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The Effect of Mineral and Organic Fertilization on Common Osier (*Salix viminalis* L.) Productivity and Qualitative Parameters of Naturally Acidic *Retisol*

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Abstract: One of the potential options for sewage sludge as an alternative organic material is the fertilization of energy crops. To evaluate the effect of granulated sewage sludge and mineral fertilization N60P60K60 on common osier's (*Salix viminalis* L.) biomass productivity and soil parameters, field trials were held in Western Lithuania's naturally acidic *Retisol* (WB 2014; pH_{KCl} 4.35–4.58). After four years of cultivation and dependent on fertilization type, common osier dry matter (DM) yield varied from 49.60 to 77.92 t ha^{−1}. Higher DM yield was related to an increased number of stems/plants. The application of a 90 t ha^{−1} sewage sludge rate had a significant and positive impact on common osier productivity, as well as on the increment of soil organic carbon, total N, and mobile P₂O₅ content in the upper 0–30 cm soil layer. The use of both sewage sludge rates (45 and 90 t ha^{−1}) had a similar impact on soil bulk density, water-stable aggregates, and the active soil microbial biomass. Annual mineral fertilization had little effect on the parameters studied. When growing common osier in *Retisol*, 45 t ha^{−1} of a single sewage sludge rate was enough to maintain both plant and soil productivity.

Keywords: common osier; fertilization; dry matter yield; soil chemical parameters; soil bulk density; water-stable aggregates; soil microbial carbon

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1. Introduction

Sludge is a byproduct of domestic or industrial wastewater treatments. Recycling sewage sludge has remained a significant problem in many countries worldwide [1–4]. By containing a high concentration of organic carbon, nitrogen, phosphorus, and other nutrients, sewage sludge serves as a good organic matter source for plants, either providing the soil with beneficial physical and microbial properties [5–7]. As a sewage sludge substrate is of organic origin, the use of the substrate might maintain soil productivity for several consecutive years. Börjesson and Kätterer point out that the application of 12 t ha^{−1} sewage sludge every four years represents a valuable resource for improving soil fertility vis-à-vis soil organic matter and soil structure; however, its efficiency for nutrient (particularly phosphorus, nitrogen) cycling is very low within this timeframe [8]. Most improvement for the soil aggregate stability is associated with an increase in soil organic carbon content [9,10]. However, other sewage sludge constituents (e.g., heavy metals, pathogens) could be harmful to the environment and human health [11].

According to Polish research, the cultivation of willow on soil treated with 3 and 9 t ha^{−1} sewage sludge results in a gradual increase of humus fractions, total organic carbon content, and bacterial abundance, and a large increase of willow biomass. Organic

compounds and high content of sewage sludge nutrients activate soil microbial activity [12]. Low rates of sewage sludge increase soil microbial activity; however, some other research indicates that the excessive application of sewage sludge can cause the accumulation of both organic and inorganic pollutants, which may cause a negative effect on the soil ecosystem [13,14]. It is important to keep in mind that the application of sewage sludge can also result in environmental problems. Apart from organic content and nutrients, sludge also includes toxic compounds, heavy metals, dissolved inorganic salts, chlorinated lignin, and phenolic derivatives [15,16]. The application of sewage sludge can cause a negative ecological impact on terrestrial ecosystems and pose a human health risk [11,17]. For this reason, the use of sewage sludge as an organic fertilizer is limited in many countries worldwide [2,5,18].

Since sewage sludge contains unwanted pollutants, its utilization for traditional crop fertilization is problematic. Yet, to reduce cultivation costs, sewage sludge might be an appropriate alternative fertilizer for energy crops. Many authors have noted that to avoid competition with traditional food crops, energy crops (as well as other non-food crops) should be grown in less productive soils, polluted soils, brownfields, marginal, set-aside, and abandoned lands, all of which might be appropriate for energy crop cultivation [19–22]. For example, *Retisols* and *Fluvisols* are typically found in Western Lithuania. However, due to these soils' high acidity and worsening physical, chemical, and microbial properties, traditional farming is often unprofitable [23]. With increased biomass being used for alternative energy purposes, a share of such fertile land could be assigned for energy crop cultivation.

Salix species are fast-growing and high-yielding; therefore, they can be widely cultivated worldwide. Many studies have assessed the impact of sewage sludge on both common osier (*Salix viminalis* L.) productivity and qualitative indicators [24,25]. However, before our field experiment, we found scarce information on how a common osier (*Salix viminalis* L.) is suitable for cultivation in highly acidic *Retisol* and how sewage sludge affects soil parameters in the common osier growing site.

By executing the experiment, we set a goal complex to evaluate the impact of single sewage sludge on *Salix viminalis* productivity, and changes of soil chemical, physical, and microbial properties of acid moraine loam soil in *Retisol*.

2. Materials and Methods

2.1. Location of the Experimental Site

The experiment with an energy crop common osier (*Salix viminalis* L.) was established at the Vėžaičiai Branch of the Lithuanian Research Centre for Agriculture and Forestry. The site was located at the eastern edge of a seaside lowland area (Western Lithuania, 55°43' N, 21°27' E).

2.2. Soil Characteristics

The soil type was a naturally acid moraine loam Bathygleyic Dystric Glossic *Retisol* (WRB 2014). The following soil chemical parameters (in upper soil layer) were evaluated prior to the experiment: pH_{KCl} was 4.27–4.59, mobile aluminum was 13.69–34.21 mg kg^{−1}, total nitrogen was 0.11–0.12%, total carbon was 1.19–1.25%, mobile P₂O₅ was 50.3–68.3 mg kg^{−1}, and mobile K₂O was 251–303 mg kg^{−1}.

2.3. Mineral Fertilizers and Granulated Sewage Sludge

Mineral fertilizers. The annual application rates for nitrogen, phosphorus and potassium were equal: 60 kg ha^{−1} N, P₂O₅, and K₂O (N60P60K60) (in active ingredient).

Sewage sludge. The chemical composition of the granulated sewage sludge was as follows: pH—5.56, total nitrogen—33.4 g kg^{−1}, total phosphorus—5.02 g kg^{−1}, total potassium—2.80 g kg^{−1}, organic matter—64.97%. The sewage sludge contained the following heavy metals concentrations: lead (Pb)—14.47 mg kg^{−1}, cadmium (Cd)—0.44 mg kg^{−1},

chromium (Cr)—11.51 mg kg⁻¹, copper (Cu)—47.8 mg kg⁻¹, nickel (Ni)—8.22 mg kg⁻¹, zinc (Zn)—287 mg kg⁻¹, and mercury (Hg)—0.96 mg kg⁻¹.

Using 45 t ha⁻¹ sewage sludge rate, the following amounts of nutrients were inserted into the soil: 1503 kg of total nitrogen, 230 kg of total phosphorus, and 126 kg of total potassium. Accordingly, by the use of 90 t ha⁻¹ sewage sludge rate, 3006 kg of total nitrogen, 460 kg of total phosphorus, and 252 kg of total potassium were inserted into the soil.

2.4. Experimental Design

Field research began in 2013. Common osier's (cv. "Tordis") cuttings of about 0.30 m long were planted in the soil on 5 May 2013. Each treatment was composed of two parallel 10 m long rows. The distance between the rows was 0.75 m, the distance between each plant was 0.50 m, the distance between the rows of different treatments was 1.25 m. Next year, i.e., on 23 April 2014, to increase the branching ability, common osier's stems were cut at ~5 cm height. The weight of the first-year stems was not calculated.

The experiment was composed of four treatments: (1) Control (not fertilized); (2) N60P60K60 (mineral fertilization) (in active ingredient); (3) 45 t ha⁻¹, and (4) 90 t ha⁻¹ sewage sludge rates. All four treatments were randomly allocated. The number of replications—3. The fertilization of granulated sewage sludge was done once in the 2nd growing year (on 6 May 2014). The granules were immediately inserted into the soil by tillage implements. NPK fertilization was done each year at the beginning of spring vegetation.

2.5. Sampling and Analytical Methods

Common osier yield was harvested after four years of cultivation (2014–2017) on 19 September 2017. The following structural parameters were evaluated: the number of stems per plant stems height, and biomass yield. To evaluate these parameters, five typical plants were chosen from each treatment from all three replications. The common osier dry mass (DM) mass yield was measured by drying plant samples at 105 °C to the constant weight. Dried plant samples were weighed and recalculated into dry matter (DM) yield (t ha⁻¹).

Soil chemical analyses at the growing site of common osiers were done in 2013 (at the beginning of the experiment) and 2016 (in the 3rd experimental year). In both cases, soil samples (in 0–30 cm upper soil layer) were taken in October. The following parameters were evaluated: pH_{KCl} was measured by a potentiometric method in 1 M KCl (1:2.5, *w/v*) extract (ISO 10390:2005); organic C (C_{org}) content—by a spectrophotometric measurement at 590 nm after dichromatic oxidation using glucose as a standard (ISO 10694:1995), total N (N_{tot}) content—by the Kjeldahl method (ISO 11261:1995), mobile P₂O₅, and K₂O contents—by extraction (A-L) method (both by LVP D-07:2016).

Soil samples for soil physical analysis were taken from the topsoil in 2015 and 2017. Soil samples for soil physical analysis were taken from the topsoil in 2015 and 2017. Dry aggregates size distribution was determined by the standard dry and wet sieving Savinov method [26]. Briefly, 1000 g of air-dried, soil sample is sieved through a nest of sieves having 10, 5, 3, 2, 1, 0.5, and 0.25 mm square openings so eight aggregate size classes are obtained (>10, 10–5, 5–3, 3–2, 2–1, 1–0.5, 0.5–0.25, and <0.25 mm). The soil of each aggregate size classes is weighed separately, and the percentage of the fraction is calculated from the total soil weight. A sample of 50 g is taken from the aggregate fractions in proportion to their percentage composition for wet sieving analysis. By the wet sieving procedure 6 classes were separated >3, 3–2, 2–1, 1–0.5, 0.5–0.25, and <0.25 mm. The soil bulk density (100 cm³) was estimated according to the Kachinsky method. Soil moisture content was measured by the weighting method.

Soil samples for microbial analysis were taken twice per 2014–2016 in spring and autumn for three treatments (Control, 45 t ha⁻¹, and 90 t ha⁻¹ sewage sludge) in 0–30 cm

upper soil layer. The chloroform fumigation-extraction (CFE) method was used to evaluate soil microbial biomass carbon ($\mu\text{g g}^{-1} \text{C}$) [27].

2.6. Statistical Analysis

To evaluate the significance of the obtained biomass productive parameters (i.e., number of stems/plants, stems height, stems diameter, and dry mass yield), a one-way statistical analysis was performed on the fertilization rate, using analysis of variance (ANOVA) at LSD_{05} and LSD_{01} (95% and 99% probability levels).

3. Results

3.1. Common Osier Yield and Structure

The biometric parameters for the common osier yield are presented in Table 1. Biomass yield was harvested after 4 years of cultivation.

Table 1. The structural parameters of the common osier's yield after 4 years of cultivation.

Treatments	Number of Stems/Plants	Stems Height, cm	Stems Diameter, mm	DM Yield, t ha^{-1}
Control	2.34	567	29.98	49.60
N60P60K60	2.80	552	29.12	52.00
45 t ha^{-1} sewage sludge	2.87	554	30.80	65.68 **
90 t ha^{-1} sewage sludge	3.47 *	528	31.60	77.92 **
$LSD_{05/01}$	1.12/ns	ns/ns	ns/ns	6.90/10.45

*,** significant at 95% and 99% probability levels, respectively; ns—not significant.

In comparison with the unfertilized plot (in control treatment), fertilizing 90 t ha^{-1} of sewage sludge caused the number of stems/plants too, on average, increase to 3.47. Irrespective of fertilization type, the stem height varied from 528 to 567 cm. The use of sewage sludge also increased stem diameter, though the increment was not statistically substantial. Both (45 and 90 t ha^{-1}) sewage sludge rates increased total dry matter (DM) yield (accumulated per 4 growing years) to 65.68 and 77.92 t ha^{-1} , respectively (significant at 99% probability level). Thus, compared to the control treatment (when growing without fertilization), DM yield increased by 32.4–57.1%. There was a positive average correlation (+0.66) between the number of stems/plants and DM yield: $Y_{(\text{DM yield})} = 24.67 + 0.0008x_{(\text{number of stems/plants})}$. The other two parameters had a weak correlation with DM yield.

It should be noted that the annual use of mineral NPK fertilizers had a weak impact on common osier's DM yield; the increase was not significant. Earlier studies in Sweden showed that nitrogen fertilizers had a positive effect on common osier's yield during the 2nd and 3rd growing years [28].

3.2. Soil Chemical Properties

During the experimental years, soil pH_{KCl} values remained substantially unchanged (Table 2). In 2013, the average soil pH in the common osier's growing site was 4.40 ± 0.16 . After three experimental years (in September 2016), irrespective of fertilization type, soil pH_{KCl} varied from 4.41 to 4.49. Thus, the application of sewage sludge had no impact on soil acidity level.

Table 2. Soil chemical content at the growing site of a common osier, specifically for the 0–30 cm upper soil layer (2013 and 2016).

Treatments	pH _{KCl}	Organic C (%)	Total N (%)	C _{org} :N _{tot}	Mobile	
					P ₂ O ₅ (mg kg ^{−1})	K ₂ O (mg kg ^{−1})
2013 (before the experiment)						
	4.40 ± 0.16	1.18 ± 0.06	0.07 ± 0.01	16.51 ± 0.98	59.3 ± 13.6	277 ± 0.02
2016						
Control	4.44	1.16	0.07	15.69	69.4	296
45 t ha ^{−1} sewage sludge	4.41	1.34 *	0.09 *	14.92	332	226
90 t ha ^{−1} sewage sludge	4.49	1.52 **	0.11 **	13.74 *	816	251
LSD _{05/01}	ns/ns	0.15/0.23	0.02/0.03	2.71/ns	146/222	ns/ns

*,** significant at 95% and 99% probability levels, respectively; ns—not significant.

In 2013, the average organic C (C_{org}) content in the topsoil layer was 1.18 ± 0.06%. Over three years of research, the application of 45 and 90 t ha^{−1} sewage sludge rates caused a substantial increase of organic C content (at 95% and 99% probability levels, respectively).

Before the experiment, the average N_{tot} content was 0.07 ± 0.01%. The application of both sewage sludge rates significantly increased N_{tot} content to 0.09–0.11% (at 99% probability level). In the control treatment, even though the common osier utilized high amounts of N for biomass accumulation, the total N content in the topsoil did not significantly change throughout the experimental period.

The application of both sewage sludge rates decreased C_{org}:N_{tot} ratio from 16.51 ± 0.98 (in 2013) to 13.74 (in 2016).

In 2013, the amounts of phosphorus (P₂O₅) and potassium (K₂O) at the experimental site were 59.3 ± 13.6 and 277 ± 0.02 mg kg^{−1}, respectively, indicating that soil reserves were low. On the contrary, potassium concentration in the upper soil layer was sufficient. In 2016, at the end of the growing rotation, mobile P₂O₅ content in the topsoil sharply increased to 332–816 mg kg^{−1} (significant at the 99% probability level). Meanwhile, at the end of the field experiment study, mobile K₂O content in the upper soil layer remained largely unchanged.

3.3. Soil Aggregate Composition and Aggregate Stability

The obtained research data revealed that during the research period the majority (66–73%) of aggregates in the moraine loam soil were composed of agronomically and ecologically valuable mesoaggregates (0.25–5 mm) (Table 3).

Table 3. Soil aggregate composition and the amount of water-stable aggregates in the growing site of common osier dependent on fertilization type in 2015 and 2017.

Treatment	2015 (One Year after Sewage Sludge Application)					2017 (Three Years after Sewage Sludge Application)				
	macro-aggregates > 5 mm	meso-aggregates 5–0.25 mm	mikro-aggregates < 0.25 mm	water-stable aggregates > 1.0 mm	water-stable aggregates > 0.25 mm	macro-aggregates > 5 mm	meso-aggregates 5–0.25 mm	mikro-aggregates < 0.25 mm	water-stable aggregates > 1.0 mm	water-stable aggregates > 0.25 mm
Control	11.66	67.48	20.86	13.10	47.53	9.15	70.54	20.31	18.8	55.3
NPK	8.02	68.36	23.62	11.68	47.25	-	-	-	-	-
45 t ha ⁻¹ sewage sludge	12.35	65.86	21.79	21.42 *	64.55 *	9.53	72.95 *	17.52	16.4	54.6
90 t ha ⁻¹ sewage sludge	11.58	65.60	22.82	14.45	54.77	14.10 *	69.43	16.47 *	18.8	57.2
LSD ₀₅	ns	ns	ns	8.64	11.63	1.37	2.36	2.81	ns	ns

*—significant at 95% probability level; ns—not significant.

The amount of these aggregates varied slightly from year to year, depending on climatic conditions and fertilization. In 2017, the share of mesoaggregates was 4% higher than in 2015. Compared to the unfertilized soil (i.e., the control), the most valuable mesoaggregates were formed in the common osier growing site three years after the application of the lower sewage sludge rate (45 t ha^{-1}). Sewage sludge had a positive effect not only on the formation of aggregates of different sizes but also on their stability. One year after 45 t ha^{-1} of sewage sludge application, ecologically valuable water-stable aggregates ($>1.0 \text{ mm}$ and $>0.25 \text{ mm}$) accounted for 21.4 and 64.6%, respectively.

In comparison to the unfertilized soil (i.e., the control treatment), the application of 45 and 90 t ha^{-1} increased the amount of water-stable aggregates by 38 and 26%, respectively; and by 45% and 26% in comparison to NPK application. In 2017, three years after the application of sewage sludge (45 t ha^{-1}), the amount of water-resistant aggregates in the soil ($>1.0 \text{ mm}$ and $>0.25 \text{ mm}$) was 5 and 10% lower, respectively, than those determined one year after the application of sludge. This indicates that sewage sludge did not have a long-lasting effect on the stability of aggregates.

According to the average data of 2015 and 2017, in the soil where sewage sludge was used for fertilization, the water-stable aggregates was 9–16% ($>0.25 \text{ mm}$) and 4–18% ($>1.0 \text{ mm}$) higher compared to the soil in which the sewage sludge was not applied (Control) (Figure 1).

Figure 1. The dependence of soil water-stable aggregates on the fertilization type at the common osier growing site. Average data for 2015 and 2017.

3.4. Soil Bulk Density and Moisture

During the study period, in the common osier growing site, soil bulk density values fluctuated in the range of $1.19\text{--}1.32 \text{ Mg m}^{-3}$ (Table 4).

The lowest bulk density value was determined in the soil where the lower rate of sewage sludge (45 t ha^{-1}) was applied. Sewage sludge substantially reduced soil bulk density. On average, the soil bulk density was 6.0–7.5% lower compared to unfertilized soil (i.e., the control). The application of sewage sludge (especially its highest 90 t ha^{-1} rate) caused a higher accumulation of soil moisture (by 11.2%) than the control treatment (without fertilization). Compared to soil fertilized with mineral fertilizers, fertilization with organic fertilizers (sewage sludge) accumulated a higher amount of organic carbon in the soil. It was a result of higher organic C content and moisture content in the soil applied by sewage sludge.

Table 4. Soil bulk density and moisture in relation to fertilization type at the common osier growing site in 2015 and 2017.

Treatment	2015 (One Year after Sewage Sludge Application)		2017 (Three Years after Sewage Sludge Application)		Average Per 2015–2017	
	Bulk Density Mg m ⁻³	Moisture %	Bulk Density Mg m ⁻³	Moisture %	Bulk Density Mg m ⁻³	Moisture %
Untreated	1.32	22.13	1.32	17.87	1.32	20.00
NPK	1.33	21.65	-	-	-	-
45 t ha ⁻¹ sewage sludge	1.19 *	20.56	1.28	20.42 *	1.24 *	20.49
90 t ha ⁻¹ sewage sludge	1.22 *	23.29	1.23	21.33 *	1.22 *	22.31
LSD ₀₅	0.09	ns	0.09	1.90	0.60	ns

*—significant at the 95% probability level; ns—not significant.

3.5. Microbial Activity

The biomass of microorganisms in the soil is expressed as the amount of organic carbon (C) in the biomass, known as microbial biomass carbon [29,30]. The results are presented in Table 5.

Table 5. The changes in soil microbial biomass carbon ($\mu\text{g g}^{-1}\text{ C}$) in humus horizon (0–30 cm depth) at the common osier's site from 2014 to 2016.

Treatments	Soil Microbial Biomass Carbon ($\mu\text{g g}^{-1}\text{ C}$)	
	Spring	Autumn
2014		
Control	423.1 $\pm$ 21.7 a	420.9 $\pm$ 14.7 a
45 t ha ⁻¹ sewage sludge	434.7 $\pm$ 21.7 a	432.1 $\pm$ 14.5 a
90 t ha ⁻¹ sewage sludge	457.0 $\pm$ 13.5 a	480.0 $\pm$ 24.0 b
On average per year	445.8 $\pm$ 12.7/	456.1 $\pm$ 14.8
2015		
Control	432.4 $\pm$ 18.1 a	434.4 $\pm$ 19.2 a
45 t ha ⁻¹ sewage sludge	451.2 $\pm$ 12.9 ab	455.3 $\pm$ 20.7 a
90 t ha ⁻¹ sewage sludge	472.9 $\pm$ 16.1 b	492.3 $\pm$ 11.0 b
On average per year	462.1 $\pm$ 10.3/	473.8 $\pm$ 12.2
2016		
Control	421.6 $\pm$ 8.0 a	433.2 $\pm$ 19.9 a
45 t ha ⁻¹ sewage sludge	539.1 $\pm$ 31.4 b	625.2 $\pm$ 22.1 c
90 t ha ⁻¹ sewage sludge	625.3 $\pm$ 20.6 c	625.6 $\pm$ 21.3 c
On average per year	582.2 $\pm$ 21.0/	625.4 $\pm$ 14.9

Mean values $\pm$ standard deviation. The differences between values by different letters are significant.

To evaluate the soil microbial biomass carbon ($\mu\text{g C g}^{-1}$), we sampled soil before the application of sewage sludge (at the beginning of May 2014). In autumn 2014, microbial biomass carbon in the 0–30 cm upper soil layer significantly increased up to 480 $\mu\text{g C g}^{-1}$ only where the 90 t ha⁻¹ sewage sludge rate was applied. Similar results were obtained in 2015; in comparison to 2014, soil microbial biomass carbon increased slightly (particularly using the 90 t ha⁻¹ sewage sludge rate). Thus, soil microbial biomass carbon during both the 2014 and

2015 seasons (both in spring and autumn) increased only slightly. Nevertheless, during the 3rd year of investigation (in 2016), soil microbial biomass carbon increased significantly in both sewage sludge application sites—in autumn, soil microbial biomass carbon in both sites (applied by 45 t ha^{−1} and 90 t ha^{−1} rates) reached up to 625 µg C g^{−1}. This study showed that the consistent increase in soil microbial biomass during three investigation years could be indicated as a result of the ecophysiological approach of soil microorganisms to adapt to changing soil physical properties and fluctuation of nutrients after sewage sludge application in the common osier's sites.

4. Discussion

Our field and laboratory results revealed that other than a substantial increase in common osier dry matter (DM), the single use of sewage sludge had a positive effect on changing the chemical, physical, and microbiological properties in *Retisol*. Since sewage sludge is an alternative organic matter that contains high amounts of macro- and micronutrients, it might be a successful substitute for mineral fertilization of energy crops and particularly common osier. According to the research data, the use of high 90 t ha^{−1} granulated sewage sludge significantly increased plant biomass. Further, N60P60K60 fertilization had a rather weak impact on DM yield. Irrespective of fertilization type, common osier DM yield varied from 49.60 to 77.92 t ha^{−1} (or 12.4–19.5 t ha^{−1} per year). Canadian authors noted that regarding *Salix* cultivars and the number of growing rotations, the application of sewage sludge caused the dry mass yield to increase from 15 to 22 t ha^{−1} per year [31]. Other research data conducted in Denmark showed that the application of very high sewage sludge rates (i.e., increasing N amount from 120 to 240 kg ha^{−1}) did not have any impact on common osier productivity [32]. Comparing these data with other experimental data in which *Salix viminalis* was annually fertilized with NPK fertilizers, it could be seen that annual mineral fertilization does not have any advantage over organic sewage sludge [33]. We estimated that the productivity of common osier (cv. “Tordis”) depended mainly on the number of stems/plants. Neither branch height nor stems diameter had a reliable correlation with DM yield. Based on the literature data of other authors, it can be observed that common osier growth parameters such as the number of stems/plants, stem diameter, stems height, as well as their correlation with DM yield, depending on genotype, growth location, harvest rotation, and their correlation [34].

The application of sewage sludge had no significant impact on soil pH_{KCl}. In contrast to our results, other authors emphasized that sewage sludge substantially decreased soil acidity [35,36]. Other authors state that there is a direct relevance between soil pH and calcium carbonate content of sewage sludge [36]. The application of a 90 t ha^{−1} sewage sludge rate significantly increased C_{org}, N_{tot}, and mobile P₂O₅ content in the 0–30 cm upper soil layer. Other authors have reported the significant impact of sewage sludge on soil C_{org} content and N_{tot} content, as well as on the fastening of C and N mineralization processes [37–39]. The lower is C:N ratio, the more intense are N mineralization rates in soils [39,40]. Since mineral phosphorus resources are a limited resource, sewage sludge is a promising secondary source containing considerable amounts of phosphorus [41,42].

Water aggregate stability is considered an important indicator of soil physical quality, as it impacts soil functions such as soil aeration, the movement and storage of soil water, soil erodibility, and carbon sequestration. Soil aggregate stability is an important aspect of soil ecological services and health [36,43]. Fertilization with an organic amendment including sewage sludge could potentially alter soil physical properties and thereby affect aggregate stability [8,9]. According to our results, both 45 and 90 t ha^{−1} sewage sludge rates had a positive impact on increasing water-stable aggregates and decreasing soil bulk density. The effect of mineral fertilization on soil quality was insignificant.

Changes in microbial biomass carbon indicated that the increase in microbial carbon was not only due to the providing of the high content of available nutrients in sewage sludge but also due to the intensified rooting system of energy crops that could potentially stimulate microbial biomass increment [44–46].

An increase in soil microbial biomass carbon indicated that microbial activity could indirectly depend on sewage sludge application but either effected by intensified rooting of the energy crops with potential stimulation of microbial biomass increment

Although the 90 t ha^{−1} sewage sludge rate had a significant impact on DM productivity and soil chemical content, the parallel experiments indicated that sewage sludge might be energetically and environmentally inexpedient [7,47]. Thus, to improve soil qualitative parameters and obtain a high common osier DM yield, the application of 45 t ha^{−1} single sewage sludge rate might be sufficient.

Not only from the point of view of plant productivity and soil quality but also from the economic point of view, sewage sludge is a cost-effective organic matter, therefore it is superior to more costly mineral fertilization.

The positive effects of single sewage sludge application on common osier productivity and soil qualitative parameters should remain in the future growing seasons. The most important disadvantage of sewage sludge is its high concentration of heavy metals. We will soon publish another article detailing the dynamics of heavy metal concentration in soil (or its decontamination process) in *Salix viminalis* biomass during the experimental period. Further, field and laboratory experiments are continuing until 2022.

5. Conclusions

The studies conducted in naturally acid *Retisol* revealed that the single application of sewage sludge had a significant impact on plant and soil productivity. The use of 90 t ha^{−1} sewage sludge rate had the highest impact on common osier (*Salix viminalis* L.) dry matter (DM) yield per four years growing rotation. By contrast, the effect of annual mineral fertilizers on DM yield was significantly inferior. As concerning soil parameters, the use of sewage sludge did not change soil pH_{KCl} level, whereas the application of 90 t ha^{−1} rate significantly increased organic C, total N, and mobile P₂O₅ content in the upper 0–30 cm soil layer over three years of research. Irrespective of sewage sludge application rate, the amount of water-stable aggregates increased, while soil bulk density tended to decrease. It was estimated that the significantly higher microbial biomass carbon content in soil was indicated only in the third year after sewage sludge application. This alteration showed that sewage sludge amendment effect on soil microbial biomass was prolonged and positive with stimulated soil microbial adaptation.

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