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Combined effects of sewage sludge or compost with lignite on early-stage poplar growth under As and Cu excess: A two-year mesocosm study

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ABSTRACT

The initial growth of poplar was investigated in an outdoor barrel experiment on low-fertility sandy soil using high-dose sewage sludge and sewage sludge-derived compost as fertilization for plantation management. Besides, lignite was applied to assess the possible synergistic effect between the tested organic materials. Since poplar species are often used for phytoremediation, the experiment also evaluated the effects of additional arsenic and copper loading, as well as the role of sludge, compost, and lignite in this process. Measurements included aboveground (leaves, woody biomass) and belowground (root electrical capacitance, stem basal area) biomass, the elemental (N, P, K, As, Cu) composition of aboveground plant tissues, and leaf chlorophyll content. These parameters serve as reliable indicators of nutrient availability, plant stress, and biomass production potential. The novelty of this research lies in examining the combined effects of sewage sludge, its compost and lignite under As, Cu loading on low-fertility sandy soil using poplar, with special attention to belowground biomass - an aspect rarely emphasized in similar studies. The results showed that the biomass of young poplars was significantly enhanced by both sludge and compost, especially by sludge during the first year in aboveground parts. Lignite alone had no detectable effect but slightly promoted growth when combined with sludge. Sludge and compost improved nutrient uptake, while lignite reduced arsenic accumulation. The increase in chlorophyll content was mainly due to sludge and compost treatments. Sludge and compost, together with lignite, offer a sustainable option for improving the soil quality in short-rotation forestry practices.

1. Introduction

Municipal sewage sludge and sewage sludge compost are widely studied as tree fertilizers (Gabira et al., 2021; Chu et al., 2023). Woody plants' high nutrient demands in early growth stages mean that higher doses of sewage sludge or compost are required in tree plantations than in the case of field crops. According to literature data, low doses of sewage sludge (0.4–3 t ha^{-1}) had little effect on 10-year-old *Larix decidua*, though 3 t ha^{-1} temporarily increased soil N, P, and Ca (Praspaliauskas et al., 2018). Higher doses (8–23 t ha^{-1}) boosted wood volume in young *Eucalyptus* plantations (Abreu-Junior et al., 2017). Compost at 2.5 % w/w (≈50 t ha^{-1}) enhanced *Populus euramericana* height and fine root length (Simiele et al., 2022), while 10 t ha^{-1} dried sludge increased *Populus trichocarpa* basal area within two years (Karacic and Adler, 2023).

Despite their positive effects on soil fertility and plant biomass, their application can be controversial due to potential toxic compounds (Duan and Feng, 2022).

Environmental risks of sewage sludge and its compost, originating mainly from potentially toxic elements (Kołodziej et al., 2016) can be reduced by adding adsorbents (Awasthi et al., 2017; Penido et al., 2019). Carbon-based adsorbents like biochar, coals, and lignite are promising due to their high humic and fulvic acid content, which immobilizes inorganic micropollutants via complexation and adsorption (Anemana et al., 2020). Lignite, the youngest form of hard coal with a woody structure and low heating value (Thielemann et al., 2007), has been used as a soil amendment. It helps to immobilize toxic elements (Simmler et al., 2013), improves nutrient availability, and enhances soil water, heat, air balance, and biological activity (Clouard et al., 2014; Kośodziej et al., 2016). No studies were found in the literature that have

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investigated the combined effects of lignite, sewage sludge, and compost on woody plants, nor on field crops. Similarly, data are lacking on how the combined application of biochar (which in many respects has effects similar to lignite) and sludge or compost influences tree growth; instead, most research focuses on pyrolyzed sludge and the effects of the resulting biochar on woody species (Silva et al., 2017, Yu et al., 2023). There is, however, evidence that biochar alone (20 t/ha) has only a modest effect on plant growth in *Populus trichocarpa* plantations (Muraro et al., 2025).

Poplar is a suitable species for energy plantations (Minotta et al., 2025), where initial vitality is crucial for early survival, root development, long-term growth, stress tolerance, and final tree size (Niinemets, 2010). Treatments supporting the vital initial growth period are important for healthy poplar development. Studies have examined sewage sludge and compost effects on poplar growth (Guoqing et al., 2019; Salehi et al., 2025) mainly focusing on aboveground biomass and nutrient or pollutant uptake. Data on tree vitality remain limited. Although not directly measurable, root biomass (Dobbertin, 2005) and photosynthetic activity (Taiz et al., 2021) are useful indicators of vitality. The effects of sewage sludge on chlorophyll content are unclear, with positive (Demirezen Yilmaz and Temizgül, 2014), neutral (Yilmaz and Temizgül, 2012), and negative reports (Manios et al., 2003), mostly for herbaceous plants, with such data lacking for poplars. Root electrical capacitance is a simple, non-destructive method to estimate root biomass (Cseresnyés et al., 2018; Ehosioke et al., 2020) and has been validated for poplars (Preston et al., 2004) and willows (Pitre et al., 2010). However, no studies have examined how the incorporation of sewage sludge, compost, or lignite into the soil affects the root electrical capacitance of poplar, and consequently root development and initial tree vitality.

In an outdoor barrel experiment (under controlled yet near-natural conditions) on low-fertility sandy soil the initial poplar growth was tested in response to high-dose sewage sludge (sludge) and sewage sludge-derived compost (compost) starter fertilization, with lignite added to assess potential synergistic effects on plant growth. A poor soil was chosen to observe the effects of the treatments more clearly. Because of poplars' common use in phytoremediation (Ancona et al., 2020; Yeşilyurt et al., 2024; Sirgedaitė-Šėžienė et al., 2025), the experiment also examined the effects of added arsenic (As) and copper (Cu) (hereafter PTEs) on plant growth, and the potential of organic materials and lignite to immobilize these elements. As and Cu were chosen for their frequency, contrasting soil behaviour, and differing roles: As is toxic and non-essential, while Cu is an essential micronutrient that can be harmful at high concentrations. These differences allow examination of distinct mechanisms, and both elements are common industrial contaminants (Lombi et al., 2004). While As may also come from geochemical sources or pesticides (Aide et al., 2016), Cu is often present in high concentrations in sewage sludge (Fjällborg and Dave, 2003). Tree growth and vitality were assessed via above- and belowground biomass (leaf and woody biomass, stem basal area and root electrical capacitance), elemental composition (N, P, K, As, Cu), and leaf chlorophyll content. Together, these measurements provide direct and indirect indicators of tree vitality, reflecting nutrient and water availability, stress responses, and overall biomass production potential (Godbold, 1998).

The hypotheses were that (1) both sludge and compost increase the above- and belowground biomass of poplar, with sludge having a stronger effect, especially in the first year; (2) lignite, used as an additive, presumably has a positive effect on above- and belowground biomass through its beneficial impacts on soil properties; (3) treatments with sludge and compost enhance nutrient uptake in the plants, while lignite decreases the absorption of certain PTEs, including the added As and Cu; (4) an increase in leaf chlorophyll content is expected due to the combined application of sludge or compost with lignite, though research findings to date have been contradictory and inconclusive.

The novelty of this study lies in examining the effects of treatments based on sewage sludge and compost produced from the same sewage sludge, combined with lignite as well as As and Cu elements, on various growth and physiological parameters of poplar tree parameters over a two-year period. These parameters have been scarcely addressed, or not at all, in the existing literature for these specific treatment combinations.

2. Materials and methods

2.1. Materials

The experimental soil was a Humic Arenosol (IUSS WRB Working Group, 2022) originating from a sand mine in Kecskemét, Hungary (46°54′N, 19°41′E). The communal digested sewage sludge was collected from a treatment plant located in Kecskemét, Hungary. Secondary sludge removed from the sludge stream of the plant was gravity pre-thickened, digested and further dewatered with the addition of polyelectrolyte. Compost, made from the digested sewage sludge at the same treatment plant, was produced in an actively aerated pile composting system on an industrial scale. In this plant, sludge is mixed with green waste for composting at a ratio of 1:4. Active decomposition lasts for 21 days at 60°C, followed by maturing for another 21 days. The lignite used in the experiment came from Visonta, Hungary. The parameters of the applied materials are presented in Table 1. The test plant was a hybrid black poplar tree (*Populus* × *euramericana (Dode) Guinier cv. Kopecky*) used in the form of stem cuttings. Soil and lignite were sieved through a 0.5 cm and a 1 cm mesh, respectively, before use.

2.2. Experimental setup

The outdoor barrel experiment was set up in October 2019 in a sunlit spot at the experimental site of the HUN-REN CAR Institute for Soil Sciences (46 °54'N, 18 °31'E). Plastic drums with a volume of 200 l (100 cm deep and 60 cm in diameter) were used, with plastic taps at the bottom for the controlled collection of leachate water. In order to prevent the soil from overheating during summer, the drums were wrapped around with reed fencing. The drums were arranged in a completely randomized design.

The bottom of the drums was filled first with a 10 cm layer of washed gravel (4–8 mm) that was covered with synthetic veil fabric. Three layers of soil were spread on it in the following order from bottom to top: 40 cm of untreated soil, 40 cm soil with the amendments, and 18 cm untreated soil again on the surface. This layer served to ensure that the initial development of the seedlings was not hindered by the materials used. All the amendments were mixed into the middle soil layer. Compost and sludge were applied at a dose of 50 t_{dm} ha^{-1} (1.5 kg d.m./drum), and lignite at a dose of 5 % (7.5 kg/drum) based on bulk density. The doses of sewage sludge and sewage sludge compost were determined based on the guidelines of Wolstenholme et al. (1992) and Bakti

Table 1
Characteristics of the applied materials. Concentration values refer to dry matter.

Parameter	Unit	Sewage sludge	Sewage sludge-derived compost	Lignite	Soil
pH$_{H2O}$		6.76	6.74	4.38	8.38
Organic matter	%	16.2	19.1	32.3	0.72
CaCO$_3$		-	-	-	3.55
Dry matter		30.3	75.4	-	-
Total N		3.19	2.85	0.687	0.051
Total P	mg/kg	14797	15269	1081	554
Total K		857	3270	1043	556
Total As		24.9	19.7	24.3	1.97
Total Cr		62.4	56.1	12.7	-
Total Cu		158	128	7.80	16.7
Total Ni		58.4	31.7	16.7	-
Total Zn		965	892	52.5	16

(2016). In Hungary, the agricultural use of sewage sludge and sewage sludge compost is regulated by Government Decree No. 50/2001 (IV. 3.), which defines permissible limits for toxic elements and hazardous substances in sludge and soils in harmony with the Joint Decree No. 6/2009 (IV. 14.), while the Forest Act allows the application of sewage sludge on forest land only in exceptional cases subject to official authorization.

As for the potentially toxic elements: As was applied in a 22.5 mg kg^{-1} concentration in the form of Na_2HAsO_4 7 H_2O solution, and Cu at 112.5 in the form of $CuSO_4$. The As and Cu concentrations refer to the total mass of soil filled into each drum and represent 1.5 times the threshold limits prescribed in the Hungarian regulation (Joint Decree of 6/2009. (IV. 14.) KvVM–EüM–FVM) for contamination (15 mg kg^{-1} for As and 75 mg kg^{-1} for Cu). The treatment combinations are shown in Table 2. Each treatment was set up in three replicates, except for the control, where there were 6 replicates to allow plant physiological measurements, resulting in a total of 39 drums.

After being filled the drums were kept covered for incubation for 18 days. At the end of November one poplar clone was planted in each drum and irrigated with 10 l of water. A monitoring system measured the soil moisture content at a depth of 10–15 and 20–25 cm every hour in three selected drums (Sensor: Decagon EC-5). These moisture data were used to ensure that the trees received sufficient tap water to satisfy their water requirements for the duration of the experiment, which lasted for two and a half years.

2.3. Sampling, monitoring and analysis

2.3.1. Plant biomass

The height of the trees was determined by measuring them from the graft to the top three times during the experiment: March 17, 2020; March 9, 2021; January 6, 2022. Diameter measurements were carried out more frequently, at the same time as root capacitance analysis (as detailed below).

Leaf biomass was measured at the end of each growing season. In order to collect all the falling leaves, the trees were wrapped around with a net in early autumn. The leaves were dried, weighed and ground for element analysis (N, P, K, As, Cu, Cr, Zn, Ni).

At the termination of the experiment after two and a half years in January 2022 the trees were cut down below the graft. The lower part of each tree was cut off 2 cm above the graft and discarded. After recording the weight and height of the trees, they were processed using a branch grinder, weighed again and dried for element analysis (N, P, K, As, Cu, Cr, Zn, Ni) as well.

2.3.2. Root electrical capacitance measurements

The root development was monitored by measuring the root electrical capacitance (C_R) regularly during the growing season, from March to November (11 and 8 times in the first and second year, respectively). The method is based on the linear correlation between C_R, detected between a ground and a plant electrode, and root size traits, including the absorptive root surface area (Carlson and Smart, 2016). The ground electrode (303S31; RS Pro GmbH, Gmünd, Austria) was a sharpened stainless steel rod, 15 cm in length and 6 mm i.d, pushed vertically into the soil 5 cm away from the stem to a depth of 12 cm. The plant electrode was clamped to the stem 2 cm above the soil surface through a 5 mm wide and 25 μm thick aluminum foil that bent the stem. The stem was smeared with conductivity gel to ensure good electric contact. C_R (in parallel mode) was measured with a handheld U1733C LCR meter (Agilent Co. Ltd., Penang, Malaysia) at 1 kHz AC frequency with 1 V terminal voltage. Due to the sensitivity of C_R to soil moisture conditions, the volumetric soil water content (SWC) in the 0–12 cm layer was measured in the root zone using a HS2 TDR instrument (Campbell Inc., Logan, UT, USA) attached to a CS659 probe. Based on a predetermined experimental C_R–SWC function, the recorded C_R was converted to a root electrical capacitance (C_{FC}) value, which could be measured at field capacity water content (0.16 cm^3 cm^{-3} for this soil) to ensure data comparability. See Cseresnyés et al. (2018) for a detailed description of the method.

Thereafter, at the height of the plant electrode, two perpendicular stem diameters ($Ø_1$ and $Ø_2$) were taken with a digital caliper (±0.1 mm), and the stem basal area was calculated as $BA = (Ø_1/2) \times (Ø_2/2) \times \pi$.

Table 2
Treatment combinations used in the experiment (-: no; +: yes).

Number of treatment	Applied materials		
	Potential toxic elements (As, Cu)	Organic amendment	Lignite
1	-	-	-
2	+	-	-
3	-	sludge	-
4	-	compost	-
5	+	sludge	-
6	+	compost	-
7	-	-	+
8	+	-	+
9	-	sludge	+
10	-	compost	+
11	+	sludge	+
12	+	compost	+

2.3.3. Chlorophyll content

The leaf chlorophyll concentration (Chl) was detected in situ using a handheld MC-100 instrument (Apogee Inc., Logan, UT, USA) seven times in 2020 and six times in 2021 from May to October. Six healthy, fully developed leaves of roughly the same age (or position) were chosen randomly from each tree, and measurements were carried out on the top side of the leaf blades, avoiding edges and main veins. The six readings were averaged to obtain Chl data for each tree.

2.3.4. Plant analyses

The N content in plant samples was analysed according to the Kjeldahl method (ISO 11261, 1995). The element content of the plant samples was determined after HNO_3 - H_2O_2 digestion and measured using the ICP-OES method (ISO 12914:2012). The element concentrations in each extract were determined by means of ICP-OES (Jobin-Yvon Ultima 2 sequential instrument), using Merck calibration standards and following the manufacturer's instructions. In each measurement session the extract of a standard plant sample (Poplar leaf, WEPAL sample ID 177) was also analysed as a control. The calibration curves were determined after every 12th sample.

2.3.5. Statistics

The data were analysed for treatment effects using three-way factorial analysis of variance (ANOVA). The factors were the organic amendment, the lignite and the As and Cu treatments. The variance was calculated for the treatments and treatment levels. The normality of the data and the homogeneity of the variances of model residuals were assessed using Shapiro–Wilk test and the Levene test, respectively. Significant differences between the treatment groups were calculated with Tukey's HSD post hoc test at the $p < 0.05$ level. Statistica v.13 (StatSoft Inc.) software was used for all the statistical evaluations. Data visualization was made with R statistical software (R Core Team 2024) using the ggplot2 package (Wickham 2016).

3. Results

3.1. Leaf biomass and element content

The leaf biomass values for 2020 and 2021 are illustrated in Fig. 1. In the first year, sludge and compost increased leaf biomass by + 80 % and + 33 %, respectively, compared to the control, with sludge exceeding

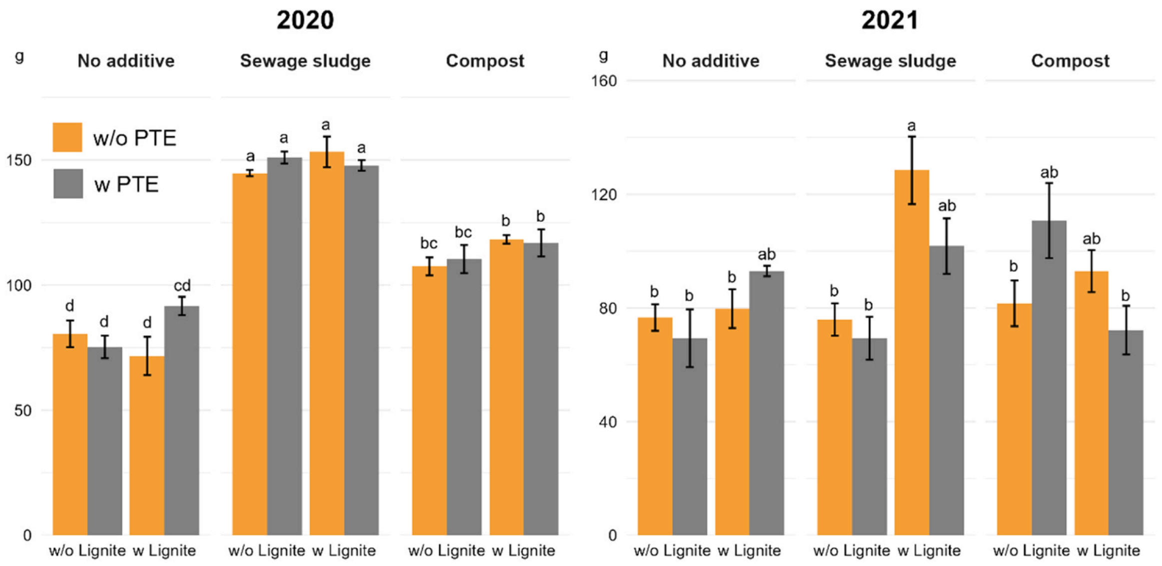

Fig. 1. Leaf biomass in 2020 and 2021, PTE- potential toxic element, w/o– without, w– with.

compost by + 35 %. In the second year, the sludge–lignite treatment increased biomass by + 68 % compared to the control and by + 61 % compared to lignite only. The sludge–lignite treatment, with or without added PTE, resulted in an average + 65 % increase compared to treatments without lignite. In this year the compost treatments did not cause significant changes.

The leaf element contents (N, P, K, As, Cu) for 2020 and 2021 are shown in Fig. 2. In the first year, both sludge and compost increased leaf N content significantly (+71 % and +87 %) compared to the control, respectively, but there was no difference between the two organic treatments. The highest N level was observed in the sludge–lignite–PTE treatment (+105 %). In the second year, the highest N levels were again observed in the sludge treatments: + 147 % compared to the control, + 186 % compared to the lignite only treatment, and + 141 % compared to the PTE only treatment, and also 54 % higher than in the compost treatment. The compost–lignite combination also significantly increased leaf N content (+78 % compared to the control and +106 % compared to lignite only).

In the first year, the highest leaf P content was observed in the compost treatments (+34 % compared to the control). Compost addition increased the P content compared to the PTE only (+54 %), lignite only (+47 %), and lignite–PTE (+48 %) treatments. The sludge–lignite–PTE treatment increased P content by + 37 % compared to the lignite–PTE treatment. In the second year, the above changes were less pronounced; the compost–PTE treatment decreased leaf P by −37 % compared to PTE only.

In the first year, the highest leaf K content was measured in the compost treatments (+40 % in compost-PTE compared to PTE only), while the sludge only treatment decreased it (−33 % compared to the control, −45 % compared to compost). In the second year, the compost only treatment reduced the leaf K content by −41 %, and compost–PTE by −42 % compared to the control or PTE only addition. Sludge treatments did not cause significant changes.

The results obtained in the first year showed that As treatment increased leaf As content by over + 400 % compared to the control, whereas in the presence of lignite, leaf As content decreased to nearly one-third (−66 %). Both sewage sludge and compost exhibited approximately + 40 % stabilizing effects compared to the PTE only treatment, but this was not significant. In the second year, leaf As content was lower in the presence of lignite than without it, but this difference was not statistically significant. In this year, sludge also showed a stabilizing effect: leaf As content decreased to −66 % compared to the PTE only treatment.

The Cu treatment did not significantly affect the Cu content of the leaves. In the first year, the lowest Cu content was observed in treatments without sludge or compost. In the second year, the Cu treatment still had no effect, but the Cu content in treatments without sludge and compost was significantly lower than when these were added. The effect of lignite had no significant effect on Cu content.

3.2. Stem biomass and element content

Stem biomass in 2021 is shown in Fig. 3. Sludge and compost increased woody biomass by + 65 % and + 48 %, respectively, compared to the control. Lignite and PTE had no effect on stem biomass.

According to Fig. 4, there was no significant difference in stem basal area in the first year. In the second year, although the basal area increased in the sludge and compost treatments compared to the control, this increase was not significant. The sludge–PTE treatment increased stem basal area by + 57 % compared to the PTE only treatment, regardless of the presence of lignite. The compost–lignite treatment exceeded the control by + 41 % and the lignite only treatment by + 56 %.

According to the stem element content in 2021 (Fig. 5), the N and P contents of the woody biomass were the lowest in the control and in treatments without sludge or compost, while the highest values were observed in sludge treatments. Sludge nearly tripled the N content, and compost doubled it. As for P, sludge and compost caused a + 100 % and a + 60 % increase, respectively, with sludge being significantly more effective. PTE and lignite had no effect on N and P contents. K content did not differ significantly among the treatments. Arsenic concentration remained below the detection limit in all treatments. Cu content more than doubled in the sludge and compost treatments compared to the control. The highest Cu concentrations were found in the sludge–PTE treatment partly due to the added Cu, whereas no effect was observed for lignite.

3.3. Root electrical capacitance and leaf chlorophyll content

For estimating the belowground biomass, root electrical capacitance measurements were taken in mid-summer, at the peak of vegetative development and physiological activity, in both years. The value of C_{FC} is presented in Fig. 6. In the first year, no significant differences were observed in C_{FC} values. In the second year, the sludge and sludge–lignite treatments significantly increased C_{FC} values by about + 25 % compared to the control and by + 20 % compared to the lignite only

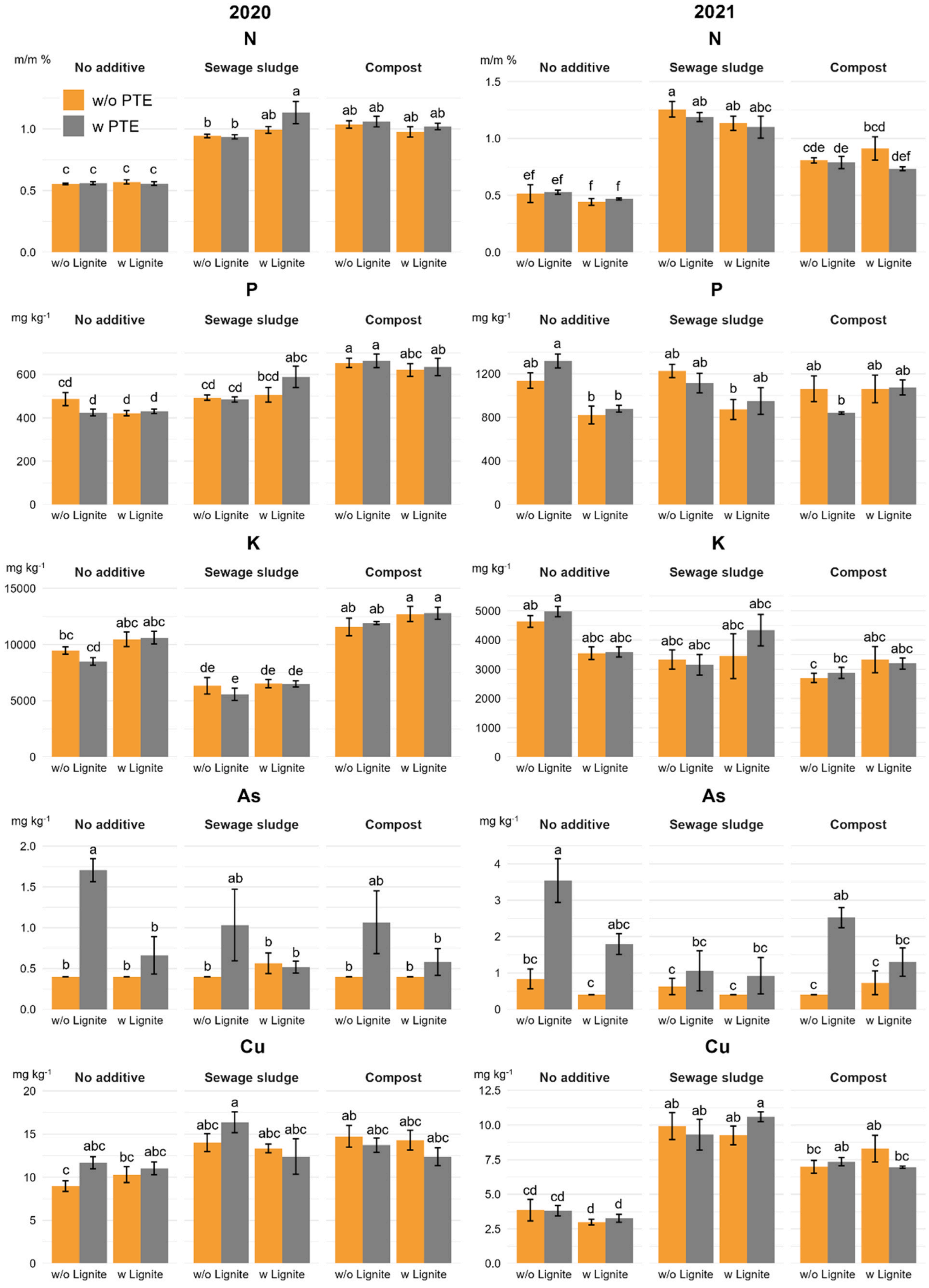

Fig. 2. Leaf element content in 2020 and 2021, PTE - potential toxic element, w/o– without, w– with.

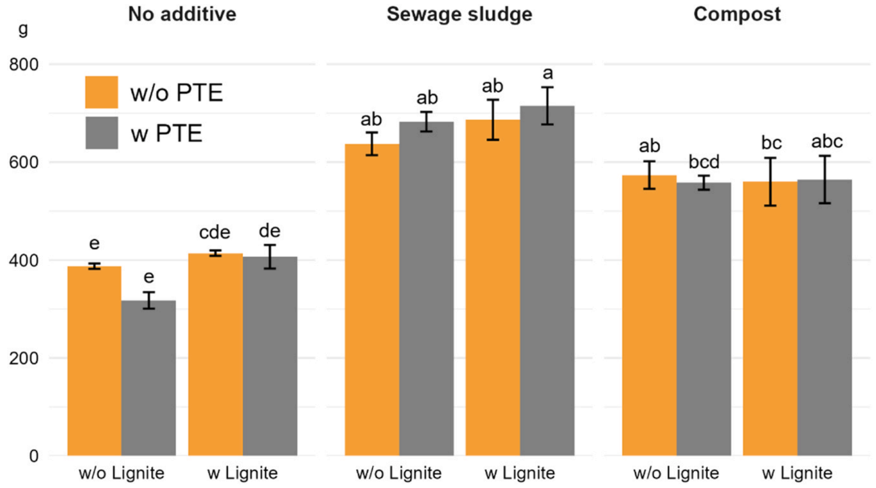

Fig. 3. Stem biomass in 2021, PTE - potential toxic element, w/o– without, w– with.

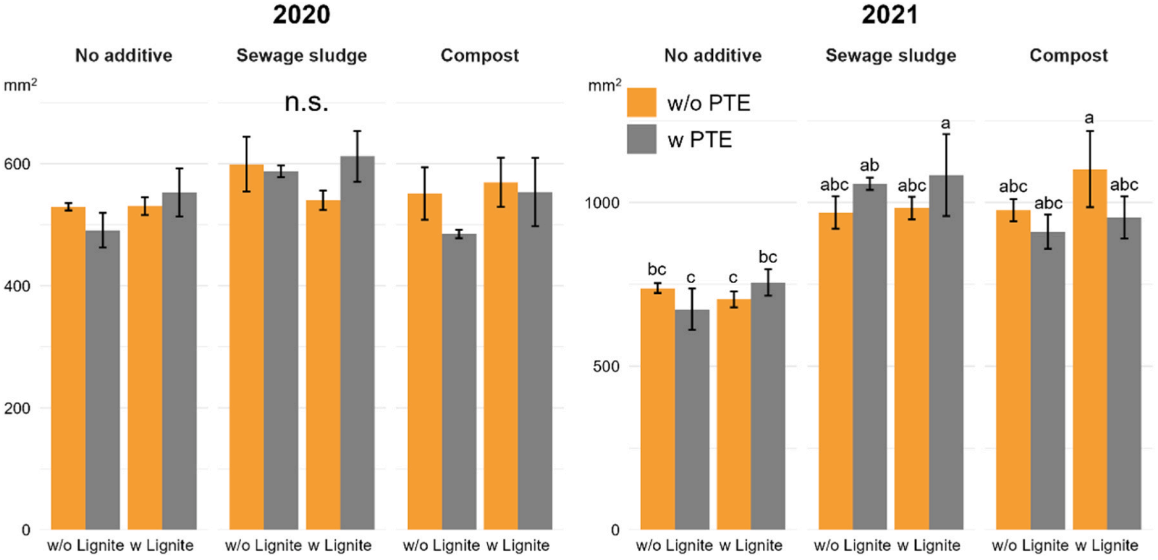

Fig. 4. Changes in stem basal area in 2020 and 2021, PTE - potential toxic element, w/o– without, w– with.

treatment. The compost treatment showed a positive trend but was not significant, and lignite or PTE alone had no effect.

The leaf chlorophyll content (Fig. 6.) was not greatly influenced by the treatments in the first year. Although the sludge–lignite–PTE treatment increased it by 34 % compared to the control, there were no differences between the various sludge treatments. In the second year, treatments with sludge or compost increased chlorophyll content, with the smallest increase in the compost–lignite–PTE treatment, yet even here it was over 70 % higher than in the control.

4. Discussion

4.1. Leaf biomass and element content

In the first year, the increase in leaf biomass was probably due to the presence of readily available nutrients derived from sewage sludge and compost (Warman and Termeer, 2005; Alvarenga et al., 2015). In the second year, the combined application of lignite and sludge had a beneficial effect on leaf biomass (Amoah-Antwi et al., 2020). This was likely attributable to the humic acid content of lignite, the improved soil water and aeration conditions, and the resulting stimulation of microbial activity. Consistent with our findings, organic fertilizers such as wastewater, sewage sludge, or compost generally increase poplar biomass, particularly during the early stages of growth (Guoqing et al., 2019; Bai, 2022). Although the effects of lignite on poplar biomass have not yet been reported, biochar, which exhibits similar soil-amending properties, generally has little impact on biomass production (Muraro et al., 2025).

In the first year, sewage sludge treatments resulted in higher leaf nitrogen content, irrespective of lignite or PTE addition. This was likely due to the presence of readily available nitrogen forms supplied by the sludge, primarily NH_4^+ and NO_3^- ions (Petersen et al., 2003). However, the observed effect may also be related to the beneficial influence of lignite (Kwiatkowska et al., 2008), as well as to low copper concentrations, which can enhance enzyme activity in certain soils and thereby promote nitrogen uptake (Mattos-Jr et al., 2024).

In the second year, the effect of sewage sludge was reflected in the highest leaf nitrogen content of the treated plants. In contrast, the effect of the compost–lignite combination likely resulted from the release of organically bound nitrogen in the compost (Warman and Termeer, 2005), facilitated by lignite, thereby making nitrogen more accessible to plants (Kwiatkowska et al., 2008).

In the first year, changes in leaf P content were likely due to orthophosphates and microbially mineralizable organic phosphorus present

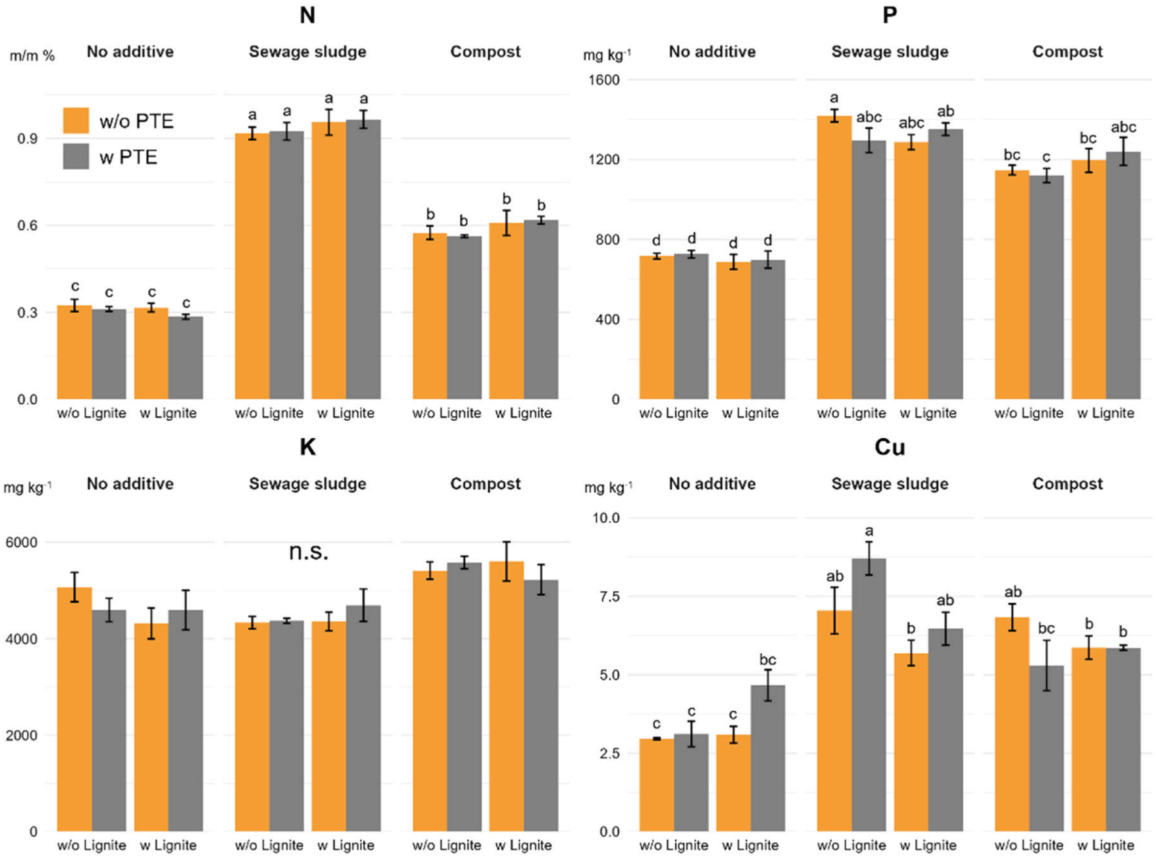

Fig. 5. Stem element content in 2021, PTE - potential toxic element, w/o– without, w– with.

in the compost (Jakubus, 2016). Sludge increased leaf P content to a lesser extent than compost, probably because part of the P was strongly bound to the Al and Fe from coagulants used during sludge treatment (Lanno et al., 2021), while these elements from technological sources could be partially available to plants (Antonkiewicz et al., 2025). Nevertheless, the positive effect of sludge was evident when applied together with lignite, which can be attributed to the soil-improving effects previously mentioned for N (Kwiatkowska et al., 2008; Yu et al., 2021). In the second year, the reduction in leaf P content under the compost-PTE treatment compared to PTE alone was presumably the result of As competition, Cu-phosphate complex formation, or microbial P immobilization (Fang et al., 2012; Wu et al., 2022). In the absence of sludge or compost, lignite alone also decreased leaf P content. This occurred likely because humic acids in the lignite were able to bind soil phosphorus in the second year, primarily through association with metal ions or direct adsorption, reducing the amount of P available to the plants (Makarov and Malysheva, 2006; Gerke, 2010).

Changes in leaf K content in the first year can be attributed primarily to the K^+ ions and the weakly bound, exchangeable K present in the compost (Ho et al., 2022), while the reducing effect of sludge on leaf K was likely due to its dominant cations (Ca^{2+}, NH_4^+), influencing the amount of K^+ available for plant uptake (Hoopen et al., 2010). In the second year, the decrease in leaf K content under compost treatments might be caused by its depletion of readily available K and/or by the K immobilizing effect of the organic matter in the compost or microorganism (Basak, 2018).

No studies were found that compare the N, P, and K content of poplar leaves over the first and second years under sewage sludge and compost application with or without lignite. Although it is known that the readily available N forms in sewage sludge or compost can increase the poplar leaf N content (Karacic and Adler, 2023), such studies typically focus on biomass yield (Gabira et al., 2021; Tsvetkov et al., 2021). In a two-year trial Guoqing et al. (2019) found that sludge fertilization increased the N and P content of poplar leaves compared to the control, while leaf K content showed a decreasing trend. This is largely consistent with the present findings.

In the first year, leaf As content decreased following lignite application, suggesting the As-binding capacity of lignite, likely via cation bridging or complexation with dissolved organic matter (Ojeda et al., 2023). Based on the first year results, it can also be assumed that part of the As was bound to the mobile, less stable organic matter fractions in sludge and compost, which exhibited a more limited stabilizing effect (Zhou et al., 2000; Stietiya and Wang, 2011). In the second year, the stabilizing effect of lignite was less pronounced in the presence of sewage sludge; the observed leaf As content was partly attributable to the stabilizing effect of the sludge, likely related to Fe and Al ions released from the sludge, forming metal ion complexes and thereby reducing As availability to plants (Altowayti et al., 2022). Numerous studies have shown that poplar can uptake and accumulate As in its tissues, making the species suitable for phytoremediation (Aryal and Reinhold, 2015; Hussain et al., 2017). Moreover, in soils treated with lignite, poplar may also be suitable for phytostabilization applications.

The Cu treatment did not significantly affect its concentration in the leaves, which can be explained by the Cu content of the sludge and compost (Bowszys et al., 2015; Dokulilová et al., 2018). These materials had a stronger effect than the element treatment. This is consistent with the results of Salehi and Ghasemi (2025), who found that sewage sludge treatments increased the Cu content of *Populus nigra* trees.

4.2. Stem biomass and element content

The treatment effects became apparent in the second year, when the high nutrient content and beneficial effects on soil water retention and aeration of sludge and compost resulted in a positive impact on basal

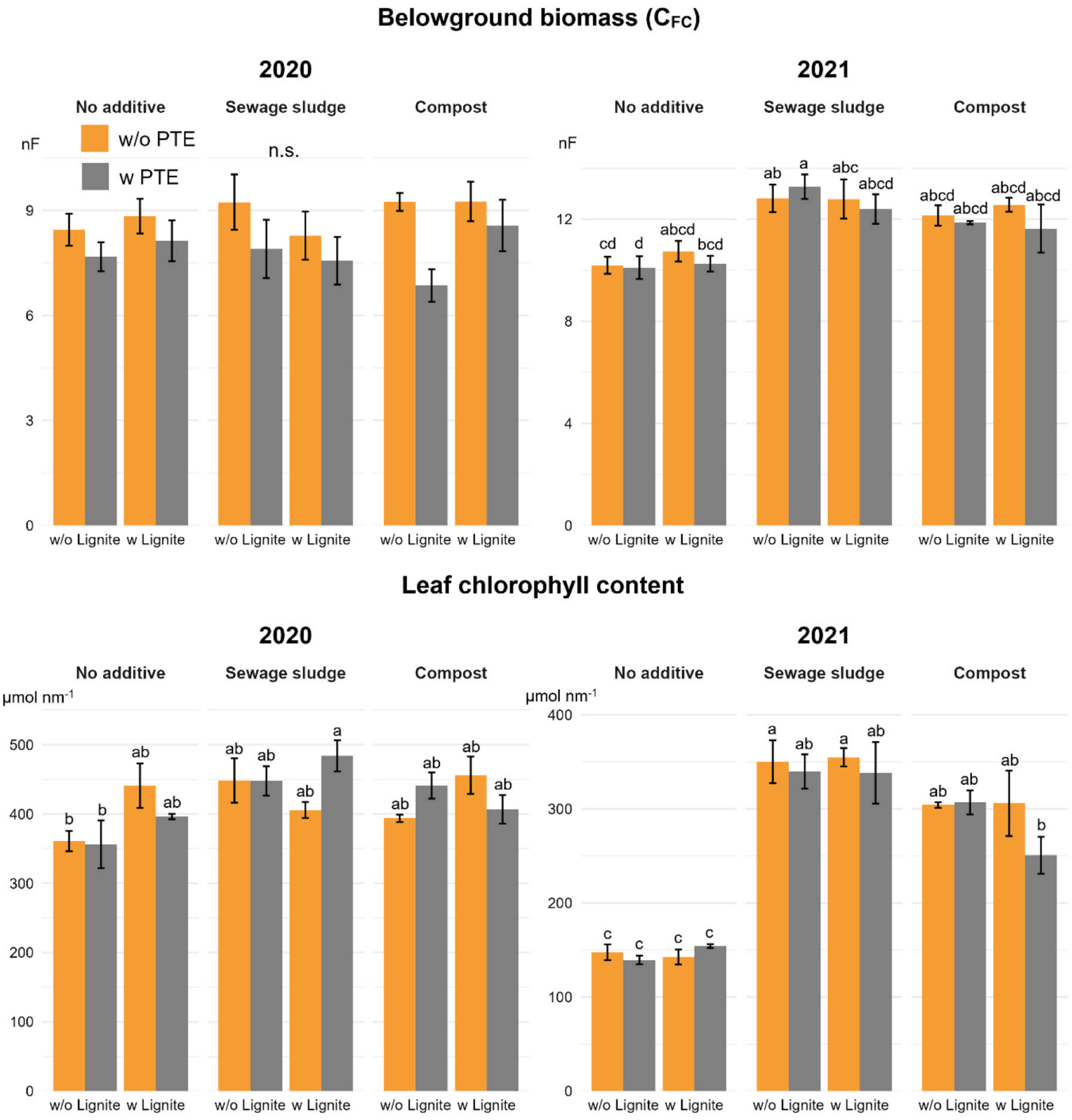

Fig. 6. Belowground biomass (C_{FC} value) and leaf chlorophyll content in 2020 and 2021, PTE - potential toxic element, w/o– without, w– with.

area (Dimitriou and Aronsson, 2011; Guoqing et al., 2019). The role of lignite was observed in enhancing the effectiveness of compost, although this was not significant (Kwiatkowska et al., 2008). In line with our findings, several authors reported significant increases in stem diameter and tree height in the studied plantations after sludge application (Abreu-Junior et al., 2017; Rodriguez et al., 2018; Rigueiro-Rodríguez et al., 2021). According to Bai et al. (2022), composted sewage sludge significantly increased the mean height and basal diameter of pine trees.

Among the changes observed in woody biomass, the increase in N and P concentration can be attributed to the nutrient content of sludge and compost (Ferraz et al., 2016). The unchanged K content in woody tissues is likely due to the high mobility of K and its limited storage capacity in wood (Tripler et al., 2006). The higher Cu content observed under sludge, compost, and PTE treatments can be explained by Cu mobilization and uptake in organic chelate forms (Madhupriyaa et al., 2024). The Cu accumulation in woody tissues also corroborates the findings of Lukaszewski et al. (1993). Although Hussain et al. (2017) observed arsenic accumulation in woody tissues at 5–20 mg/kg soil As content, in the present study As was primarily localized in the leaves.

4.3. *Root electrical capacitance and leaf chlorophyll content*

Since no studies were found in the literature applying these materials and measuring root electrical capacitance for estimating the belowground biomass, these results have novelty value. The increase in C_{FC} in the second year was possibly the result of the positive effects of sludge and compost (Mohamed et al., 2018; Giuliani et al., 2024). The chlorophyll content changes in the leaves can be attributed to the fact that the two-year-old trees were able to utilize the Mg and N derived from sludge and compost more efficiently, thus promoting chlorophyll synthesis (El-Motaium, 2007; Urbaniak et al., 2017). It is well known that the application of substrates with high organic matter content increase chlorophyll content in trees, provided that the dosage is not toxic to them (Song and Lee, 2010; Bourioug et al., 2015). The present results are consistent with these findings, although this effect was only observed in the second year. Inorganic pollutants inhibit chlorophyll content in poplars only at toxic doses (Chandra and Kang, 2016; Talebzadeh and Valeo, 2022), suggesting that the As and Cu added in this experiment were presumably below this level.

5. Conclusions

The results confirmed that (1) both sewage sludge and sewage sludge-derived compost increased the above- and belowground biomass of young poplar trees, although the effect of sludge was stronger, especially in the first year and regarding aboveground biomass. (2) Lignite alone had no detectable effect, but it contributed to greater aboveground biomass when combined especially with sewage sludge. (3) Sewage sludge and sewage sludge-derived compost enhanced nutrient uptake in the plants, while lignite reduced the uptake of certain potentially toxic elements (e.g. arsenic) through its stabilizing effect. (4) Leaf chlorophyll content was primarily increased by treatments with sewage sludge and sewage sludge-derived compost; lignite had no independent effect in this regard, so the rise in chlorophyll levels was mainly due to the nutrients present in these materials.

The results indicate that sewage sludge and its compost, applied at high doses and possibly combined with lignite, can be promising for short-rotation forestry on low-fertility soils. Future research should investigate the long-term effects of these materials within soil–tree systems, including potential analyses of the soil biota. It is also important to determine site- and species-specific application rates, compare the effects of different qualities of sewage sludge and compost, and examine other carbon-based amendments. Such studies could support the sustainable use of sewage sludge and its compost while minimizing associated environmental risks.

CRediT authorship contribution statement

Nikolett UZINGER: Writing – original draft, Investigation, Funding acquisition, Data curation, Conceptualization. **Orsolya SZÉCSY:** Writing – review & editing, Investigation. **Imre CSERESNYÉS:** Writing – review & editing, Methodology, Investigation. **Péter RAGÁLYI:** Writing – review & editing, Investigation, Data curation. **Anita SZABÓ:** Writing – review & editing, Investigation. **Béla PIRKÓ:** Investigation. **Nóra SZŰCS-VÁSÁRHELYI:** Investigation. **Márk RÉKÁSI:** Writing – review & editing, Supervision, Investigation, Data curation, Conceptualization.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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