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Utilization of biochar derived from municipal sewage sludge as a raw material for fertilizer production

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ABSTRACT

The study aimed to evaluate the potential use of sewage sludge–derived biochar as a soil amendment and nutrient source. Biochar was produced through torrefaction of municipal sewage sludge collected from a wastewater treatment plant located in the Upper Silesia region (Poland). The process was carried out at 250 °C for four hours under oxygen-limited conditions and atmospheric pressure, yielding a stable, porous material with approximately 80% reduction in initial volume. Chemical analysis of the obtained biochar revealed a high content of organic matter (62.8%), carbon (34.4%), and essential nutrients such as nitrogen (5.7%) and phosphorus (3.1%), along with safe concentrations of heavy metals. To assess the bioavailability of macro- and micronutrients, a pot experiment with a grass mixture was conducted using four treatments: control soil, soil with biochar, soil with ash–sludge mixture, and soil with raw sludge. The results showed that biochar addition significantly enhanced plant biomass production – by approximately 67% compared to the control – indicating its high fertilizing potential and positive influence on soil structure. Furthermore, the torrefaction process ensured complete hygienization of the sludge and degradation of potential organic micropollutants. Sewage sludge torrefaction thus represents a sustainable approach for nutrient recovery and waste volume reduction within the circular economy framework.

Keywords: biochar, sewage sludge, torrefaction, soil amendment.

INTRODUCTION

Modern sewage sludge management represents one of the key challenges in environmental engineering and sustainable development. With the growing urbanization and intensification of municipal activities, the quantity of sewage sludge produced in Europe has been steadily increasing, prompting the need for innovative and environmentally safe utilization methods (Werle and Wilk, 2010; Fytili, Zabaniotou, 2008). Traditional approaches – such as landfilling, composting, or agricultural use after stabilization – face increasing limitations due to environmental regulations, sanitary risks, and the presence of organic and metallic micropollutants (Al-Wabel et al., 2017). In this context, thermo-chemical conversion technologies for biomass and organic waste, including torrefaction, are gaining importance as processes that combine waste reduction efficiency with the potential for nutrient recovery.

Torrefaction, a mild form of pyrolysis conducted at 200–300 °C under oxy-gen-deficient or anoxic conditions, allows for the conversion of biomass into a solid product known as biochar or torrefied carbon (torreficate) (Bach et al., 2016). Compared with conventional biochar produced at higher temperatures (350–700 °C), torrefied biochar is characterized by a higher organic matter content and better preservation of nutrients, particularly nitrogen and phosphorus (Libra et al., 2011; Kwapinski et al., 2010). Moreover, the process leads to a significant reduction in feedstock volume, thereby lowering transportation and storage costs.

In recent years, there has been growing scientific and practical interest in using sew-age sludge-derived biochar as a soil amendment that can enhance both physicochemical and biological soil properties (Zielińska et al., 2015). The incorporation of biochar into soil can improve aggregate stability, increase sorption capacity, enhance water retention, and improve the availability of plant nutrients. Due to its large specific surface area and stable carbon structure, biochar also contributes to greenhouse gas mitigation through long-term carbon sequestration in soils (Lehmann, 2021). Furthermore, the thermal treatment of sewage sludge results in complete hygienization of the material and decomposition of organic micropollutants, including pharmaceuticals and endocrine-disrupting compounds (Gondek, Mierzwa-Hersztek et al., 2019).

In this study, sewage sludge from a municipal wastewater treatment plant located in the Upper Silesia agglomeration (southern Poland) was subjected to torrefaction in an intermediate reactor at 250 °C under near-atmospheric pressure and total oxygen exclusion. The process lasted four hours and produced a friable, homogeneous solid material composed of irregular granules. The obtained torreficate was characterized in terms of its chemical composition and fertilizer potential and subsequently tested in a pot experiment to assess its effect on plant biomass growth under controlled laboratory conditions.

To evaluate the bioavailability of nutrients and the influence of biochar addition on plant development, four experimental variants were established: (1) control soil (without additives), (2) soil with biochar, (3) soil with a mixture of fly ash and sewage sludge, and (4) soil with raw sewage sludge (approximately 19% dry matter). The experiment aimed to determine how torrefaction affects the availability of macro- and micronutrients and the resulting biomass growth compared with unprocessed material.

The results demonstrated that the highest biomass yield was achieved in the treatment with biochar addition, indicating its positive impact on both the physical and chemical properties of the soil environment. A similar effect was observed for raw sludge; however, this material did not meet the sanitary and stability requirements necessary for agricultural application. The conversion of sludge into biochar enhanced the bioavailability of nutrients while slightly reducing water retention capacity, which results from structural modifications induced during the torrefaction process (Zhang et al., 2021).

An additional benefit of torrefaction is the approximate 80% reduction in material volume, confirming the process's efficiency in municipal waste management. Sewage sludge-derived biochar can thus be considered a dual-purpose product – ensuring safe waste utilization while serving as a source of essential nutrients and a stable carrier of organic carbon in soil.

In the broader context of circular economy and sustainable resource management, technologies such as torrefaction align with strategies for nutrient recovery and greenhouse gas mitigation, while simultaneously supporting sustainable agriculture (European Commission, 2020). This research therefore contributes to the ongoing exploration of sew-age sludge biochar as a soil amendment that enhances fertility and structure, ensuring environmental safety and compliance with modern sustainability principles.

MATERIALS AND METHODS

Research material

The base substrate used in the experiment was garden soil collected from a single urban site, representative of typical green areas within city environments. The soil was characterized by a sandy-clay texture, a slightly neutral pH (6.7), and a moderate organic matter content of approximately 2.3%.

Four substrate variants were prepared for the experiment:

- Sample 1: (Control): garden soil without any additives,
- Sample 2: garden soil with the addition of 9 g of biochar,
- Sample 3: garden soil with the addition of 20 g of a mixture of fly ash and sewage sludge,
- Sample 4: garden soil with the addition of 40 g of untreated sewage sludge (19% dry matter).

For each pot, 580 g of garden soil was weighed and thoroughly mixed with the appropriate additive to ensure uniform composition.

Plant species composition

Sowing was carried out by evenly distributing 3 g of a grass seed mixture across the prepared surface to ensure uniform coverage and optimal establishment conditions. The seed mixture consisted of five grass species selected for their complementary characteristics in terms of growth habit, durability, and adaptability to environmental conditions.

The composition of the mixture was as follows: *Festuca duriuscula* (hard fescue) – 5%, included for its drought tolerance and low maintenance requirements; *Poa pratensis* (Kentucky bluegrass) – 10%, valued for its strong rhizome development and ability to form a dense, resilient turf; *Festuca rubra* (red fescue) – 40%, serving as the dominant component due to its fine texture, shade tolerance, and suitability for a wide range of soil conditions; *Lolium perenne* (perennial ryegrass) – 20%, incorporated for its rapid germination and quick establishment, providing early ground cover; and *Festuca ovina* (sheep fescue) – 25%, selected for its tolerance to poor soils and resistance to drought stress.

The seeds were applied manually (or mechanically, if applicable) in a uniform manner to minimize clustering and ensure even germination. After sowing, the surface was lightly raked (or rolled, if appropriate) to improve seed-to-soil contact, which is essential for successful germination and early growth.

Experimental conditions

The pots were placed in a laboratory room under controlled environmental conditions, where the temperature was consistently maintained within the range of 20–23 °C to support optimal seed germination and plant development. The experimental setup was exposed to natural daylight, without the use of supplemental artificial lighting, allowing the plants to grow under conditions resembling a typical indoor environment.

Irrigation was carried out regularly to ensure adequate soil moisture for seedling establishment and growth. Each experimental variant was watered every second day with a constant volume of approximately 100 ml per pot. This standardized watering regime was applied uniformly across all treatments to eliminate variability related to water availability.

No mineral fertilizers, soil amendments, or plant growth regulators were introduced during the experiment. This approach allowed for the assessment of plant growth and development solely under the influence of the initial soil conditions and the applied treatments, without additional nutrient inputs or external growth stimulation.

The experiment was conducted over a total period of 30 days, starting from the day of sowing and continuing until the grass reached the tillering stage. This growth phase was selected as the endpoint of the experiment because it represents a key stage in grass development, characterized by the formation of lateral shoots and the establishment of plant density.

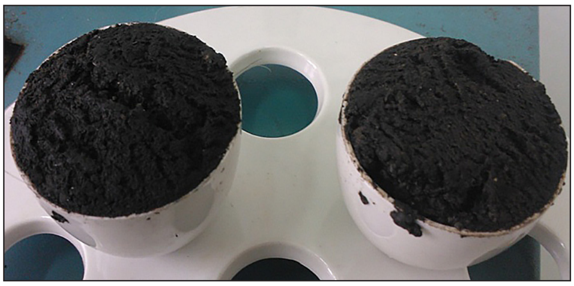
Chemical characteristics of the biochar used in the experiment

The torrefaction process applied to the municipal sewage sludge resulted in a significant reduction in its volume. Figure 1 A presents a sample of the sludge before torrefaction, while Figure 1 B shows the material after the process.

During thermal treatment under limited oxygen conditions at temperatures ranging from 250 to 350 °C, dehydration and thermal decomposition of the organic fraction occurred, leading to a densification of the material structure and loss of volatile components.

A comparative analysis of the samples revealed that the volume of the material decreased by approximately 80% after torrefaction compared with the original sample (A). Such a substantial volume reduction indicates the high efficiency of the process in stabilizing and compacting the organic matter contained in sewage sludge.

(a)



(b)

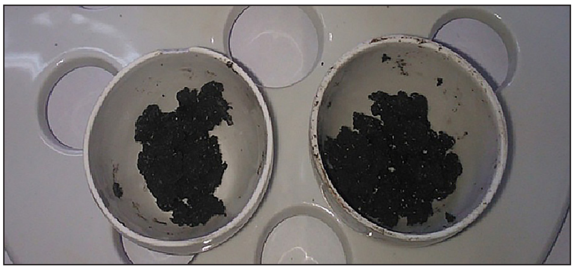


Figure 1. A raw municipal sludge, B municipal sludge after torification

The biochar produced from municipal sewage sludge at a pyrolysis temperature of 250 °C exhibited a high content of organic matter (62.8%), reflecting the relatively mild thermal treatment applied during its production (Table 1). Low-temperature pyrolysis generally promotes the preservation of organic structures and nitrogen-containing compounds, resulting in higher nutrient retention compared with biochars produced at higher temperatures. At the same time, the carbon content (34.39%) remained lower than values typically reported for woody biochars, which frequently exceed 60–70% carbon. This characteristic is commonly observed in sewage sludge-derived biochars due to their elevated mineral and ash contents. The total nitrogen concentration reached 5.68%, indicating significant nutrient value of the material. Such a high nitrogen content is typical for sewage sludge-derived biochars processed at relatively low temperatures, where thermal degradation and volatilization of nitrogen compounds are less intensive than during conventional pyrolysis above 400–500 °C. Consequently, the investigated biochar may serve not only as a carbon amendment but also as an important source of plant-available nutrients. A distinguishing feature of the analyzed biochar was its high phosphorus concentration, amounting to 3.10% P (7.09% P_2O_5). Sewage sludge is recognized as one of the richest waste-derived feedstocks in terms of phosphorus content, and pyrolysis promotes the concentration of phosphorus in the solid phase. As a result, sludge-derived biochars are increasingly considered potential alternative phosphorus fertilizers contributing to nutrient recycling within a circular economy framework. The concentrations of calcium (4.18%) and magnesium (0.91%) indicate a considerable content of alkaline mineral components. These elements may improve soil fertility through pH regulation, enhancement of soil aggregation, and stimulation of root development. The relatively high iron content (2.95%) is also characteristic of municipal sewage sludge-derived biochars and reflects the accumulation of mineral constituents during pyrolysis. Iron may additionally contribute to phosphorus sorption processes in soil, influencing nutrient availability after biochar application. The potassium content (0.58%) was relatively low compared with crop-residue or plant-derived biochars. This result is consistent with the chemical characteristics of municipal sewage sludge, which is usually richer in nitrogen and phosphorus than potassium. Therefore, the investigated biochar should be regarded primarily as a source of N

Table 1. Chemical composition of the investigated biochar (dry matter basis)

Parameter	Unit	Value biochar	Value ash+sludge
Organic matter	% w/w	62.8	24.2
Total nitrogen (N)	% w/w	5.68	2.3
Carbon (C)	% w/w	34.39	15.3
Sulfur (S)	% w/w	1.21	0.94
Phosphorus pentoxide (P_2O_5)	% w/w	7.09	4,14
Total phosphorus (P)	% w/w	3.10	1,81
Potassium (K)	% w/w	0.58	1,71
Magnesium (Mg)	% w/w	0.91	1,07
Calcium (Ca)	% w/w	4.18	6,81
Iron (Fe)	% w/w	2.95	2,16
Cadmium (Cd)	mg kg^{-1} (ppm)	2	0,64
Chromium (Cr)	mg kg^{-1} (ppm)	38	38,1
Copper (Cu)	mg kg^{-1} (ppm)	150	129
Manganese (Mn)	mg kg^{-1} (ppm)	335	293
Mercury (Hg)	mg kg^{-1} (ppm)	0.9	0,31
Nickel (Ni)	mg kg^{-1} (ppm)	24	26,1
Lead (Pb)	mg kg^{-1} (ppm)	50	20,7
Zinc (Zn)	mg kg^{-1} (ppm)	946	536

and P rather than K. The concentrations of potentially toxic elements were generally within ranges reported for sewage sludge-derived biochars. Zinc showed the highest concentration among the analyzed trace elements (946 mg kg^{-1}), followed by copper (150 mg kg^{-1}). Such enrichment is typical because pyrolysis reduces the mass of organic matter while concentrating mineral constituents in the solid residue. Nevertheless, concentrations of cadmium (2 mg kg^{-1}), chromium (38 mg kg^{-1}), nickel (24 mg kg^{-1}), lead (50 mg kg^{-1}), and mercury (0.9 mg kg^{-1}) remained within values commonly reported for sludge-based biochars in the literature. Overall, the chemical composition indicates that the investigated material is a nutrient-rich sewage sludge biochar with substantial fertilizing potential. The combination of high nitrogen, phosphorus, calcium, and iron contents suggests that its primary agricultural value lies in nutrient recycling and soil fertility improvement rather than long-term carbon sequestration. The relatively low pyrolysis temperature (250 °C) favored the preservation of nutrients and organic matter, which may enhance agronomic effectiveness compared with more severely carbonized biochars.

RESULTS

The reduction in material volume observed after the torrefaction process is directly related to the loss of moisture and the degradation of low-molecular-weight organic com-pounds, such as carbohydrates and lipids. The remaining solid fraction is characterized by a dark color, a porous structure, and a high resistance to further biological degradation.

The increased content of elemental carbon, along with the presence of macro- and microelements including calcium (Ca), phosphorus (P), magnesium (Mg), and iron (Fe), indicates that the resulting product – biochar (torreficate) – has significant potential for use as a soil-conditioning material.

From a waste management perspective, torrefaction represents an efficient method for reducing the mass and volume of municipal sewage sludge, thereby facilitating its further utilization. The product obtained through this process exhibits enhanced chemical stability, a lower odor emission potential, and minimal risk of secondary contamination.

When implemented on an industrial scale, the torrefaction process could contribute to reducing transportation and storage costs of sewage sludge, while simultaneously enabling the recovery of secondary raw materials in the form of nutrient-rich biochar suitable for agricultural and environmental applications.

To determine the fertilizer potential of the biochar used in the experiment, a comprehensive analysis of its basic physicochemical and elemental parameters was conducted. The results are summarized in Table 1.

For comparison, the chemical composition of the ash–sludge mixture applied in the experiment was also characterized and is presented in Table 1. The obtained results allow for a direct comparison of the physicochemical properties of both materials and facilitate the interpretation of their effects on plant biomass production and fertilizing potential proven by the pot experiment.

BIOMASS ANALYSIS

Methodology

After 30 days of growth, the plants were harvested to assess biomass yield under controlled laboratory conditions. The aboveground parts of the plants were carefully cut approximately 1 cm above the soil surface to ensure consistency across all samples while avoiding contamination with soil particles.

The collected plant material was immediately subjected to fresh mass determination. Each sample was weighed using a precision laboratory balance (Mettler Toledo), ensuring high accuracy and repeatability of measurements. Immediately after recording the fresh weight, the plant material was transferred to a drying oven.

Drying was conducted at a temperature of 105 °C for 24 hours until a constant weight was achieved, ensuring the complete removal of moisture from the samples. After drying, the material was reweighed using the same Mettler Toledo precision balance to determine the dry mass.

The results were expressed on a per-pot basis (g dry mass per pot), which allowed for direct and reliable comparison of growth efficiency and biomass production among the tested experimental variants (Table 2).

Table 2. Results of dry biomass measurements in pot experiments

No.	Substrate variant	Dry biomass 1 [g]	Dry biomass 2 [g]	Dry biomass 3 [g]	Relative to control [%]	Visual characteristics
1	Control (garden soil)	0.33396	0.33211	0.33396	100.0	Uniform growth, intense greening
2	Biochar (9 g)	0.55829	0.55829	0.55829	167.2	Most vigorous growth, dense foliage
3	Ash–sludge mixture (20 g)	0.35093	0.35093	0.35093	105.1	Moderate growth, minor discoloration
4	Raw sludge (40 g)	0.42580	0.42580	0.42580	127.5	Uneven emergence, looser plant form

Analysis and interpretation of results

The data obtained from the individual variants reveal distinct differences in the substrates' ability to stimulate biomass accumulation.

- Trial 2 (biochar) showed the highest dry mass yield, 67.2% higher than the control. This indicates a clear stimulatory effect associated with improved physical soil properties, increased water retention capacity, and enhanced nutrient availability.
- Trial 3 (ash–sludge mixture) produced results similar to the control, suggesting limited nutrient bioavailability or potential inhibitory effects due to factors such as high salinity or alkaline pH.
- Trial 4 (raw sludge) resulted in a 27.5% increase relative to the control; however, uneven germination and possible biotic stress symptoms were observed, suggesting partial phytotoxicity of organic compounds present in the untreated sludge.

The mean dry biomass across all variants was 0.417 g, with a standard deviation of 0.095 g, confirming a clear differentiation in growth response among the tested substrates.

A comparative analysis of the four experimental groups revealed clear differences in mean values (Figure 2). The highest mean was observed in the Biochar (9 g) group (0.56496), significantly higher than in the control group (0.34024), while also showing a low standard deviation (0.01155), indicating high measurement repeatability. The difference between these groups substantially exceeds both the observed variances and the range of natural variability, suggesting a statistically significant effect of biochar application.

The Ash–sludge mixture (20 g) and Raw sludge (40 g) groups showed mean values of 0.36756 and 0.42163, respectively, both higher than the control. However, the ash–sludge mixture exhibited the highest variance (0.00083), indicating greater material heterogeneity. The increase observed in the Raw sludge group is more stable (lowest SD = 0.00722), but the difference from the control remains smaller than that observed for the biochar group.

Considering the relation between mean differences and the variance within each group, it can be concluded that only the Biochar (9 g) group demonstrates differences that are highly likely to be statistically significant (Figure 3).

A one-way ANOVA was performed to compare the effects of the four soil amendments on the measured parameter. The analysis revealed a statistically significant difference between group means ($F = 102.63$, $p = 1.0 \times 10^{-6}$), indicating that the treatments had markedly different effects on the variable of interest. ANOVA result clearly demonstrates that the biochar treatment produced the highest mean value, while the control exhibited the lowest response.

DISCUSSION

The research conducted on the chemical and agronomic properties of biochar derived from the torrefaction of municipal sewage sludge provides a comprehensive assessment of its potential as a soil-improving agent and as a functional component within the circular economy framework.

The obtained biochar exhibited a high content of elemental carbon (34.39%) and organic matter (62.8%), confirming a substantial degree of carbonization and strong sorption capacity. The presence of carbon in this stable form supports the formation of humus soil complexes, improves soil aeration and water retention, and contributes to the long-term stability of soil organic matter (Borgulat et al., 2024). The porous structure resulting from the thermal decomposition of

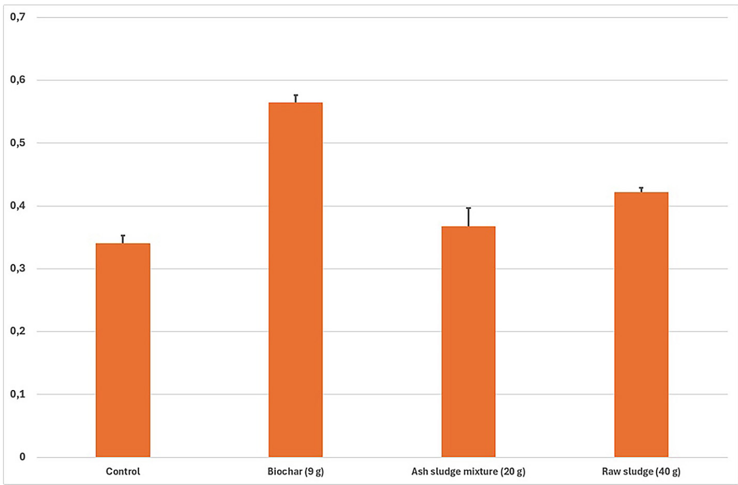


Figure 2. A comparative analysis of the four experimental groups mean and SD

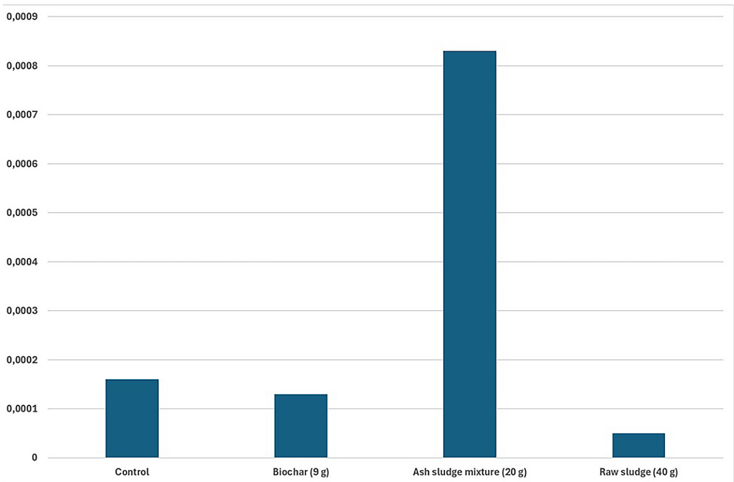


Figure 3. A mean differences and the variance within each experimental group

organic fractions enhances the cation exchange capacity (CEC) and facilitates the sustained adsorption and gradual release of nutrients – key factors influencing crop productivity (Lehmann et al., 2021; Laird et al., 2010).

The relatively high concentrations of nitrogen (5.68%) and phosphorus (3.10%) indicate a clear fertilizing potential of the biochar. Both elements are essential for photosynthesis and root development, and their gradual release from the biochar matrix minimizes the risk of leaching and eutrophication of aquatic ecosystems (Zhang et al., 2021). Furthermore, the notable presence of calcium (4.18%) and magnesium (0.91%) can help correct soil acidity and promote microbial activation in the rhizosphere, thereby enhancing nutrient cycling (Waheed et al., 2025).

A similar trend was observed for phosphorus. The phosphorus concentration (3.10%) was considerably higher than the average values reported for many plant-derived biochars and was situated in the upper half of the literature range (0.5–6.0%). This result is typical of municipal sewage sludge-derived biochars, where phosphorus is concentrated during thermal processing and remains largely retained in the solid residue. The high phosphorus content is especially important from the perspective of sustainable nutrient management and phosphorus recovery from waste streams.(Zhang et al., 2025)

The analysis of heavy metal concentrations in the biochar showed that all measured elements remained within the permissible limits for agricultural use. Low levels of cadmium, lead, mercury, and nickel confirm that torrefaction effectively immobilizes potentially toxic metals, thereby reducing their bioavailability and environmental risk (Liu et al., 2021). The elevated process temperature also ensured complete hygienization of the sewage sludge, eliminating pathogenic microorganisms and degrading pharmaceutical and endocrine-active compounds, yielding a chemically and microbiologically stable product (Buss et al., 2016).

The analyzed biochar also contained substantial amounts of calcium (4.18%) and magnesium (0.91%). Although both elements fell within the typical ranges reported in the literature, the calcium concentration can be considered relatively high, suggesting that the material may exert a liming effect when applied to acidic soils. Such a composition may contribute not only to nutrient supplementation but also to the improvement of soil physicochemical properties, including pH regulation and aggregate stability. (Lehmann, 2021)

Assessment of potentially toxic elements demonstrated that the concentrations of Cd, Cr, Ni, and Pb were relatively low compared with the ranges commonly reported for biochars. The values obtained for cadmium (2 mg kg^{-1}), chromium (38 mg kg^{-1}), nickel (24 mg kg^{-1}), and lead (50 mg kg^{-1}) were situated near the lower part of the respective literature ranges, indicating limited contamination of the feedstock and favorable environmental characteristics of the final product. (Nakić et al., 2025)

The chemical composition of the torrefied sewage sludge biochar was compared with that of the ash–sludge mixture (Table 1). Significant differences were observed in the content of both organic and mineral components. Biochar contained considerably higher levels of organic matter (62.8% vs. 24.2%), total carbon (34.39% vs. 15.3%), and total nitrogen (5.68% vs. 2.30%), indicating a substantially greater potential to improve soil organic carbon stocks and provide a slow-release source of nutrients. Similarly, the concentration of phosphorus expressed as P_2O_5 was markedly higher in biochar (7.09%) than in the ash–sludge mixture (4.14%).

In contrast, the ash–sludge mixture exhibited higher concentrations of potassium (1.71% vs. 0.58%), calcium (6.81% vs. 4.18%), and magnesium (1.07% vs. 0.91%), reflecting the enrichment of mineral constituents during the ash production process. Although these elements are essential plant nutrients, the low organic matter content of the ash–sludge mixture limits its ability to improve soil physical properties and microbial activity.

The concentrations of trace metals remained relatively low in both materials and did not exceed commonly accepted limits for agricultural applications. Biochar showed slightly higher concentrations of Cu, Mn, Pb, Zn, Cd, and Hg than the ash–sludge mixture, which can be explained by the concentration effect associated with torrefaction resulting from moisture and volatile matter removal. However, these values remained within acceptable ranges and did not adversely affect plant growth during the pot experiment.

The pot experiment results further demonstrated that the highest plant biomass yield was achieved in the biochar-amended variant, where the dry biomass reached 0.558 g, compared to 0.334 g in the control—representing an increase of approximately 67%. This confirms the beneficial influence of biochar on both the physical and chemical conditions of the soil environment. Biochar functions as a water–air buffer, supporting seed germination and root growth by stabilizing pH and improving nutrient retention (Sohi et al., 2010).

A comparable increase in biomass was also recorded for the raw sludge treatment, though its agricultural usability remains limited due to the presence of unstable organic fractions and potential sanitary hazards. The torrefaction process effectively transforms these unstable organic residues into a stable, environmentally safe product, while pre-serving valuable nutrients. The ash–sludge mixture variant, on the other hand, produced moderate results—likely due to high alkalinity, which may have inhibited plant growth. Future optimization of its composition could, however, make it a viable complementary amendment.

Comparison with literature data indicates that the investigated biochar can be classified as a nutrient-rich sewage sludge biochar characterized by high nitrogen and phosphorus concentrations, substantial calcium content, and relatively low levels of most potentially toxic elements. These characteristics suggest a significant potential for agricultural use, particularly as a soil amendment supporting nutrient recycling. However, the moderate carbon content (34.39%) also suggests that the material may be less effective for long-term carbon sequestration than high-temperature, lignocellulosic biochars, whose carbon content often exceeds 60–70%. (Zhou, 2017)

Overall, the findings confirm that biochar from sewage sludge torrefaction can serve as a multifunctional material – combining waste reduction, nutrient recovery, and soil improvement. Its dual role as both a carbon sink and a soil amendment aligns with the principles of sustainable resource management and supports the broader objectives of climate-smart agriculture and circular bioeconomy development.

CONCLUSIONS

From the perspective of the circular economy, the torrefaction of municipal sewage sludge represents an effective method for converting waste into a value-added product, reducing its volume by approximately 80% and transforming it into a stable carrier of organic carbon. The resulting biochar can be utilized in agriculture, land reclamation, and as a component of soil substrates in urban green infrastructure. The results obtained in this study confirm the need for further research focused on the long-term effects of biochar on soil structure, nutrient cycling, and the microbiological dynamics of soil ecosystems. The investigated sewage sludge biochar appears to be better suited for nutrient recovery and soil fertility improvement than for long-term carbon sequestration, owing to its high nutrient content, moderate carbon concentration, and relatively low pyrolysis temperature (250 °C). The higher biomass production observed in soils amended with biochar is consistent with its superior chemical characteristics. The combination of elevated organic matter, carbon, nitrogen, and phosphorus contents provides a more balanced nutrient supply while simultaneously improving soil structure and water retention. These properties likely contributed to the approximately 67% increase in plant biomass compared with the control treatment, confirming that the agronomic benefits of biochar extend beyond its nutrient content alone.

In summary, the biochar produced from municipal sewage sludge via torrefaction exhibits high agronomic, chemical, and environmental potential. It is a stable, safe, and effective material for improving soil quality, representing a significant element of circular economy strategies and innovative approaches to sustainable agriculture and resource management.

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