser gave quick, non-destructive analyses of critical elements, including potassium (K), calcium (Ca), and heavy metals in the soil. In each sample, pH was also measured after four weeks since the start of the experiment. Meanwhile, the biomass yield of the plants was measured in grams at the end of the study.

Data for both soil nutritional analysis and plant growth measurement were collected and documented in a systematic manner for comparison.

3. Results and Discussion

3.1. Ash Composition Changes Throughout the Years

The average measured pH for biomass ash collected from the heating plant was 12.3, showing that while large fluctuations do occur (Fig. 4), the general trend stays within constant ranges between 11.8 and 12.8. Such high alkalinity is important in pellet production, as it contributes to soil pH buffering in acidic urban soils and enhances the neutralisation capacity of the pellet when applied as a fertiliser.

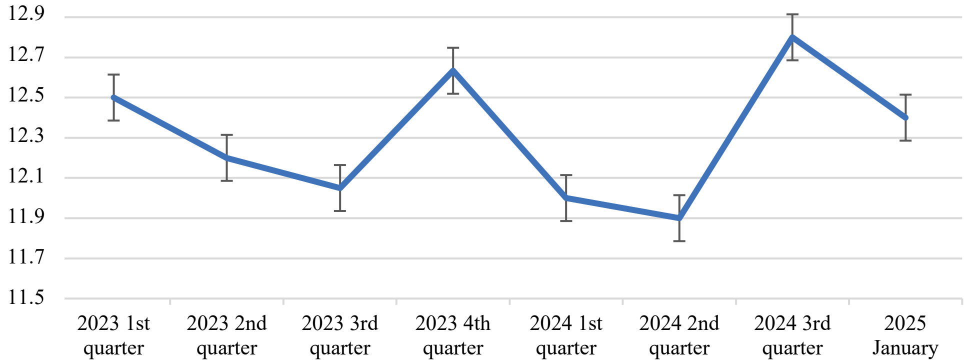

Fig. 4. pH levels fluctuation in biomass ash 2023–2024.

Potassium (K) in biomass ash sampled from heat plant across 2023–2025 is demonstrated in Fig. 5.

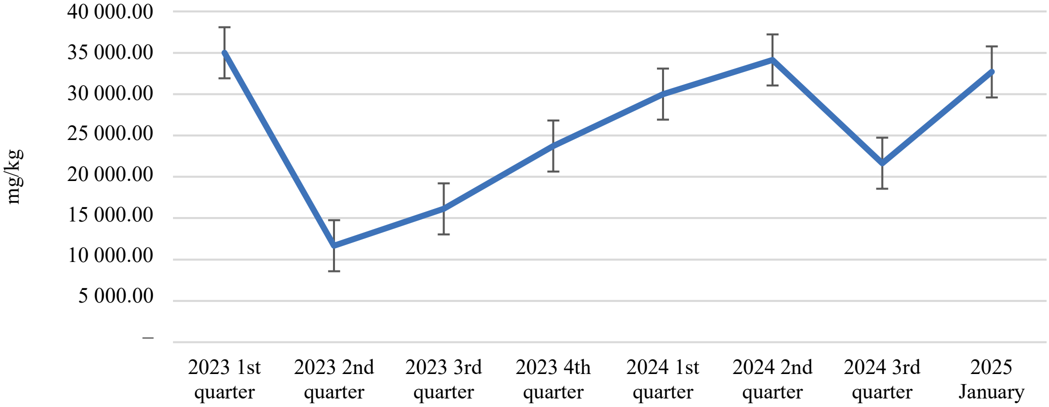

Fig. 5. Potassium levels fluctuation in biomass ash samples 2023–2025.

Results indicate that K concentration in ash fluctuates significantly. The highest level of 35 000 mg/kg was measured in Q1 2023 before falling to the lowest level of 11 667 mg/kg in Q2 2023. According to collected data, potassium concentration averages at about 25 622 mg/kg. Rising trends in K, especially in Q2 2023 to Q2 2024, indicate shifting biomass feedstock composition or process. Measuring potassium levels in the biomass ash is crucial because potassium is a key macronutrient for plant growth, so variations in K levels influence the fertilising value of the ash-gypsum pellets and must be monitored to ensure consistent nutrient delivery in soil application.

The average concentration of calcium in biomass ash is presented in Fig. 6. For the two-year period, it is approximately 102 015 mg/kg and far surpasses other average concentrations of the most important essential nutrients, such as potassium (24 613 mg/kg). This indicates the dominance of calcium as the major nutrient of the biomass ash.

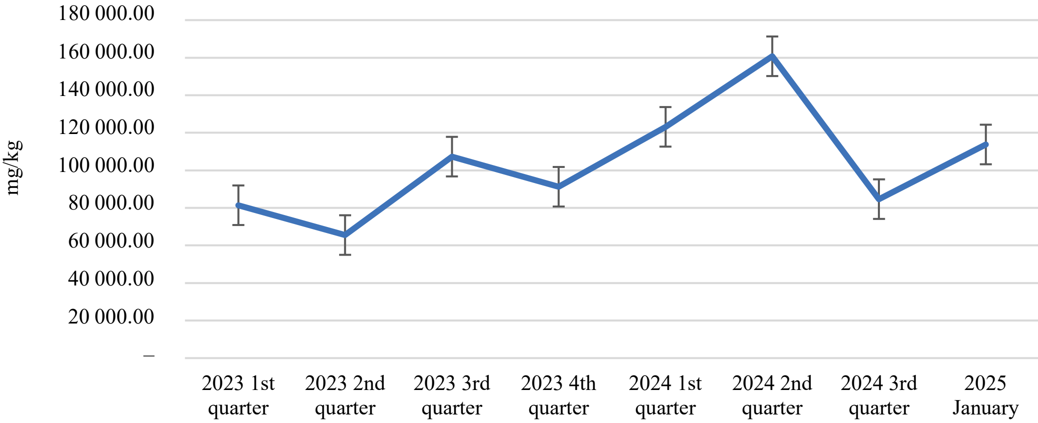

Fig. 6. Calcium levels fluctuation in biomass ash samples 2023–2025.

Calcium concentration in biomass ash trend is partially in sync with potassium, as both have increasing levels up to mid-2024, and it is probable that all of them might have similar drivers like feedstock or operational status.

Biomass ash typically contains heavy metals such as vanadium (V), nickel (Ni), chromium (Cr), cadmium (Cd), arsenic (As), copper (Cu), lead (Pb), and zinc (Zn) [15]. Accumulation of these metals can cause various negative effects on the environment, such as reduction of the biological activity in soil, impacting essential processes like nitrogen fixation and nutrient cycling [16]. To use biomass ash as a soil amendment, heavy metal concentrations in ash should be measured before insertion in soil; the results of heavy metal concentration changes are presented in Figs. 7–9.

The highest concentrations in biomass ash are chromium (Cr) in the initial group of elements (V, Ni, Cr, Cd, As), with some samples measured above 30 mg/kg. The vanadium (V) shows high variability, which could be related to biomass type and source. Nickel (Ni), cadmium (Cd) and arsenic (As) show low quarterly variability and are with the lowest concentrations.

Copper (Cu) and lead (Pb) also show variable concentrations. Cu remains fairly consistent around 50–70 mg/kg, while Pb ranges widely from about 30 to over 100 mg/kg depending on the quarter. Zinc (Zn) is the most abundant heavy metal in ash samples, with concentrations spiking above 1000 mg/kg in some periods and dipping to 600 mg/kg in others.

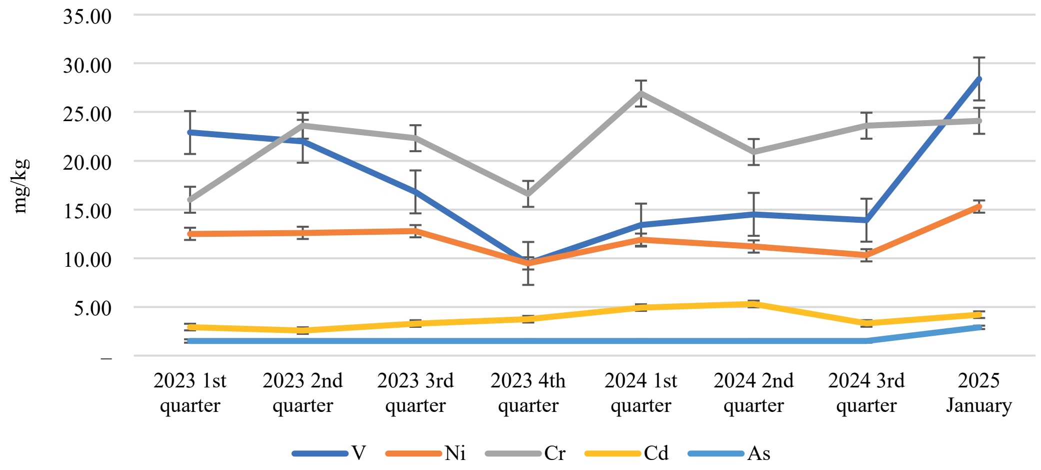

Fig. 7. Vanadium (V), nickel (Ni), chromium (Cr), cadmium (Cd) and arsenic (As) concentrations changes in biomass ash samples 2023–2025.

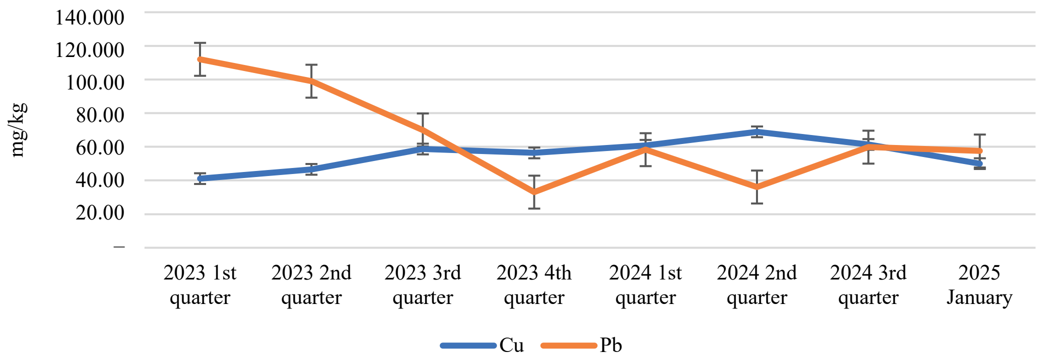

Fig. 8. Copper (Cu) and lead (Pb) concentrations changes in biomass ash samples 2023–2025.

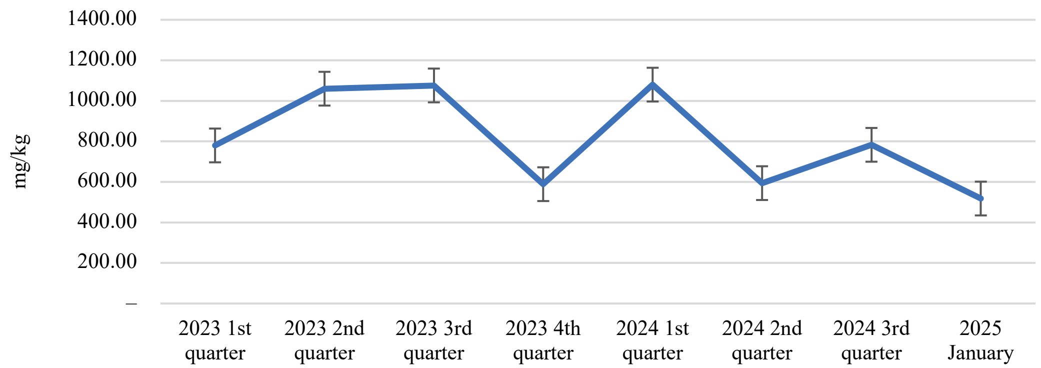

Fig. 9. Zinc concentrations changes in biomass ash samples 2023–2025.

The concentrations of heavy metals in ash do not show any clear trend; instead, they vary seasonally or due to multiple factors which could be further investigated.

The maximum permissible concentrations of heavy metals in ash used in forestry, agriculture, and the reclamation of degraded areas in Lithuania are regulated by the Order of the Minister of Environment of the Republic of Lithuania "Regarding the Approval of the Rules for the Management and Use of Wood Fuel Ash." The maximum permissible concentrations of heavy metals in ash used for reclamation of degraded areas are presented in Table 2.

TABLE 2. MAXIMUM PERMISSIBLE CONCENTRATIONS OF HEAVY METALS IN ASH USED IN AGRICULTURE, AND THE RECLAMATION OF DEGRADED AREAS (D1–14)

Element	**Maximum permissible concentration, mg/kg in dry matter**
Vanadium	150
Nickel	30
Chromium	30
Cadmium	5
Lead	50
Copper	200
Zinc	1500
Arsenic	3
Mercury	0.2

For reclamation of degraded areas, the ash would be acceptable for some of the samples where lead content falls within acceptable levels for agriculture, but for most of the samples, these are higher than acceptable. So regular inspection is needed to ensure lead levels remain safe. Other heavy metals such as copper, vanadium, nickel, chromium, cadmium, and arsenic levels are, in general, within tolerable levels for reclamation in degraded areas, with the exception of the 2024 2nd quarter, where cadmium levels were above legal limits.

3.2. Biomass Ash and Gypsum Pellets Production

As shown in Fig. 10, the best pellets performance was achieved with a 5:1 proportion of biomass ash and gypsum. The higher content of gypsum in this mixture acted as an effective binding agent, resulting in hard and strong pellets. After pellet formation, they were air-dried at room temperature for several days to allow for natural curing. Once dried, the pellets were packed and transported to a designated site. During this process, they retained their structural integrity, showing no signs of crumbling or breakage, indicating good durability under standard handling conditions. This suggests that the 5:1 mixture produced pellets with high mechanical stability, making them suitable for transport and storage.

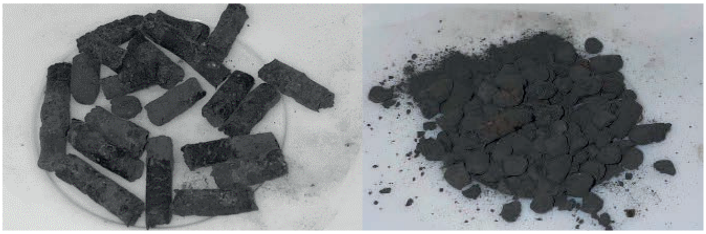

Fig. 10. Biomass ash and gypsum pellets ratio of 5:1 and ratio of 15:1.

The 10:1 ratio produced pellets that were relatively hard but showed visible crumbling during transportation, implying lower mechanical resistance. Despite their successful production, the pellets' vulnerability made transportation less convenient. The ratio was thus less convenient than the 5:1 ratio.

Conversely, the 15:1 ratio failed to work. The significantly lower amount of gypsum leads to weak structural integrity in the pellets and the breakdown of most of the pellets into fine powders upon extrusion (Fig. 10). Such results made the 15:1 ratio inappropriate for pellet production in terms of meeting the requirements for size and strength.

Overall, the most effective ratio was 5:1, as it produced the most stable and transportable pellets. A rise in ash content beyond this ratio, as in a 10:1 and 15:1 mix, detracted from pellet stability and usability. The most effective ratio to utilise in mass production is 5:1 (which corresponds to 16.7 % of the binder in total pellet mass).

A recent study done by Dash *et al*. [17] various binders were tested to produce ash aggregates. Aggregates were achieved with the addition of binder (sodium hydroxide) to ash at a ratio of 15:85. Similar results were obtained with the inclusion of binder (sodium silicate) to ash at a ratio of 17:83. In the study done by Buneviciene *et al*. [18], lime kiln dust was used as a binder in the production of biomass ash pellets, with binder-to-ash ratios of 30:70, 50:50, and 70:30. The study lasted two years, and the results showed that pellets with more binder (like 70:30) released nutrients more slowly and steadily, which helped keep the soil rich for a longer time. In contrast, pellets with lower binder content (e.g., 30:70) led to a more rapid and pronounced release of nutrients during the first year, followed by a noticeable decline in the second year. The evidence suggests that a reduced binder ratio may be advantageous in scenarios requiring immediate nutrient availability, while higher binder content is better suited for long-term, sustainable fertilisation strategies.

3.3. Soil pH Level Changes

Fig. 11 presents the changes in soil pH before and after the experiment. The control group, which had no application of ash pellets (0 t/ha), recorded a minor reduction in soil pH from 7.75 to 7.63. Microbiological processes, leaching, or other acidifying processes within the soil over time could cause this consistent decline. Interestingly, we observed a minor decline in soil pH from 7.76 to 7.70, even at a low ash application rate of 1 t/ha. This implies that such a low concentration may not be sufficient to reverse acidifying processes or significantly alter the buffering capacity of the soil.

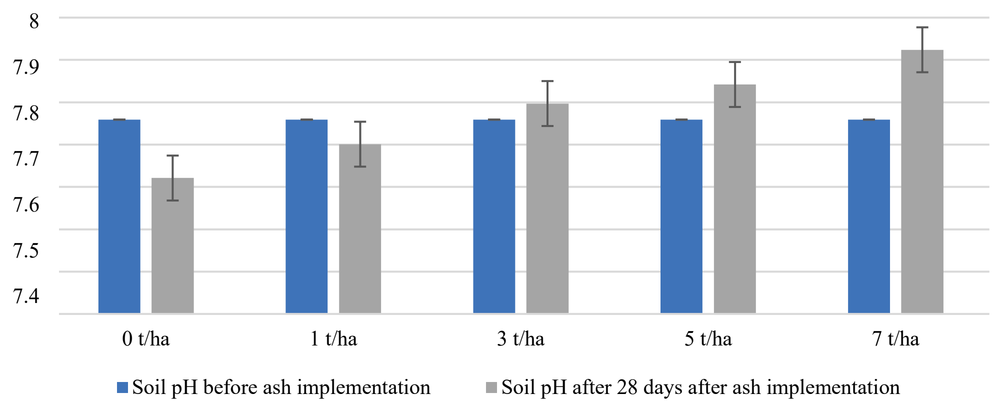

Fig. 11. Soil pH levels changes before and after fertilization.

At 3 t/ha, soil pH increased slightly, from 7.76 to 7.78. This small rise could show that the ash pellets begin to counteract natural pH reduction processes in soil. The effect is more visible when fertiliser is applied at a greater rate. At 5 t/ha, the pH went up more significantly to about 7.85, showing greater neutralisation of soil acidity. The most substantial change was observed at a fertiliser application rate of 7 t/ha, when the pH rose to 7.94. Biomass ash pellets fertiliser application rates of 1 t/ha were not enough to counter natural soil pH reduction. While application rates of biomass ash (3 t/ha) can be to keep soil pH stable. Application rates of 5 t/ha and higher are useful for increasing the pH of soils.

The highest rate of ash fertiliser (7 t/ha) increased soil pH by 0.28 in 28 days from the initial 7.76 to 7.94 at the end of the experiment. Results correspond to the data presented in other studies. In a study done by Albuquerque *et al.* [19], ash of 12 pH was used as a fertiliser in acidic Amazonian soil. In this study, a fertiliser rate of 8.75 t/ha, 20 days after application, increased soil pH by nearly 0.4, and high fertiliser rates (35 t/ha, 70 t/ha) increased soil pH by between 1.17 and 1.60 pH units when compared to the soil that did not receive ash input. This implies that ash pellets may be a good soil amendment, especially for correcting slightly acidic soils or maintaining pH levels in neutral to slightly alkaline soils.

3.4. Ryegrass Biomass Yield

Ryegrass (*Lolium perenne*) growth was not affected by the 1 t/ha fertilisation rate, and the 3 t/ha rate showed no significant growth either (Fig. 12). However, fertilisation rates of 5 t/ha and 7 t/ha showed a great improvement in biomass yield, increasing it by 30.9 % and 38.0 %, respectively, after 21 days of growth.

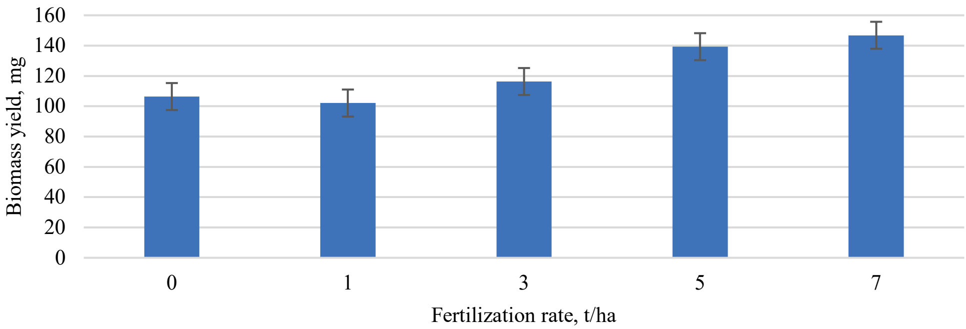

Fig. 12. Ryegrass biomass yield after 21 days since germination.

The findings show that the increase in biomass output slows down with increasing fertiliser concentration above 5 t/ha. More studies are needed to evaluate if further increases in ash pellet fertiliser positively affect biomass yield and if above a certain concentration the effect becomes negative.

Results correspond to studies done by other authors. For example, in the study done by Manisha Basu *et al.* [20], fly ash with a combination of other organic fertilisers with an application rate of 10 t/ha resulted in a sabai grass (*Eulaliopsis binata*) biomass yield increase of up to 27.6 %. Variations of biomass yield increase are strongly correlated with plant species and ash elemental composition. In the study done by Petlickaitė *et al.* [21], lower concentrations (2 t/ha) of biomass application resulted in a bean sprout’s dry biomass increasing by up to 120 % after a month of growth when compared to sprouts in non-fertilized soil.

3.5. Soil Composition Changes

Soil composition changes were taken every 4 days for 28 days after biomass ash pellets insertion in soil. Control samples elemental composition changes are presented in Table 3. After 28 days potassium and calcium concentration slightly decreased, which could be explained by leaching of the soil. Heavy metal concentration stayed relatively the same before and after the experiment.

TABLE 3. SOIL COMPOSITION CHANGES IN CONTROL SAMPLE (0 T/HA FERTILIZER)

Metal	**Days**	
Element	4	28
K, %	1.2450 ± 0.0225	1.2242 ± 0.0245
Ca, %	1.7931 ± 0.0225	1.7842 ± 0.0245
V, mg/kg	29 ± 3.8	31 ± 3.8
Cr, mg/kg	31 ± 4.1	28 ± 4.1
Ni, mg/kg	15 ± 6.1	13 ± 5.8
Cu, mg/kg	16 ± 5.5	18 ± 5.0
Zn, mg/kg	58 ± 4.7	52 ± 4.5
As, mg/kg	Not detected	Not detected
Cd, mg/kg	Not detected	Not detected
Hg, mg/kg	Not detected	Not detected
Pb, mg/kg	16 ± 2.3	16 ± 2.1

At a fertilisation rate of 1 t/ha, potassium (K) content in the soil increased steadily over the 28-day period, rising from 1.2484 % to 1.3893 %, indicating a continuous release of potassium from the ash pellets. Calcium (Ca) levels also increased from 1.8016 % to 2.0882 %, with the highest concentration observed on day 20, after which levels stabilised. Heavy metal concentrations stayed relatively the same as in the control pot before and after the experiment, while As, Cd and Hg concentrations were below the device detection level. Similar results were observed in soil with a fertiliser rate of 3 t/ha, with further increases in K and Ca concentration in the soil compared to the control sample. More detailed results are presented in Table 4.

TABLE 4. SOIL COMPOSITION CHANGES IN SOIL SAMPLES (1 T/HA AND 3 T/HA FERTILIZATION RATE)

	1 t/ha		**3 t/ha**	
	Days		**Days**	
Element	4	28	4	28
K, %	1.2484 % ± 0.0239	1.3893 % ± 0.0230	1.3037 % ± 0.0245	1.4061 % ± 0.0257
Ca, %	1.8016 % ± 0.0213	2.0882 % ± 0.0214	1.8340 % ± 0.0231	2.2112 % ± 0.0270
V, mg/kg	26 ± 4.1	29 ± 3.8	29 ± 4.0	31 ± 4.0
Cr, mg/kg	25 ± 4.2	21 ± 4.0	26 ± 4.7	24 ± 4.0
Ni, mg/kg	18 ± 6.2	12 ± 6.1	ND	13 ± 6.0
Cu, mg/kg	9.8 ± 5.2	11 ± 5.4	9.4 ± 5.3	9.2 ± 5.2
Zn, mg/kg	58 ± 4.7	69 ± 5.8	56 ± 4.8	56 ± 4.7
As, mg/kg	Not detected	Not detected	Not detected	Not detected
Cd, mg/kg	Not detected	Not detected	Not detected	Not detected
Hg, mg/kg	Not detected	Not detected	Not detected	Not detected
Pb, mg/kg	19 ± 2.4	22 ± 2.6	18 ± 2.4	19 ± 2.5

In pots with high fertiliser concentrations (5 t/ha and 7 t/ha) increased significantly compared to the control sample. Potassium (K) content showed the highest relative increase. rising from 1.2450 ± 0.0225 % to 1.4061 ± 0.0257 % (approximately 13 %) over 28 days following pellet application. Calcium (Ca) content also increased from 1.7842 ± 0.0245 % to 2.2112 ± 0.0270 % (approximately 24 %). These results suggest a steady release of nutrients from the fertiliser into the soil over time as presented in Table 5.

TABLE 5. SOIL COMPOSITION CHANGES IN SOIL SAMPLES (5 T/HA AND 7 T/HA FERTILIZATION RATE)

	5 t/ha		**7 t/ha**	
	Days		**Days**	
Element	4	28	4	28
K, %	1.2986 % ± 0.0258	1.4889 % ± 0.0268	1.3256 % ± 0.0240	1.4769 % ± 0.0235
Ca, %	1.8784 % ± 0.0261	2.3153 % ± 0.0287	1.8790 % ± 0.0216	2.3238 % ± 0.0230
V, mg/kg	30 ± 3.9	39 ± 4.0	27 ± 3.6	30 ± 3.9
Cr, mg/kg	20 ± 4.3	30 ± 4.2	28 ± 4.2	27 ± 4.1
Ni, mg/kg	12 ± 6.2	16 ± 6.2	10 ± 6.1	12 ± 5.7
Cu, mg/kg	8.6 ± 5.5	11 ± 5.3	10 ± 5.5	15 ± 5.1
Zn, mg/kg	46 ± 4.8	59 ± 4.8	61 ± 5.0	58 ± 4.6
As, mg/kg	Not detected	2.9 ± 1.5	Not detected	3.2 ± 1.5
Cd, mg/kg	Not detected	Not detected	Not detected	Not detected
Hg, mg/kg	Not detected	Not detected	Not detected	Not detected
Pb, mg/kg	17 ± 2.5	22 ± 2.6	17 ± 2.7	15 ± 2.2

All samples showed a similar trend wherein nutrient levels became stable 24 days after the pellets were introduced. This shows that the pellets had gradually released during that time. leading to the leaching of the nutrients into the soil. However, in pots with higher ash concentrations. Cd and Hg concentrations were still below device detection levels. and an arsenic concentration raise was detected and reached 3.2 mg/kg. Even though it does not exceed the European Union's maximum permissible arsenic concentration in soil of 20 mg/kg [22]. It proves that biomass ash implementation as a soil amendment could cause an increase of some heavy metal concentrations in soil and should be monitored. Since no statistical analysis (e.g., ANOVA or t-tests) was conducted. The differences observed between treatment groups and over time are descriptive and not statistically validated. Interpretations are based on observed trends and variability estimates.

Studies have shown that while initial applications may not significantly increase heavy metal levels, repeated applications can lead to higher concentrations, especially under varying weather conditions – the highest concentrations of the analysed elements were typically recorded in the second year of the study [23]. These findings indicate that while biomass ash amendments can improve soil structure and enhance nutrient availability in the short term, possible long-term negative effects could be identified and warrant careful monitoring. Continued research is essential to assess the sustainability of ash use under repeated application scenarios.

4. CONCLUSION

The biomass ash derived from the heat plant had a strongly alkaline pH, averaging 12.3 and ranging from 11.8 to 12.8 in the years 2023–2025. The ash was rich in essential plant nutrients, particularly calcium (average 102 015 mg/kg) and potassium (average 25 622 mg/kg), indicating the potential use as a soil amendment. However, the composition varied between seasons, which was presumably due to changes in feedstock or combustion practices.

Biomass ash contained various heavy metals, including Cr, V, Ni, Cd, As, Cu, Pb, and Zn, which can negatively affect soil biology if not properly managed. Therefore, monitoring their concentrations is essential before soil application. In ash samples taken in 2023–2025, chromium (Cr) had the concentration levels of 15–26 mg/kg. Vanadium (V) showed quarterly fluctuating levels 10–28 mg/kg, possibly influenced by varying biomass types. Nickel (Ni), cadmium (Cd), and arsenic (As) showed low, stable levels. Copper (Cu) was quite stable, ranging from 50 to 70 mg/kg, with varying levels of lead (Pb) ranging from 30 to more than 100 mg/kg. Zinc (Zn) was the most dominant. ranging from 600 to over 1000 mg/kg. Overall, heavy metal concentrations showed no commonly occurring trend but varied by season. This variation is possibly due to changes in the feedstock or operational regime.

Among the combinations tested, the 5:1 biomass ash to gypsum ratio yielded pellets that were not only strong but also long-lasting. making them suitable for transport and field application. Blends with a lower ratio of gypsum (10:1 and 15:1) exhibited impaired structural integrity, thus reducing their feasibility for application in practice.

The application of biomass ash pellets influenced soil pH. The impact of 1 t/ha and 3 t/ha rates was negligible. 5 t/ha and 7 t/ha significantly increased pH. The highest rate (7 t/ha) increased pH by 0.28 within 28 days. This confirms biomass ash's potential as a liming agent in acidic soils.

Fertiliser rates of 5 t/ha and 7 t/ha enhanced ryegrass biomass by 30.9 % and 38.0 %, respectively. after 21 days. However, the lower fertiliser rates did not show any significant effect on biomass yield. Reduced effects of biomass ash pellets on yield when compared to 3 t/ha to 5 t/ha and 5 t/ha to 7 t/ha fertilisation rates suggest that there might be a threshold application level for optimal growth response. beyond which yield gains may plateau.

Application of ash pellets resulted in rapid and sustained increases in soil potassium and calcium levels over 28 days. confirming gradual release and uptake. Soil samples composition stabilised 24 days after pellet implementation, suggesting that in 24 days pellets fully dissolved, and nutrients were absorbed by the soil. Heavy metal concentrations in the soil before and after fertilisation remained largely stable. However, arsenic concentrations showed a slight increase at higher application rates, but still within EU safety limits. The findings highlight the need for periodic soil testing when using biomass ash as fertiliser to avoid heavy metal contamination.

Biomass ash and gypsum pellets proved to be a potential use in urban areas as a degraded soil amendment.

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