Assessment of a single application of sewage sludge on the biomass yield of *Silphium perfoliatum* and changes in naturally acid soil properties

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Abstract

In order to estimate the effect of granulated sewage sludge on the productivity of the cup plant (*Silphium perfoliatum* L.), soil physical and microbial properties, a field experiment was carried out in Western Lithuania, on a naturally acid moraine loam *Bathygleyic Dystric Glossic Retisol* with a pH of 4.3–4.9. The dry matter yield of the cup plant consistently increased over the experimental years from 2.83 t ha⁻¹ (in 2013) to 12.86 t ha⁻¹ (in 2016). Each year, the optimum sewage sludge rate for dry matter yield of cup plant was 45 t ha⁻¹. The use of both sewage sludge rates 45 and 90 t ha⁻¹ had a similar and positive impact on soil chemical composition, water-stable aggregate formation, topsoil bulk density, soil penetration resistance and moisture content. Each experimental year, the application of sewage sludge at a rate of 90 t ha⁻¹ had the strongest impact on the increase in soil microbial biomass carbon at the 0–30 cm depth.

Experimental results suggest that when growing cup plant as an energy crop on a moraine loam *Retisol*, it is expedient to use granulated sewage sludge at a rate of 45 t ha⁻¹.

Key words: cup plant, fertilization, productivity, soil aggregates, soil chemical parameters, soil microbial biomass.

Introduction

Sewage sludge as a cheap organic product of water treatment may substitute mineral fertilizers, because it contains high amounts of organic matter, nitrogen and phosphorus (Annabi et al., 2011; Chen et al., 2012). For energy and other non-food crops sewage sludge might be a suitable fertilizer. The application of sewage sludge improves soil physical properties, such as bulk density, aggregate stability, water holding capacity, total porosity and saturated hydraulic conductivity (Ojeda et al., 2008; Annabi et al., 2011). Addition of sewage sludge deposit may cause undesirable changes, such as decreasing soil acidity (pH) and increasing heavy metal contents.

Since sewage sludge contains high amounts of heavy metals and pathogenic bacteria, its further application as an organic fertilizer for food crops is restricted in all European Union countries and its extensive use as organic fertilizer is still problematic (Kelessidis, Stasinakis, 2012; Latare et al., 2014). Mondal et al. (2015) have reported that short-term application of sewage sludge has effect on different soil properties, particularly on soil fertility improvement. Soil microbial activity, microbial diversity and fertility are closely related, as during the process of sewage sludge mineralization the released mineral nutrients become available and readily absorbed by soil microorganisms and plants (Ros et al., 2003). Therefore, the applied sewage sludge contributes to an increase in the organic carbon and macronutrient contents in the soil (Kołodziej et al., 2016). According to Usman et al. (2012), low rates of sewage sludge had beneficial effects on microbial activity, while excessive soil application with sewage sludge caused an increase in the bioavailability of heavy metals and negative effect on soil ecosystem.

The impact of sewage sludge on soil environment is closely related to the cation exchange capacity, organic matter content and soil acidity (Singh et al., 2012). It is very important to evaluate the possibilities of sewage sludge application on acid soils, where heavy metals are easily accessible to plants (Losada et al., 2017). Naturally acid and less productive soils – *Retisol* and *Fluvisol* – are prevalent in Western Lithuania. Intensive agricultural practices in these soils have significant effects on soil degradation through loss of soil organic matter, decline of soil structure, resulting in soil compaction and root growth retardation (Karcauskiene et al., 2018). As an alternative, some of these acid soils might be designated for non-food crop species cultivation, while paying special attention to the species, which tolerate high soil acidity. In general, energy crops and other non-food crops should be grown in the regions, where growing of traditional agricultural crops is less profitable (Nilsson et al., 2015).

In the light of increasing importance of perennial energy crops, several coarse stem herbaceous species originating from North America and belonging to *Silphium genus: S. perfoliatum* L., *S. integrifolium* Michx.

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and S. lacinium L., might be promising as energy crops due to high annual biomass yield (Voigt et al., 2012; Assfea et al., 2015). Perennial energy crops usually have a well-developed root system, which together with fungal hyphae are important factors in the formation of stable soil aggregates (de Vries, Bardgett, 2012). Cup plant is among those energy crops that could be grown on acid soils; however, the effect of sewage sludge on the productivity of cup plant and soil has not been studied before.

The aim of this study was to carry out a complex evaluation of sewage sludge impact on the biomass yield of cup plant and on the properties of acid moraine loam soil.

**Materials and methods**

**Experimental site and design.** A field experiment with an energy crop – cup plant (Silphium perfoliatum L.) – was started in 2013 at Vežaičiai Branch of the Lithuanian Research Centre for Agriculture and Forestry in Western Lithuania (55°43’ N, 21°27’ E). The soil of the experimental site is naturally acid moraine loam Bathygleyic Dystric Glossic Retisol (WRB, 2014), with a clay (<0.002 mm) content of 15.0% and acidity (pH_KCl) of 4.30–4.93. Sprouts of cup plant were planted at the end of May in 2013. One factorial experiment was composed of the following treatments: 1) not fertilized (control treatment), 2) fertilized N_60 P_60 K_60 3) 31.5 t ha^-1 and 4) 90 t ha^-1 of granulated sewage sludge. All the treatments with three replications were randomly allocated. The granulated sewage sludge was incorporated into the soil during the third ten-day period of May in 2014. NPK fertilization was carried out each year before the beginning of the growing season.

**Granulated sewage sludge.** The material was obtained from the water treatment plant JSC “Silutės vandenys”. The composition of the treated sewage sludge was as follows: pH – 5.56, total nitrogen – 33.4 g kg^-1, total phosphorus – 5.02 g kg^-1, organic matter – 64.97%. The concentrations of heavy metals were as follows: lead (Pb) – 14.47 mg kg^-1, cadmium (Cd) – 0.44 mg kg^-1, nickel (Ni) – 8.22 mg kg^-1, copper (Cu) – 47.8 mg kg^-1, zinc (Zn) – 287 mg kg^-1 and mercury (Hg) – 0.96 mg kg^-1. According to contamination with heavy metals, the sewage sludge met the requirements laid down for the 1st category.

**Sampling and analytical methods employed.** The assessments of cup plant productivity (dry matter (DM) yield) were started in 2014. Each year, at the end of September, the stems of cup plant were cut by a rotary reaper. The cup plant productivity was recalculated into the air-dry matter yield.

**Soil chemical analyses** (in 0–30 cm topsoil layer) were done twice in October 2013 (before the experiment) and in October 2016. Soil samples for the analyses were taken from three treatments (except N_60 P_60 K_60) and three replications. Soil analyses were done using the following techniques: pH_0.05 – potentiometrically, organic carbon (C_0) – by Turin method, total nitrogen (N_0) – by Kjeldahl method, plant available phosphorus (P_0) and potassium (K_0) – by the Egner-Riehm-Domíngo (A-L) method.

**Statistical analysis.** The data of the studied parameters and their interactions were statistically processed using the analysis of variance (ANOVA) to determine significant differences at 95% and 99% probability levels (LSDₙₒ and LSDₙₒ) (Raudonius, 2017).

**Results and discussion**

**Dry matter (DM) yield.** The effect of fertilization type (mineral and sewage sludge application) on the DM yield of cup plant is presented in Table 1. Since the cup plant formed approximately 12–14 leaves in a rosette and did not produce stems during the first year of growing, the biomass yield was not observed. During the first harvest year, the DM yield of cup plant averaged 2.83 t ha^-1. Typically, the yield of the second growing season is not high. A significant DM increase was observed during the second and third harvest years (in 2015 and 2016). Accordingly, the dry matter yield increased to 5.84 t ha^-1 in 2015 and 12.86 t ha^-1 (or by 190% and 440% compared to the first growing season). The average DM yield of cup plant was slightly lower in 2017 – 11.95 t ha^-1. Generally, during the first growing season, the aboveground biomass yield of cup plant was relatively low. However, it substantially increases in the subsequent growing years (Gansberger et al., 2015; Staudins et al., 2015).

The cup plant produced relatively high DM yield in the control treatment (without fertilization) during each experimental year, which suggests that the amount of mineral nutrients in the experimental site’s soil was sufficient. Thus, the cup plant was able to accumulate enough nutrients from the soil upper layer in order to maintain normal physiological metabolism and produce the annual DM yield from 2.20 t ha^-1 (in 2014) to 8.78 t ha^-1 (in 2016).

The annual application of mineral fertilizers (N_60 P_60 K_60) increased DM yield from 2.93 t ha^-1 (in 2013) to 10.41 t ha^-1 (in 2016), i.e. from 18.56% to 43.58% compared to the control treatment. However, the increase of DM was not statistically significant. Given that mineral fertilization is an expensive investment, mineral fertilizer use for energy crops is economically inexpedient.

Overall, the application of 45 t ha^-1 of granulated sewage sludge was most effective in terms of dry matter accumulation in cup plant biomass. Compared to the control treatment the dry matter yield increased by 50–210%, depending on the growing year. Sewage sludge
The activity of cup plant may vary from 8.22 to 13.48 t ha⁻¹ depending on the meteorological conditions, annual dry matter productivity of cup plant is relatively low – 2.00–6.80 t ha⁻¹ (Voigt et al., 2012). Contrarily, the data obtained in Chile shows that under different plant density and fertilization levels, the dry matter yield of cup plant may vary from 15.0 to 20.0 t ha⁻¹ (Pichard, 2012). It is important to note that the seed material of cup plant is not homogeneous. Its productivity depends not only on climate and soil conditions, but also on the available seed material (Assefa et al., 2015; Gansberger et al., 2015).

Soil chemical properties. At the beginning of the field trial, soil pH value (in the 0–30 cm topsoil layer) at the experimental site was 4.50, on average (irrespective of the treatment) (Table 2).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>pH</th>
<th>Corg</th>
<th>Ntot</th>
<th>Corg:Ntot</th>
<th>P₂O₅</th>
<th>K₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>4.45</td>
<td>1.25</td>
<td>0.08</td>
<td>15.36</td>
<td>80.6</td>
<td>245</td>
</tr>
<tr>
<td>45 t ha⁻¹ sewage sludge</td>
<td>4.27</td>
<td>1.75</td>
<td>0.13</td>
<td>13.64</td>
<td>933</td>
<td>245</td>
</tr>
<tr>
<td>90 t ha⁻¹ sewage sludge</td>
<td>4.59</td>
<td>1.79</td>
<td>0.13</td>
<td>13.15</td>
<td>984</td>
<td>246</td>
</tr>
<tr>
<td>LSD05/01</td>
<td>0.30</td>
<td>0.16</td>
<td>0.01</td>
<td>1.64</td>
<td>1862</td>
<td>63.1</td>
</tr>
</tbody>
</table>

**Table 1.** The effect of fertilization type on the dry matter yield (t ha⁻¹) of cup plant during the 2014–2017 experimental years.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>2.20</td>
<td>3.74</td>
<td>8.78</td>
<td>8.68</td>
</tr>
<tr>
<td>N60P60K60</td>
<td>2.93</td>
<td>6.83</td>
<td>17.58</td>
<td>14.05</td>
</tr>
<tr>
<td>45 t ha⁻¹ sewage sludge</td>
<td>3.31</td>
<td>6.02</td>
<td>14.68</td>
<td>13.49</td>
</tr>
<tr>
<td>90 t ha⁻¹ sewage sludge</td>
<td>2.87</td>
<td>5.49</td>
<td>12.86</td>
<td>11.63</td>
</tr>
<tr>
<td>LSD05/01</td>
<td>1.93</td>
<td>2.67</td>
<td>3.35</td>
<td>3.30</td>
</tr>
</tbody>
</table>

**Note.** The differences between values marked by different letters are significant.

In the following three years, the soil analyses revealed that sewage sludge application had no significant impact on soil acidity. On the contrary, other authors argue that the application of sewage sludge tends to reduce soil acidity (Neilsen et al., 1998; Eitminavičiūtė et al., 2009). The average soil Corg content at the trial site was 1.26% (in 2013). Meanwhile other authors state that sewage sludge tends to decrease soil acidity (Lattare et al., 2014). In 2016, after three growing seasons, the application of 45 t ha⁻¹ sewage sludge significantly increased Corg content by up to 1.75%. However, the use of double rate (90 t ha⁻¹) of sewage sludge had similar impact on the increasing of soil Corg content – 1.69%.

At the beginning of the experiment, the average Norg content was 0.78%. The application of both sewage sludge rates had a similar and significantly positive impact on soil nitrogen content; thus three years after sewage sludge application, Norg content was 0.13%. By increasing both Corg and Norg content in the upper soil layer, the Corg:Norg ratio tended to decrease from 15.36 (in unfertilized soil) to 13.15–13.64 (in the soil applied with sewage sludge). According to the results of other authors, the application of sewage sludge increases soil organic content, improves soil Corg and Norg mineralization processes (Roig et al., 2012). It is noteworthy that after three experimental years, there were no significant differences between both sewage sludge rates for all the studied soil chemical parameters. Accordingly, the data of other authors reveal that under the sewage sludge application, the content of soil nutrients highly varies throughout the entire year. Altogether, the use of different composted rates (50 and 100 t ha⁻¹) of sewage sludge had a similar impact on the following soil parameters: organic matter, total C and N contents and C:N ratio (Larchevêque et al., 2006). Other researchers indicate that the use of the highest sewage sludge rates significantly improved soil chemical parameters already in the first year of growth. However, in the subsequent years, the beneficial effect of high sewage sludge rates on soil chemical composition becomes less evident (Alvarenga et al., 2017).

Large amounts of phosphorus were introduced into the soil with sewage sludge. Before the experiment, the average amount of mobile P₂O₅ in the topsoil layer was low – 83.73 mg kg⁻¹. After three years of growth, the amount of mobile P₂O₅ in the topsoil layer increased approximately 12 times to 933–984 mg kg⁻¹. Usually, different sewage sludge materials contain high amounts of phosphorus (Alvarenga et al., 2017). It is a good alternative for traditional mineral phosphorus fertilization, particularly for energy crops, since inorganic phosphorus resources on the Earth are quite limited (Lindermohl et al., 2012). Before the experiment, the average amount of mobile K₂O was 270 mg kg⁻¹. After three years of vegetation (in 2016) and irrespective of the fertilization type, the amount of mobile K₂O in the 0–30 cm topsoil layer remained essentially unchanged.

**Water-stable aggregates** are single-particles formed by different materials – plant roots, adhesives of bacteria and fungi, polysaccharides, and fungi hyphae. The application of organic material is a simple and effective way to restore disrupted soil structure. Particularly, sewage sludge can be an effective means.
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In 2015 (one year after the application of sewage sludge), the highest amount (14.3%) of macro-aggregates was estimated in the soil applied with 90 t ha\(^{-1}\) sewage sludge. Meanwhile in 2017 (three years after sewage sludge application), the highest amount of macro-aggregates was found in the soil with the application of the lower rate (45 t ha\(^{-1}\)) of sewage sludge. In the third experimental year (in 2017), cup plants already had a deep and dense root system; thus, the roots also contributed significantly to the formation of macro-aggregates. According to Angers (1992), vegetation affects soil structural form and stability at different scales and through various direct and indirect mechanisms. In the third experimental year, compared with the control treatment, the use of sewage sludge increased the amount of ecologically and agronomically valuable aggregates (>0.25 mm) by 24–31%. It might be explained by the fact that sewage sludge application increased soil C\(_{\text{org}}\) content by 35–40% compared with the untreated soil (Table 2). Different authors emphasized that with the application of sewage sludge, the amount of water-stable soil aggregates is increasing due to the increase in soil organic matter content and its distribution among stable soil aggregates, especially macro-aggregates (>1.0 mm) (Table 3).

### Table 3. The effect of sewage sludge on the amount (%) of water-stable aggregates in the topsoil of the growing site of cup plant

<table>
<thead>
<tr>
<th>Treatment</th>
<th>2015 (mm)</th>
<th>2017 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt;1.0 mm</td>
<td>&gt;0.25 mm</td>
</tr>
<tr>
<td>Control</td>
<td>10.1 a</td>
<td>50.3 a</td>
</tr>
<tr>
<td>N(_{60P60K60})</td>
<td>10.6 a</td>
<td>45.7 a</td>
</tr>
<tr>
<td>45 t ha(^{-1}) sewage sludge</td>
<td>13.5 a</td>
<td>50.6 a</td>
</tr>
<tr>
<td>90 t ha(^{-1}) sewage sludge</td>
<td>14.3 b</td>
<td>59.3 a</td>
</tr>
<tr>
<td>LSD(_{0.05})</td>
<td>4.17</td>
<td>13.02</td>
</tr>
</tbody>
</table>

Note. The differences between values marked by different letters are significant.

According to the results obtained in late autumn of 2017, soil penetration resistance in all treatments in deeper layers was higher than in the upper layers, which was determined by the morphogenetic peculiarities of the soil profile (Fig.). The least penetration resistance was in the 0–40 cm soil layer, where 45 t ha\(^{-1}\) sewage sludge had been applied. In other words, soil penetration resistance was by 16% lower compared with the control (without fertilization) and conventional N\(_{60P60K60}\) fertilization.

Summarizing the data, it can be concluded that the application of sewage sludge (particularly 45 t ha\(^{-1}\)) in the acid moraine loam soil increased the aggregate resistance in the upper soil layer. The differences between values marked by different letters are significant.

### Table 4. The effect of sewage sludge on topsoil bulk density and moisture content in the growing site of cup plant

<table>
<thead>
<tr>
<th>Treatment</th>
<th>2015 bulk density</th>
<th>2016 moisture %</th>
<th>2017 bulk density</th>
<th>2016 moisture %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>1.39 a</td>
<td>23.2 a</td>
<td>1.33 a</td>
<td>21.3 a</td>
</tr>
<tr>
<td>N(_{60P60K60})</td>
<td>1.32 a</td>
<td>23.5 a</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>45 t ha(^{-1}) sewage sludge</td>
<td>1.30 b</td>
<td>22.2 a</td>
<td>1.19 b</td>
<td>20.3 a</td>
</tr>
<tr>
<td>90 t ha(^{-1}) sewage sludge</td>
<td>1.33 a</td>
<td>22.2 a</td>
<td>1.12 b</td>
<td>21.0 a</td>
</tr>
<tr>
<td>LSD(_{0.05})</td>
<td>0.074</td>
<td>2.933</td>
<td>0.121</td>
<td>1.737</td>
</tr>
</tbody>
</table>

Note. The differences between values by different letters are significant.

Microbial biomass carbon in the soil is expressed as biomass of microorganisms in the soil (µg g\(^{-1}\) C). The effect of sewage sludge on soil microbial activity is presented in Table 5.

Microbial biomass carbon content changed during all experimental years. It was found that the variation of microbial biomass carbon between spring and autumn periods in the humus horizon in the cup plant site at the 0–30 cm depth was rather negligible. Since the first evaluation of soil microorganisms was done before sewage sludge application, there were aggregates are less susceptible to soil compaction. Soil penetration resistance as well as soil bulk density tests also confirmed this statement.

**Soil bulk density and penetration resistance are** the major soil properties regulating plant root elongation, water accessibility and plant productivity (Colombi et al., 2018). Optimum topsoil conditions for plant root growth in a sandy clay loam and clay loam are <1.40 Mg m\(^{-3}\) and penetration resistance <1.5 MPa.

The study data showed that moraine loam soil bulk density and penetration resistance depended on the fertilizer type (Table 4). In the growing site of cup plant, compared with unfertilized soil, the application of lower rate (45 t ha\(^{-1}\)) of sewage sludge significantly (by 6.5%) decreased soil bulk density. The application of both sewage sludge rates had no impact on soil moisture content.

![Figure. The effect of sewage sludge on the soil penetration resistance in the growing site of cup plant in 2017](image-url)
biomass as the control. It could be predicted, that conventional fertilization was slightly improving nutrient availability for cup plants but not as effective contributor to soil microbial biomass.

It is likely that not only the application of sewage sludge but also a strong rooting system of energy crops (cup plant, in our case) actively promote the growth of soil microbial biomass, and, at the same time, the immobilization of nutrients (Kallenbach, Grandy, 2010; Annabi et al., 2011; de Vries, Bardgett, 2012).

According to the obtained experimental results, cup plant as an energy crop might be successfully grown in less fertile and high acidity moraine loam Retisols. Based on the four years’ experimental data, it can be concluded that the usage of sewage sludge as organic matter at a rate of 45 t ha⁻¹ is sufficient for maintaining high annual biomass productivity of cup plant. Besides, organic sewage sludge application was far more superior to annual NPK fertilization. In a broad sense, sewage sludge is not only a source of organic matter with high amount of nutrients, but also the improver of soil physical and microbial properties and plant growth conditions in naturally acid Retisols. Besides, the annual use of mineral fertilization is costly and energetically inexpedient for perennial energy crops (particularly cup plant) cultivation; thus, sewage sludge as a cheap organic material might be an appropriate substitution. In this way, the growing expenses would be significantly reduced.

Besides the positive impact on biomass yield, sewage sludge significantly improved soil quality. The addition of sewage sludge in the soil increased the amount of water-stable aggregates and microbial activity. As a result, the soil became less compact.

It can be hypothesized that the positive effect of sewage sludge application on both biomass and soil productivity will remain in the next few years. In order to determine the long-term impact of sewage sludge on soil qualitative parameters, the intensity of soil decontamination process, dynamic of biomass productivity and its suitability as feedstock for bioenergy purposes, the experiment is going to be continued until 2022.

### Conclusions

1. The studies conducted on a Retisol indicate that the dry matter (DM) yield of cup plant (Silphium perfoliatum L.) increased significantly in the first three consecutive experimental years. A single sewage sludge application at a rate of 45 t ha⁻¹ had the highest impact on DM yield increment. The effect of annual conventional mineral fertilization on DM yield was less substantial.

2. Both rates (45 and 90 t ha⁻¹) of sewage sludge had no significant effect on soil acidity (pH) and mobile potassium (K_O) amount in the topsoil layer. Herewith, the amount of organic carbon (C₉₀), total nitrogen (Nₙₒ) and mobile phosphorus (P_O₉₀) increased significantly.

3. A single sewage sludge application (particularly 45 t ha⁻¹) in an acid moraine loam soil increased the aggregate stability, decreased the bulk density and penetration resistance in the upper soil layer.

4. Microbial biomass carbon content increased already in the first year as a result of sewage sludge application (especially 90 t ha⁻¹) and consistently increased in subsequent experimental years.

### Acknowledgements

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### References


### Table 5. The changes of soil microbial biomass carbon (μg g⁻¹ C) in the humus horizon (0–30 cm depth) in the growing site of cup plant during the 2014–2016 experimental years

<table>
<thead>
<tr>
<th></th>
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<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>217 ± 23.9 a</td>
<td>211 ± 18.2 a</td>
<td>187 ± 10.4 a</td>
<td>191 ± 10.3 a</td>
<td>183 ± 12.1 a</td>
<td>200 ± 8.2 a</td>
</tr>
<tr>
<td>N₆₀P₆₀K₆₀</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45 t ha⁻¹ sewage sludge</td>
<td>226 ± 11.8 a</td>
<td>229 ± 12.4 ab</td>
<td>243 ± 11.3 b</td>
<td>282 ± 20.1 b</td>
<td>455 ± 38.0 b</td>
<td>472 ± 45.8 b</td>
</tr>
<tr>
<td>90 t ha⁻¹ sewage sludge</td>
<td>241 ± 14.3 a</td>
<td>247 ± 13.7 b</td>
<td>287 ± 14.3 c</td>
<td>368 ± 18.0 c</td>
<td>724 ± 15.0 b</td>
<td>724 ± 19.2 c</td>
</tr>
<tr>
<td>On average</td>
<td>234 ± 13.1</td>
<td>228 ± 13.9</td>
<td>265 ± 12.8</td>
<td>287 ± 14.3</td>
<td>368 ± 18.0</td>
<td>455 ± 26.5</td>
</tr>
</tbody>
</table>

Note. Mean values ± standard deviation; the differences between values marked by different letters are significant.
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