International Journal of Environmental Studies

ISSN: 0020-7233 (Print) 1029-0400 (Online) Journal homepage: www.tandfonline.com/journals/genv20

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To cite this article: Mykola Kharytonov, Nadia Martynova, Mykhailo Babenko, Svitlana Lemishko, Alla Samarska & Maria Gispert (15 Jul 2025): The effect of biodigestate and sewage sludge on the switchgrass growth, biomass elemental composition and thermal characteristics, International Journal of Environmental Studies, DOI: 10.1080/00207233.2025.2530864

To link to this article: https://doi.org/10.1080/00207233.2025.2530864

Published online: 15 Jul 2025.

INTERNATIONAL JOURNAL OF ENVIRONMENTAL STUDIES
https://doi.org/10.1080/00207233.2025.2530864

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ARTICLE

The effect of biodigestate and sewage sludge on the switchgrass growth, biomass elemental composition and thermal characteristics

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ABSTRACT
Low-productive lands that are unsuitable for growing agricultural products can be successfully used to create plantations of energy crops. Depending on the dose, productivity increased by 1.7-2.6 times. In the first years, the biomass yield after adding biodigestate (BD) was 10-20% higher than in the experiment with sewage sludge (SS). The effect of sewage sludge application was longer than that of biodigestate. The content of mobile phosphorus in loess-like loam after the introduction of biodigestate in three doses exceeded the corresponding values for sewage sludge by 14-45%. At the same time the content of zinc, cobalt, nickel and lead in loess-like loam after the introduction of sewage sludge in three doses exceeded the corresponding values for biodigestate by 9-11%, and for cadmium and chromium by 31-40%. The content of trace elements, including toxic ones, in switchgrass biomass was small and did not exceed the recommended limits for plants even with the introduction of large doses of sewage sludge and biodigestate. In general, the uptake of trace elements in plots with sewage sludge was higher than in areas with biodigestate. The thermal effect of biodigestate application was more pronounced than that of sewage sludge.

KEYWORDS
Switchgrass; biodigestate; sewage sludge; nutrients; heavy metals; biomass thermolysis

Introduction

The use of biomass as a resource for biofuels and bioenergy is gaining momentum. A major advantage of using renewable fuels is the reduction in greenhouse gas emissions compared to traditional fossil fuel. Switchgrass as a biofuel feedstock is of great interest because of its high productivity, adaptability and potential ease of integration into existing agricultural operations [1–3]. Switchgrass has good prospects for producing ethanol, heat and electricity [4,5]. It has been shown that in the country of origin, switchgrass yields can reach 10–15 tDM/ha under optimal conditions and 20–27 tDM/ha under the most favourable conditions [6–8]. In European countries, many switchgrass varieties are also successfully grown

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Published online 15 Jul 2025

for the production of bio-raw materials. The average yield of such plantations is comparable to that of their counterparts in the USA and varies within the range of 9–18 t/ha [9–14]. There are data on successful cultivation of switchgrass in the Asian region, where the yield of this crop can reach its maximum of 20–23 t/ha in the 3–4 year, with a subsequent transition to a plateau level [15–17]. Switchgrass's high drought resistance and adaptability to environmental conditions make it possible to establish industrial plantations even in dry conditions on low-productivity lands with minimal costs [18–21]. The use of various fertilisers to increase the yield of switchgrass is very appropriate [22,23].

The high cost of mineral fertilisers can significantly reduce the economic effect of their use [24]. Being inexpensive, such biosolids as sewage sludge and digestate are more promising for use as fertilisers on marginal lands [25,26]. It is reported that the energy efficiency (EE) is highest in digestate technology (13.2–14.4) followed by sewage sludge (11.4–13.0) and lowest under mineral fertiliser treatment (6.7–8.8) [27]. It was noted that the use of sewage sludge and digestate had a positive effect on switchgrass biomass yield without harming feedstock quality [28–30]. An assessment of microbial contamination of the soil after the application of biosolids showed that after three weeks, fertilisation with organic waste in acceptable doses *does not lead* to a significant increase in soil contamination with Enterobacteriaceae [31]. Toxic trace elements (As, Cd, Pb, Hg, Ni, Co, Cr etc) contained in biosolids may be a limiting factor for their use. Land application of biosolids must meet the ceiling concentrations and cumulative loading rates for these trace elements. If the concentration limit of any one of these elements is exceeded, the biosolids cannot be land-applied.

The application of biosolids will also be required to cease, if it is estimated that the cumulative loading limit is being approached [32–34]. At the same time, biosolids contain some essential microelements for plants (e.g. B, Cl, Cu, Fe, Mn, Mo and Zn), which are absent in most conventional chemical fertilisers. Therefore, they can be used on soils with microelement deficiencies [35,36].

The risk of introducing excessive amounts of nitrogen into the soil with biosolids should also be taken into account. The type of soil, the plant species and the chemical composition of biosolids determine the dose of their introduction. According to existing data, switchgrass actively accumulates macronutrients in the above-ground biomass [37,38]. In addition, switchgrass is tolerant to heavy metals and accumulates these pollutants mainly in the root system [39,40]. There are still many open questions regarding the selection of optimal doses of biosolids for growing switchgrass. The main objective of this case study was to compare the effect of biodigestate and sewage sludge on the switchgrass growth, biomass elemental composition and thermal characteristics.

Material and methods

The field experiment design

The field experiment was carried out on the preliminary phytomeliorated loess-like loam, typical of the soil parent material of the steppes, at the Pokrov Research and Educational Station of Dnipro State Agrarian and Economic University at 47°39' N, 34°08' E, at an elevation of 60 m [41,42]. The accounting area of the site was 50 m^2 in five repetitions. Agronomic operations included ploughing, spring soil cultivation, seeding followed by rolling. Seeding of switchgrass was carried out at the end of April 2020. The width between rows was 45 cm, the seed sowing rate 300 seeds per 1 m^2 at a depth of 1.0–1.5 cm. Weeding was carried out after the emergence of switchgrass shoots in the first year of crop establishment. In the following years, soil cultivation was not carried out, with the exception of the spring of 2021, when biosolids (biodigestate and sewage sludge) were applied according to the experimental scheme. The municipal sewage sludge (SS) was taken from the Pokrov city wastewater treatment station after final treatment with a dewatering centrifuge. The solid fraction of BD was collected at the Biogas Plant of the Orel-Lider poultry farm. The application rate of soil amendments was 10, 20 and 40 t/ha. The quantitative indicators were recorded over three years, starting in 2021.

Biomass parameters and element content estimation

One month after the soil amendments application the elemental composition of the soil in the control and experimental variants was determined. Soil organic carbon (OC) was determined by dichromate oxidation [43], easily hydrolysed N (EHN) following [44]. Mobile phosphorus (MP) was estimated by extraction with sodium bicarbonate [45,46], exchangeable K by flame emission spectrophotometry [47]. Estimations of available trace elements in soils are based on extractions by various solutions: chelating agents (EDTA), buffered salts (NH4OAc), neutral salts ($CaCl_2$, $MgCl_2$, $Sr(NO_3)_2$, NH_4NO_3), and other extractants [46]. Ammonium-acetate buffer (pH 4.8) was used [48]. Essential and toxic elements were determined with atomic absorption spectrometer AA280 FS (Varian, USA).

The biomass dry matter (DM) content was measured by the drying and weighing method, after drying the sample at 105 °C until a constant weight. The content of elements was determined in dry biomass samples. N was determined by Kjeldahl analysis [45]; total P concentrations by acid digestion [49], potassium by flame photometry. Metal analyses were performed by AAS, the ash being taken up in a suitable volume of 2 M HCI, depending on the amount of the trace elements present and their sensitivity in AAS [50]. Calibration was provided by national standard multi-component samples nos. 0243–2001, 0244 and 0246. The modified bioconcentration factor (mBCF) was used to evaluate the ability of the plants to take up and accumulate the metals into the above-ground biomass fraction [51]:

$$mBCF = \frac{metal\ concentration\ in\ the\ plantfraction, mg/kg}{bioavailable\ metal\ concentration\ in\ the\ soil, mg/kg}$$

A particular element uptake by the plants was calculated by multiplying its content and the plant's respective biomass [52]. The cited data represent the arithmetic means of three replicates of each sample. The thermal characteristics of plant biomass were measured using thermogravimetric analysis. This was performed at the derivatograph Q-1500D of the 'F.Paulik-J. Paulik-L. Erdey' system (Hungary). The weight of the sample used for analysis was 100 mg. The differential mass loss and heating effects were recorded, and the results of the measurements were processed using a software package supplied with the device. The samples of biomass were analysed dynamically at a heating rate of 10°C/min in an air atmosphere. The reference substance was aluminium oxide. The results obtained were processed by statistical methods at a significance level 95%.

Results

Effect of biosolids on the height and yield of switchgrass plants grown on loess-like loam

From the second to the fourth year of life, the height of switchgrass plants increased from 99.8 ± 1.30 cm to 126.1 ± 2.16 cm. The use of biosolids had a weak effect on this parameter, the maximum height increase was only 13% (SS) − 15% (BD) (Figure 1).

Under the conditions of the steppe zone of Ukraine, without irrigation, the yield of switchgrass can reach 7.1 ± 0.17t/ha. The introduction of sewage sludge and biodigestate contributed to an increase in productivity (Figure 2). In the experiment with a dose of 10 t/ha, the biomass yield relative to the control increased by 20–30% (2nd year of cultivation) and by 73–88% (3rd and 4th years of cultivation). The maximum productivity was 12.9–13.4 t/ha. The dose of 20 t/ha gave a more significant increase in yield, by 1.5–2.4 times, reaching a maximum of 15.6–15.9 t/ha in the 4th year of cultivation. In the experiment with a dose of 40 t/ha, the biomass increase was the greatest (1.7–2.6 times) and amounted to 17.7–18.5 t/ha. It was noted that in the first years after the introduction of biosolids, the effect of biodigestate was stronger. The biomass yield was 10–20% higher than in the experiment with sewage sludge. Over time this effect came to naught and already in the fourth year of cultivation the biomass yield in the variant with sewage sludge was 3–5% higher than in the experiment with biodigestate.

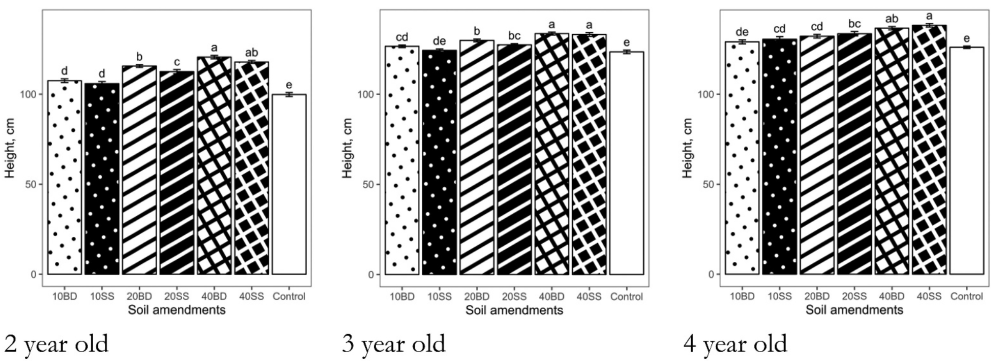

Figure 1. Effect of biosolids on the height of switchgrass plants grown on loess-like loam, mean ± se, $n = 10$, $p < 0.001$.

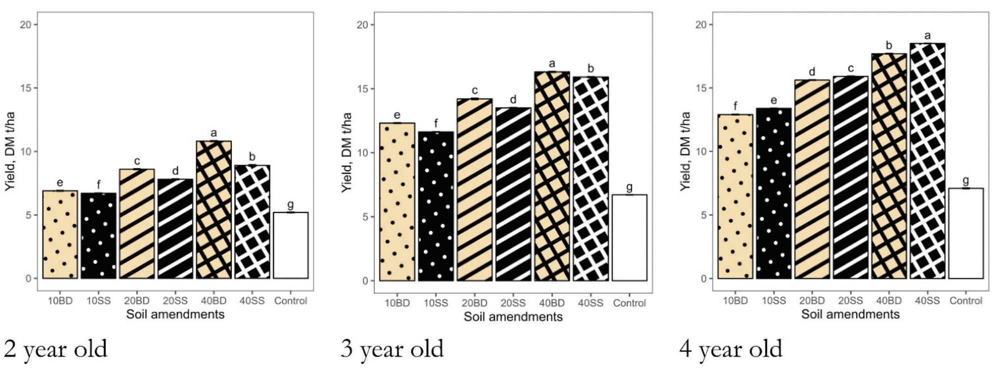

Figure 2. Effect of amendments on the switchgrass biomass yield, mean ± se, $n = 5$, $p < 0.001$.

Agrochemical parameters of the loess-like loam regarding treatments

The addition of sewage sludge and biodigestate led to a change in the chemical composition of loess-like loam (Table 1).

The greatest effect was observed in relation to the content of humus, total carbon, nitrogen and phosphorus ($p < 0.001$). Depending on the dose, the humus content in the substrate increased from 0.9% in the control to 1.72% (sewage sludge) – 2.03% (biodigestate). The mass fraction of carbon increased by 1.5–2.4 times in the experiment with biodigestate and by 1.3–2.0 times in the experiment with SS. With low doses of sewage sludge and biodigestate, the nitrogen content increased insignificantly, by 20–30%. The average and high doses of biosolids increased the content of this element in the substrate by 50–80%. Sewage sludge did not have a significant effect on the phosphorus content in loess-like loam; the introduction of biodigestate increased this indicator by 1.4–2.2 times. Both types of amendments did not affect the soil pH and potassium content.

The nitrogen, phosphorus and potassium contents in switchgrass biomass were relatively low (Table 2). The application of biodigestate and sewage sludge at a dose of 10 t/ha did not have a special effect, the amount of these elements increased by only 8–30% (SS) and by 17–37% (BD). In the SS20 experiment, the content of phosphorus and potassium in the biomass increased by 34–36%, nitrogen by 73%. At the same time, in a similar experiment with biodigestate, the content of macronutrients increased by 67–78%. When biodigestate was introduced at a dose of 40 t/ha, the amount of nitrogen, phosphorus and potassium increased by 2.1–2.2 times. The same dose of sewage sludge had a similar effect only in relation to nitrogen, the content of phosphorus and potassium increased relative to the control not so much, only by 52–83%.

Macronutrient uptake

Taking into account the yield of the aboveground switchgrass biomass, the annual uptake of macronutrients of a 4-year-old plantation was calculated (Figure 3).

The minimum uptake of nitrogen (control) was 13.5 kg/ha. The introduction of biodigestate and sewage sludge increased this indicator by 2.5 times (dose of 10 t/ha), 3.9 times (dose of 20 t/ha) and 5.5 times in the variant with a dose of 40 t/ha. Thus, the greatest uptake of nitrogen was 74.3 kg/ha (BD) and 75.8 kg/ha (SS).

Potassium uptake in the plot without amendments was 4.26 kg/ha. In plots with biodigestate, depending on the dose, this indicator increased by 2.1–5.4 times, and in plots with sewage sludge by 2.0–4.8 times. Among macronutrients, phosphorus uptake was the lowest, and in the control was 2.06 kg/ha. In the experimental plots, this indicator increased to 5.2–11.3 kg/ha (BD) and to 4.0–7.0 kg/ha (SS).

Trace elements content the loess-like loam on the experimental plot

Biodigestate and sewage sludge contributed to the change in the content of plant-available forms of trace elements in the substrate (Table 3). The amendments had the least effect on the content of manganese and copper; depending on the dose, the

Table 1. Agrochemical parameters of the loess-like loam on the experimental plot, mean ± se.

Parameter	control	10BD	20BD	40BD	10SS	20SS	40SS
DM, %^{ns}	95.9 ± 0.243	96.5 ± 0.339	95.6 ± 0.351	95.3 ± 0.387	95.6 ± 0.357	95.7 ± 0.379	95.5 ± 0.349
OM, %***	0.9 ± 0.027^{f}	1.3 ± 0.026^{d}	1.66 ± 0.018^{b}	2.03 ± 0.030^{a}	1.12 ± 0.015^{e}	1.4 ± 0.019^{c}	1.72 ± 0.017^{b}
OC, %***	0.5 ± 0.018^{e}	0.75 ± 0.021^{c}	0.96 ± 0.015^{b}	1.18 ± 0.014^{a}	0.65 ± 0.023^{d}	0.81 ± 0.020^{c}	1 ± 0.017^{b}
EHN, mg/kg***	49.6 ± 0.232^{g}	64.2 ± 0.274^{e}	77.2 ± 0.232^{c}	91.7 ± 0.212^{a}	59 ± 0.210^{f}	73.8 ± 0.179^{d}	85.9 ± 0.192^{b}
MP, mg/kg***	40.7 ± 0.277^{f}	57.2 ± 0.195^{c}	73.8 ± 0.235^{b}	89 ± 0.711^{a}	45.8 ± 0.202^{e}	51 ± 0.152^{d}	57.1 ± 0.184^{c}
EP, mg/kg***	204 ± 0.677^{d}	211 ± 0.628^{c}	219 ± 0.630^{b}	226 ± 0.917^{a}	212 ± 0.719^{c}	223 ± 0.748^{a}	226 ± 0.667^{a}
pH***	8.2 ± 0.027^{ab}	8.3 ± 0.025^{a}	8.3 ± 0.020^{a}	8.2 ± 0.023^{ab}	8.2 ± 0.030^{ab}	8.1 ± 0.020^{b}	8.1 ± 0.021^{b}

The statistical significance of each parameter in each table is shown as insignificant (ns) and significant as ($p < 0.001$) in the first column follow ANOVA calculations. The letters indicating differences in pair wise comparisons are shown in each table as each parameter degree. The absence of these letters indicates a lack of statistical significance.

Table 2. Macroelement content in switchgrass biomass.

Parameter	control	10BD	20BD	40BD	10SS	20SS	40SS
DM, %^{ns}	90.9±0.534	90.0±0.826	90.5±0.708	90.0±0.635	90.4±0.794	90.0±0.939	90.2±0.608
N, %***	0.19±0.004^{d}	0.26±0.010^{c}	0.34±0.004^{b}	0.42±0.007^{a}	0.25±0.003^{c}	0.33±0.007^{b}	0.41±0.005^{a}
P, %***	0.03±0.002^{e}	0.04±0.001^{cd}	0.05±0.001^{b}	0.064±0.002^{a}	0.035±0.002^{de}	0.039±0.001^{cd}	0.044±0.001^{bc}
K, %***	0.06±0.02^{d}	0.07±0.002^{cd}	0.1±0.006^{b}	0.13±0.004^{a}	0.065±0.002^{cd}	0.08±0.001^{c}	0.11±0.007^{b}

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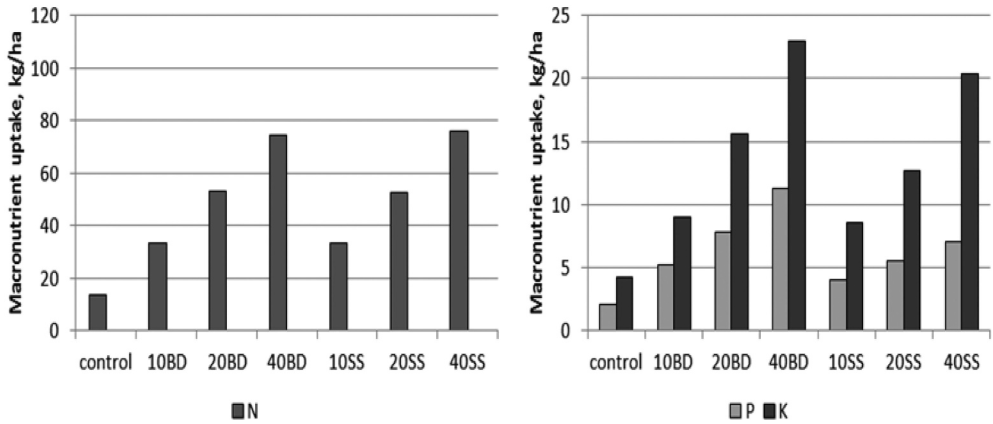

Figure 3. Macronutrient uptake by 4-year-old switchgrass plants.

indicators increased by 8–40%. The content of iron, zinc, and nickel increased by 27–38% (dose of 10 t/ha), 45–85% (dose of 20 t/ha), and by 62–90% (dose of 40 t/ha). After the introduction of biodigestate at doses of 10 and 20 t/ha, the content of cobalt in the substrate increased by 30–65%, and twice in the area with a dose of 40 t/ha. In the variant with sewage sludge, the content of this element in the substrate increased by 50% (SS10), 85% (SS20), and 125% (SS40). The amount of chromium, lead and cadmium, depending on the dose, increased by 1.3–2.6 times in the area with biodigestate and by 1.6–3.4 times in the area with sewage sludge.

3.5.Trace elements content in switchgrass biomass

The content of trace elements, including toxic ones, in the switchgrass biomass is low (Table 4), and even with the application of high doses of sewage sludge and biodigestate did not exceed the recommended limits for plants [53,54]. The obtained data were further evaluated by calculating the plant-soil ratio, commonly known as the transfer coefficient, or the modified bioconcentration factor (mBCF), a convenient way to quantify relative differences in the bioavailability of metals for plants. According to the obtained data, it can be concluded that iron and zinc are accumulated most actively by the aboveground biomass of switchgrass (mBCF = 5.2–5.9 and 4.2–4.6, respectively). High mBCF values were also noted for manganese (1.5–1.7), copper (1.8–3.7), and chromium (1.8–2.0). Cobalt, nickel, lead, and cadmium do not accumulate in above-ground switchgrass biomass; mBCF values for these metals range from 0.2 to 0.8.

3.5. Trace elements uptake by switchgrass plants

In the control plot, without adding soil amendments, the annual uptake of iron and manganese by switchgrass biomass was small and amounted to 300–350 g/ha. The uptake of other trace elements varied from 1.1 to 4.0 g/ha (Figure 4). The introduction of soil amendments contributed to the increase in this parameter. For copper, the effect was most noticeable. At a dose of 10 t/ha, the uptake level increased by 3.6–4 times, at a dose

Table 3. Trace element content in loess-like loam (mobile form), mg/kg.

Element	control	10BD	20BD	40BD	10SS	20SS	40SS
Cu***	1.10 ± 0.028^{e}	1.30 ± 0.026^{cd}	1.51 ± 0.031^{b}	1.68 ± 0.032^{a}	1.26 ± 0.024^{d}	1.40 ± 0.029^{bc}	1.51 ± 0.026^{b}
Fe***	7.1 ± 0.089^{g}	9.3 ± 0.092^{f}	10.3 ± 0.095^{d}	12.4 ± 0.095^{b}	9.8 ± 0.076^{e}	11.4 ± 0.078^{c}	13.5 ± 0.104^{a}
Zn***	2.80 ± 0.078^{e}	3.50 ± 0.068^{d}	4.1 ± 0.068^{c}	4.70 ± 0.062^{b}	3.75 ± 0.068^{c}	4.40 ± 0.067^{bc}	5.2 ± 0.063^{a}
Co***	0.204 ± 0.006^{f}	0.262 ± 0.005^{e}	0.330 ± 0.013^{cd}	0.410 ± 0.009^{ab}	0.305 ± 0.006^{d}	0.37 ± 0.009^{bc}	0.450 ± 0.011^{a}
Ni***	0.405 ± 0.009^{e}	0.510 ± 0.014^{d}	0.581 ± 0.014^{c}	0.651 ± 0.019^{b}	0.550 ± 0.016^{cd}	0.670 ± 0.014^{ab}	0.721 ± 0.018^{a}
Mn***	31.3 ± 0.202^{f}	34.0 ± 0.211^{e}	38.4 ± 0.217^{c}	42.7 ± 0.229^{b}	35.3 ± 0.212^{d}	39.1 ± 0.220^{c}	44.1 ± 0.232^{a}
Cr***	0.201 ± 0.005^{d}	0.320 ± 0.009^{c}	0.340 ± 0.09^{c}	0.481 ± 0.013^{b}	0.350 ± 0.010^{c}	0.490 ± 0.013^{b}	0.67 ± 0.018^{a}
Pb***	1.49 ± 0.050^{e}	2.16 ± 0.062^{d}	2.70 ± 0.066^{c}	3.21 ± 0.067^{b}	2.35 ± 0.059^{d}	2.85 ± 0.062^{c}	3.5 ± 0.067^{a}
Cd***	0.05 ± 0.001^{e}	0.065 ± 0.001^{d}	0.091 ± 0.002^{c}	0.13 ± 0.003^{b}	0.082 ± 0.001^{c}	0.13 ± 0.003^{b}	0.17 ± 0.004^{a}

The statistical significance of each parameter in each table is shown as insignificant (ns) and significant as ($p < 0.001$) in the first column follow ANOVA calculations. The letters indicating differences in pair wise comparisons are shown in each table as each parameter degree. The absence of these letters indicates a lack of statistical significance.

Table 4. Trace elements content in switchgrass biomass, mg/kg, mean±se.

Element	control	10BD	20BD	40BD	10SS	20SS	40SS
Cu***	2.0 ± 0.027^{g}	2.8 ± 0.065^{f}	3.6 ± 0.014^{d}	4.2 ± 0.020^{c}	3.3 ± 0.018^{e}	4.5 ± 0.021^{b}	5.6 ± 0.014^{a}
Fe***	42.3 ± 0.240^{g}	50.0 ± 0.306^{f}	55.7 ± 0.173^{d}	62.0 ± 0.174^{b}	53.0 ± 0.202^{e}	60.3 ± 0.243^{c}	67.5 ± 0.170^{a}
Zn***	12.8 ± 0.130^{g}	14.8 ± 0.110^{f}	17.9 ± 0.170^{d}	21.8 ± 0.163^{b}	15.7 ± 0.230^{e}	20.0 ± 0.152^{c}	24.0 ± 0.170^{a}
Co***	0.16 ± 0.005^{f}	0.21 ± 0.002^{e}	0.26 ± 0.003^{c}	0.30 ± 0.002^{b}	0.24 ± 0.002^{d}	0.31 ± 0.004^{b}	0.37 ± 0.002^{a}
Ni***	0.26 ± 0.003^{g}	0.35 ± 0.003^{f}	0.42 ± 0.003^{d}	0.50 ± 0.003^{c}	0.39 ± 0.003^{e}	0.52 ± 0.002^{b}	0.63 ± 0.004^{a}
Mn***	48.9 ± 0.408^{f}	54.7 ± 0.346^{e}	62.1 ± 0.469^{c}	68.1 ± 0.384^{b}	58.8 ± 0.888^{d}	66.4 ± 0.333^{b}	74.6 ± 0.542^{a}
Cr***	0.40 ± 0.011^{f}	0.48 ± 0.003^{e}	0.54 ± 0.011^{d}	0.61 ± 0.015^{c}	0.60 ± 0.011^{c}	0.68 ± 0.015^{b}	0.75 ± 0.011^{a}
Pb***	0.57 ± 0.012^{d}	0.62 ± 0.010^{c}	0.69 ± 0.011^{b}	0.75 ± 0.009^{a}	0.58 ± 0.011^{cd}	0.68 ± 0.009^{b}	0.77 ± 0.012^{a}
Cd^{ns}	0.025 ± 0.012	0.039 ± 0.010	0.142 ± 0.011	0.064 ± 0.009	0.044 ± 0.011	0.06 ± 0.009	0.08 ± 0.012

The statistical significance of each parameter in each table is shown as insignificant (ns) and significant as ($p < 0.001$) in the first column follow ANOVA calculations. The letters indicating differences in pair wise comparisons are shown in each table as each parameter degree. The absence of these letters indicates a lack of statistical significance.

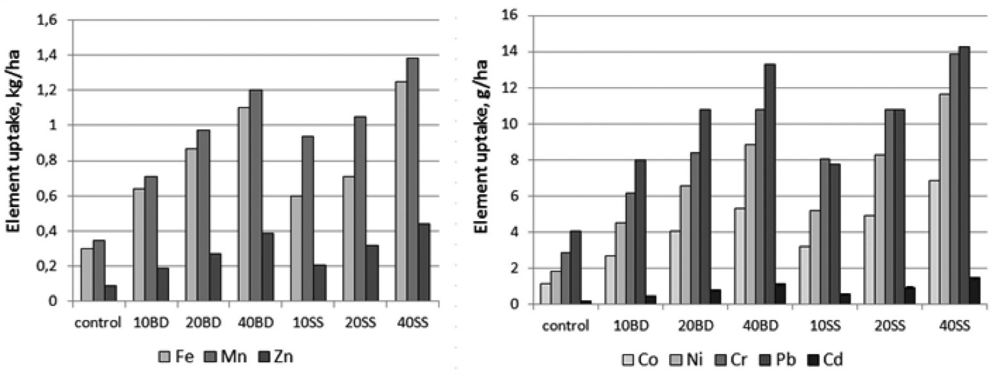

Figure 4. Trace elements uptake by 4-year-old switchgrass plants.

of 20 t/ha by 5–7 times, and at a dose of 40 t/ha by 7–10 times. For other elements, the increase was 2.0–2.8 times at a low dose, 2.9–4.5 at an average dose, and 3.7–6.3 times at a high dose. The effect of sewage sludge was more pronounced compared to biodigestate.

Effect of biosolids application on switchgrass biomass thermolysis

During the combustion of switchgrass biomass, differences in the thermal characteristics of the control and experimental samples were noted. The most noticeable changes were observed during the destruction of the main components: holocellulose and lignin. In the experiment with sewage sludge, the rates of decomposition of hemicellulose and cellulose were slightly higher than the control; the peaks of destruction were shifted to the region of lower temperatures. At the same time, lignin in the experimental samples decomposed more slowly; the peaks of destruction were shifted to the region of higher temperatures (Figure 5).

The introduction of sewage sludge did not significantly affect the ash content of the biomass, the proportion of non-combustible residue was at the level of 1.18% (control) and 1.05–1.1% (experiment). In the experiment with biodigestate, changes in the thermal characteristics of the biomass were more noticeable (Figure 6).

The peaks of hemicellulose and cellulose destruction were shifted to higher temperatures. The rates of lignin decomposition did not differ significantly between the

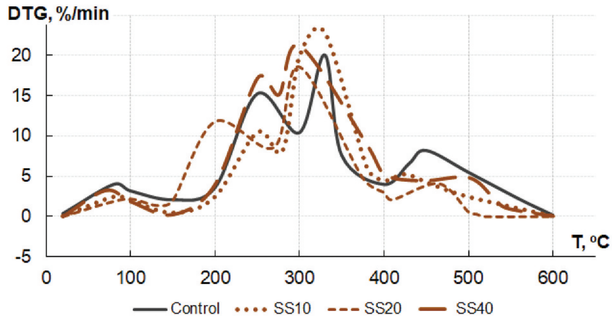

Figure 5. Effect of sewage sludge application on switchgrass biomass thermolysis.

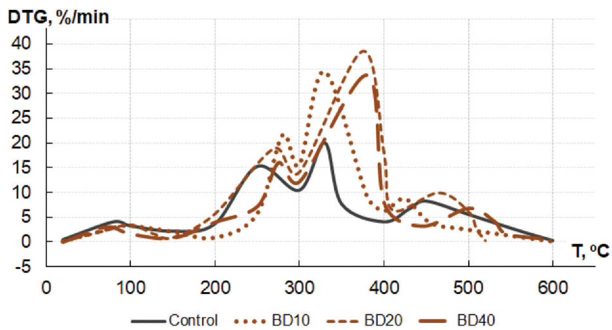

Figure 6. Effect of biodigestate application on switchgrass biomass thermolysis.

experimental variants, however, relative to the control, the peak of destruction of the sample of variant BD10 was shifted to lower temperatures, and in variants BD20 and BD40, on the contrary, to higher temperatures. The proportion of non-combustible residue in the experimental samples was slightly higher than in the control and amounted to 1.25–2.38%.

Discussion

The data on the effects of biodigestate and sewage sludge on the aboveground biomass yield of switchgrass in our experiment are consistent with the results of other similar studies [27,55,56]. The results obtained are consistent with the findings that about 90% of the total nitrogen content in digestate is short-acting owing to the high rate of mineralisation of organic matter [57]. It is known also that phosphorus is present in poultry litter in two forms inorganic (35–41%) and organic (58–65%) [58]. Inorganic phosphates include dibasic calcium phosphate, amorphous calcium phosphate and soluble phosphates [59]. It is clear that the greater availability of mobile forms of phosphorus had a corresponding starting effect on switchgrass growth in the early years in our case. The content of zinc, cobalt, nickel and lead in loess-like loam after the introduction of sewage sludge in three doses exceeded the corresponding values for biodigestate by 9–11%, and for cadmium and chromium by 31–40%. The annual uptake of microelements by biomass in our field experiment varied from several (1.1–14.2) grams (Co, Ni, Cr, Pb, Cd) to 0.3–1.2 kilograms per hectare (Fe, Mn, Zn). Depending on the dose, soil amendments increase this indicator by 2–10 times. The obtained data confirm the previously made conclusion that the introduction of soil amendments increases the risk of migration of mobile microelements and their accumulation in the plant biomass [60]. The ratio of the hemicellulose, lignin, and cellulose impacts the quality of volatile torrefaction products [61] and biomass pyrolysis and combustion process [62,63]. The proportions of the gaseous products are mainly dependent on the feedstock characteristics [62]. The changes in thermal characteristics of biomass in the experiment with biodigestate were more noticeable compared to the use of sewage sludge. The rates of thermolysis processes in the BD experimental samples in the temperature range of 280–380°C were 1.3–1.9 times higher than in the control. We can conclude that biodigestate appears to offer more prospects to improve the soil chemical properties, productivity and heat quality of aboveground biomass of the marginal lands.

Conclusions

The introduction of sewage sludge and biodigestate contributed to an increase in the productivity of switchgrass biomass. A direct dependence of the yield on the dose of the soil amendment is observed. The introduction of biosolids led to a change in the chemical composition of loess-like loam. The greatest effect was observed in relation to the content of humus, total carbon, nitrogen and phosphorus. The humus content in the substrate increased by 1.9–2.3 times. The mass fraction of carbon increased by 1.3–2.4 times, nitrogen by 1.2–1.8 times, phosphorus by 1.4–2.2 times. The content of mobile phosphorus in loess-like loam after the introduction of digestate in three doses exceeded the corresponding values for the sewage sludge by 14–45%. The application of sewage sludge and biodigestate increases the uptake of macronutrients by the aboveground switchgrass biomass. The greatest effect was achieved with a dose of 40 t/ha. The sewage sludge and digestate introduction contributed to an increase in trace elements in the substrate. The biosolids had the least effect on the content of manganese and copper. The dose of 40 t/ha of soil amendments had the greatest effect on the content of cobalt, chromium, lead and cadmium. The amount of these elements in the substrate increased by 2.0–3.4 times. Iron, zinc, manganese, copper and chromium accumulate actively in the above-ground biomass of switchgrass, but lead, nickel and cadmium do not accumulate. Their content was low, and even with the introduction of large doses of sewage sludge and biodigestate did not exceed the recommended limits for plants. It was found that the rates of some thermal reactions during combustion of biomass, grown in plots with soil amendments, were higher than in the control, and the peaks of destruction were shifted to the region of lower or higher temperatures.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This case study was supported by the Ministry of Education and Science and Ukraine.Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor the granting authority can be held responsible for them.

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