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# Effect of organic additives to mineral substrates applied to green roofs on the growth of red fescue (*Festuca rubra* L. 'Dipper')

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## ABSTRACT

This article presents the results of laboratory tests of the use of organic additives, i.e. lignite and sewage sludge to the mineral volcanic soil substrate and their effect on the biomass production of red fescue (*Festuca rubra* L. 'Dipper'). In the pots lined with geotextile fabric and filled with volcanic mineral substrate soil with the addition (by volume) of 0%, 10%, 20% and 30% lignite or sewage sludge (SS), grass was sown and regularly watered with distilled water every 10 days. The green matter and the dry matter of the yield was determined. The analysis of physicochemical properties of samples of mineral substrate, lignite and sewage sludge was carried out. On average, the dry matter of red fescue (*Festuca rubra* L. 'Dipper') harvested from the control substrate was 14.205 $g/m^2$. In the variation with the addition of 10%, 20% and 30% sewage sludge, the dry matter of red fescue (*Festuca rubra* L. 'Dipper') was 27.636 $g/m^2$, 23.299 $g/m^2$, and 9.873 $g/m^2$, respectively. The dry matter of red fescue (*Festuca rubra* L. 'Dipper') harvested from the substrate with 10%, 20% and 30% lignite was 16.609 $g/m^2$, 13.149 $g/m^2$, and 14.348 $g/m^2$, respectively. The enrichment of the volcanic mineral substrate for green roofs with a 10% and 20% addition of sewage sludge contributed to an increase in the biomass yield of red fescue (*Festuca rubra* L. 'Dipper') by 94.6% and 64.0% of dry matter, respectively. The addition of lignite to the volcanic mineral substrate for green roofs contributed to a decrease in the yield of red fescue (Festuca rubra L. 'Dipper'), where, as the dose of lignite increased, the yield decreased relative to the control (by -1.5% (10%L), -20.0% (20%L), -24.2% (30%L)), most likely due to the unfavourable ratio of C:N recorded in the applied lignite (102.1:1).

**Keywords:** green roof, grass, green matter, dry matter, lignite, mineral volcanic soil substrate, sewage sludge, biomass yield.

## INTRODUCTION

Green roofs are important elements of modern landscaping due to the range of benefits they bring to the environment. They contribute to lowering the temperatures in urban heat islands (Kolokotsa et al., 2013; Wang et al., 2022), retain rainwater (Zheng et al., 2021), improve air quality (Kostadinović 2023, Yang Jun et al. 2008), provide thermal insulation for buildings (Wei, 2022; Castleton, 2010), improve city aesthetics (Yuen and Hien, 2005; Loder, 2014), and the residents' quality of life (Chojecka, 2014). Green roofs are one of the symbols of sustainable development.

One of the most important factors for the proper functioning of green roofs is the soil substrate. It plays a key role in the effective functioning of the entire green roof system. It provides plants with the essential minerals and nutrients, stores water reserves, provides good drainage on the roof, allows the air to access plant roots, etc. (Kolk et al., 2023).

Numerous studies were conducted on the issue of the effects of organic additives to soils, substrates, and soil substrates, but not many of them relate directly to substrates for green roofs. The introduction of organic additives into substrates for green roofs can have important implications for water retention, soil quality, and plants' health. The characteristics of ready substrates for green roofs were developed by the German Society for Landscape and Agricultural Research (FLL), in 2018. They indicate the requirements for substrates for green roofs, and their properties are evaluated in 14 categories (FLL, 2018).

Standards specifying the permissible content of heavy metals in municipal sewage sludge are specified in the Ordinance of the Minister of the Environment on the use of municipal sewage sludge (Journal of Laws 2023, item 23).

Many countries have local building regulations that specify requirements for green roofs, including soil substrates. There are also general guidelines and standards for soil substrates for green roofs. In Poland, there are no standards for soil substrates and organic additives for green roofs. However, there are, among others, fertilizer recommendations for permanent grasslands developed within the framework of the long-term program of the Institute of Fertilization and Soil Science National Research Institute (published in 2010). The standards developed for organic substrate additives include:

- FLL Guidelines (Germany) on composition, retention capacity, drainage properties, structure, and nutrients (Giacomello, 2021),
- ASTM International: American Standards Association on, for example, the drainage properties of coarse-grained materials used on roofs, specifications for the use of clay and slate as a mineral component in the substrate (ASTM E2788/E2788M-24),
- European standard EN 12580:2022, which specifies the methods for determining the amount of soil and growing media,
- EN 17925:2024-08 standard specifying soil improvers and growing media – determination of profiles, temperature, and the time during composting and fermentation,
- Regulation (EU) 2019/1009 of the European Parliament and of the Council of June 5, 2019 establishing the rules for making EU fertilizer products available on the market, amending Regulations (EC) No. 1069/2009 and (EC) No. 1107/2009 and repealing Regulation (EC) No. 2003/2003,
- Act of July 10, 2007 on fertilizers and fertilization, Journal of Laws of 2024, Item 105 (in Polish).

Green roofs are divided into basic types: extensive (lighter, with low vegetation and maintenance requirements) and intensive (heavier, but with the possibility to grow taller plants including shrubs and even trees) (Perez and Perini, 2018). The layout of green roof layers is usually as follows: vegetation layer, substrate, filtration layer, drainage layer, protective mat, and root barrier (Abuseif, 2023).

The productivity of a green roof depends on the layers of which it consists, the construction of the roof itself, and the climate of the place in which it is designed (Berardi et al., 2014). The depth/thickness of the substrate layer is very important; the larger it is, the greater its retention capacity and the capacity of nutrients needed by plants (Kolk et al., 2023).

The soil substrate is the basis for the proper functioning of a green roof, as it provides water, nutrients, and a suitable habitat for plants. To create it, lightweight components such as lava, pumice, scoria, expanded shale, and good water retention components like clay should be used. The composition of substrates for roofs is often not disclosed by their manufacturers. Substrates vary depending on the type of roof for which they are intended. The main component of substrates should be mineral-based materials. The composition of substrates should also depend on locally available materials and match the needs of the vegetation to grow in it (Getter and Rowe, 2006). The retention capacity of substrates can depend on their granulometric composition, organic matter content, compaction, and structure, among other factors (Kuś, 2016).

Many off-the-shelf commercial substrates require the addition of synthetic fertilizers to ensure the required fertility. The choice of compost type for the substrate has a strong impact on plant size, rooting, the surface area covered, as well as the quality of water runoff from the green roof, and changes in the substrate's microbiology (Matlock and Rowe, 2017).

Organic additives to soil substrates are essential for plant vitality. They can provide plants with essential nutrients. Studies have shown that organic matter can retain water at 20 times its own weight. Enriching the soil with organic matter leads to an increased water-holding capacity and improved soil moisture (Lipiec et al., 2015; Kuś, 2016). However, it should be noted that they may affect the pH of the soil, as well as disrupt the structure of the substrate, which may have a negative impact on the green roof system. It is recommended that they make up about 3–15% of the substrate composition (Kazemi and Mohorko, 2017). The content of organic matter in soil substrates used for green roof establishment should not exceed 20% (Burszta-Adamiak, 2015). Organic matter should be mixed with light materials to reduce the negative effects of decomposition (Bianchini and Hewage, 2012). Excess organic matter in the soil may result in soil subsidence and thus hinder healthy root growth (Nagase and Dunnet, 2011).

Substrates consisting of clay and recycled aggregate are beneficial for plant growth, as they provide variable conditions similar to those found in natural soil profiles (Mickovski et al., 2013). A high-quality substrate can also be obtained by using coconut fibres, sugarcane waste, and green coconut fruit (Araújo de Almeida and Colombo, 2021). Incorporating dried leaves and flowers of common sea-rose (*Tanacetum vulgare* L.) into the soil can have a beneficial effect on plant development, as this plant shows bacteriostatic, fungicidal, and insecticidal properties (Ciesielczyk et al., 2017).

Also, biocarbon has the potential to increase water retention in the soil, as well as to reduce nutrient leaching (Beck et al., 2011). According to a 2018 study, the addition of 10% rice husk biocarbon increased the growth rate and biomass of grass shoots used on turfgrasses (Li et al., 2018). It can also increase soil pH, which in turn affects nutrient availability, as well as enrich the soil with water-soluble mineral salts (Olmo et al., 2016).

Sources of organic matter can include manure, slurry, compost, food industry by-products, and biodegradable fractions of municipal and industrial waste (e.g., food industry), fermentation waste, sewage sludge, etc. (Ødegaard et al., 2002; Paluch and Pulikowski, 2008; Diacono and Montemurro, 2010; Sobik-Szoltysek and Jablonska, 2010; Nkoa, 2014; Lipiec et al., 2015; Ciesielczuk et al., 2017; Bauman-Kaszubska and Sikorski, 2018.), with the condition for their use being that they meet the quality criteria defined in the regulations (Journal of Laws 2023 item 23).

Sewage sludge can be a source of organic matter and elements that are necessary for the proper growth of plants (Grobelak et al., 2016). Sewage sludge application can also have the effect of increasing plant tolerance to salt stress by improving root growth (Shan et al., 2021). The application of sewage sludge in high doses reduces the value of soil bulk density, which ensures better root proliferation (Kirchmann et al., 2016).

Sewage sludge can be used in agriculture, recultivation of degraded areas, but also in urban green spaces. Its functions include improving soil properties and thus increasing crop yield and growth (Malczewska and Jawecki, 2009; Sobczyk et al. 2015; Kuś, 2016; Antonkiewicz et al., 2018). The application of sewage sludge can help improve the chemical and physical properties of soils, for example by increasing the organic matter content (Nagar et al., 2006; Fytili and Zabaniotou, 2008).

In order to safely use sewage sludge as an additive to soils, it must be processed properly. One way to do this is by solar drying, which causes, among other things, an increase in organic matter content, an increase in infiltration rates, water holding capacity, and stability of soil aggregates (2004; Nagar et al., 2006; Fytili and Zabaniotou, 2008). However, there is a risk that sewage sludge may contain contaminants such as heavy metals, chemicals, and pathogens, which may be harmful not only to plant health, but also to the environment. The phytotoxicity of heavy metals in soil from sewage sludge can be mitigated by the addition of biocarbon (Antonkiewicz et al., 2018; Wu et al., 2022). Application of sewage sludge may also have a negative impact through their high content of heavy metals, which can reduce crop yields and also reduce crop quality (Rosik-Dulewska et al., 2007). Therefore, laboratory control of the sludge is required before its use (Journal of Laws 2023, item 23). Certain research projects are conducted at the moment on the impact and magnitude of heavy metal contamination of soils fertilized with treated sewage sludge and plants growing on them (Farahat and Linderholm, 2015; Rodrigues et al., 2013; Rezapour et al., 2019).

Coal deposits that are considered unprofitable to mine, that are an overburden or accompanying mineral to mined deposits, and that have a detrimental effect on public health and the environment, could be used as an additive to improve soils. They could improve soil structure, improve nutrient mobility, stimulate microbial activity (Akimbekov et al., 2021), and reduce leaching of organic nitrogen from the soil (Goldschmidt and Ishi, 2023). An example of such additives to substrates is lignite, whose structure, chemical composition, and properties are similar to soil humus, which has high sorption capacity and prevents leaching of nutrients from the soil. The use of lignite as a substrate additive can increase the buffer capacity of the soil, and through its sorption capacity it can be used to remove organic contaminants from the soil (Kwiatkowska, 2007; Kwiatkowska and Maciejewska, 2009; Pikuła, 2016; Amoah-Antwi et al., 2020;). Lignite also has potential as an adsorbent for wastewater treatment (Qi et al., 2011). Biocarbon additives reduce the weight of the substrate while increasing water retention in the substrate (DE10142407A1; US9918440B2; Amoah-Antwi et al., 2020; Werdin, 2021). Lignite also exhibits a high moisture content that evaporates under dry conditions (Król-Domanska and Smolinska, 2012; Amoah-Antwi et al., 2020) and has the ability to re-wet even after excessive drying (US5471786A). It can be used as a substrate additive both in the form of ashes and grains up to several mm in diameter (WO 91/08662; EP0607876B1; US5471786A; Ćatović et al., 2016; Mikos-Szymanska et al., 2019).

Coal waste combined with sewage sludge can form a high-quality component of various applications, such as an additive to soil substrates (Mwengula Kahilu et al., 2022).

This article presents the results of laboratory tests of the use of organic additives, i.e. lignite and sewage sludge to the mineral volcanic soil substrate and their effect on the biomass production of red fescue (*Festuca rubra* L. 'Dipper').

The purpose of the study is to test the effect of organic additives representing mining and municipal waste (lignite from overburdened clay deposits, as well as municipal sewage sludge) to the mineral soil substrate applied to green roofs on the growth and biomass production of red fescue (*Festuca rubra* L. 'Dipper') under the conditions of a laboratory experiment. A hypothesis has been made that the addition of lignite or sewage sludge to the mineral soil substrate used in green roofs would increase the biomass production of sown red fescue (*Festuca rubra* L. 'Dipper').

## MATERIAL AND METHODS

The study was part of a 9-month experiment on increasing the water retention capacity of mineral substrate for green roofs (Jawecki et al., 2024a, 2024b), where the stage with grass covered the period from 21/09/2022 to 22/12/2022. In plastic pots (9 × 9 × 14 cm) lined with geotextile fabric (weight 115 g/m$^2$, perpendicular permeability 0.089 m/s) and filled with volcanic mineral substrate (VSM) soil (750ml) with the addition (by volume) of 0%, 10%, 20% and 30% lignite (L) or sewage sludge (SS) (sample weights are shown in Figure 1), grass was sown (sowing standard of 10g/m$^2$) and regularly watered with distilled water (topping rate of 22.2 mm) every 10 days (Jawecki et al., 2024a, 2024b). The volumetric percentage of mineral substrate additive was converted to weight percentage of additive in each variant, where volumetrically 10%, 20% and 30% of lignite additive, corresponded to 2.7%, 5.2% and 8.7% of lignite additive by weight on average. By volume, on the other hand, 10%, 20% and 30% of sewage sludge addition, corresponded to an average of 4.9%, 10.1% and 15.8% of sewage sludge addition by weight. Each variant tested was performed in three replicates, for

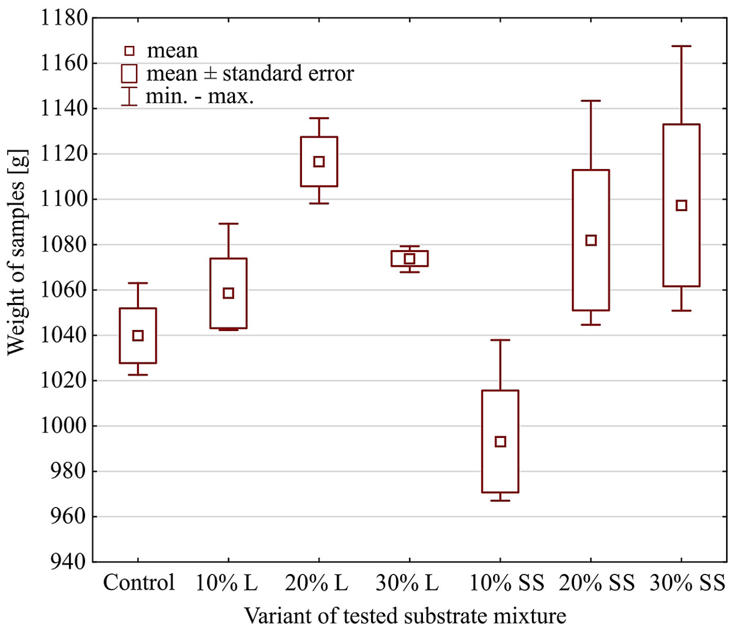


**Figure 1.** Weight of samples

which the arithmetic mean value was determined. After growth, the grass was cut at a height of 5 mm from the ground and weighed to obtain the weight of the green matter yield, then the dry matter (drying at 105 °C) of the yield was determined.

The experiment used red fescue (*Festuca rubra* L. 'Dipper'), an evergreen, low-growing grass with low soil requirements, a strong root system, and rapid growth (Gajić et al., 2020). Red fescue (*Festuca rubra*) is used in demanding/hard substrates, including in the reclamation of degraded areas (Goliński, 2000; Czyż and Kitczak, 2006; Olszewski, 2009). For example, the variety *Festuca rubra* 'Merlin' shows the ability to tolerate many heavy metals and has the potential to phytoremediate soils contaminated with them (Ma et al., 2003). Red fescue (*Festuca rubra*) tolerates high and low temperatures, drought, periodic stagnant water, sandy and clay soils, which can be rich or poor in nutrients (Vimal and Singh, 2020). This grass prefers a pH in the range of 4.5–6.0.

The experiment was conducted under laboratory conditions for a period of 90 days from 21.09.2022 to 22.12.2022. The study was conducted in a supply-heated room. Air temperature and relative humidity were measured with an automatic BENETECH GM1365 logger, with an accuracy of 0.1 °C and data recording every 1 minute (Jawecki et al., 2024a, 2024b). The average daily air temperature was determined as the actual average (Kuśmierek-Tomaszewska et al., 2013), and the average daily relative humidity was determined similarly.

The analysis of physicochemical properties of samples of mineral substrate, lignite and sewage sludge was carried out in the laboratory of the District Chemical and Agricultural Station in Wroclaw, the Centre for Environmental Quality Analysis of the WUELS, the Laboratory of the Institute of Soil Science, Plant Nutrition and Environmental Protection of the WUELS, some data were provided by ZWiK in Strzelin sp. z o.o. and ZIDA sp. z o.o. The research was carried out in accordance with binding reference methods and/or Polish standards.

A mineral volcanic substrate for growing ornamental plants on flat and sloping roofs was used as the soil substrate (Table 1). It complies with the guidelines for substrates for green roofs according to the recommendations of FLL (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V., Association for the Study, Development and Shaping of Landscape), meets the requirements for growing media as specified in the Law on Fertilizers and Fertilization (Journal of Laws of 2024, Item 105) and the Ordinance on the Implementation of Certain Provisions of the Law on Fertilizers and Fertilization (Journal of Laws of 2024, Item 1261), and was approved for marketing by the Minister of Agriculture and Rural Development by Decision No. P-737/18 dated 07.02.2018.

**Table 1.** Physical and chemical properties of the substrate used in the experiment (based on the product data sheet of ZIDA sp. z o.o.)

| Composition | Aggregate of volcanic origin, natural porous aggregates | Parameter |
|---|---|---|
| Physical properties: | Fractional content less than 0.063 mm | < 10% weight |
| | Fractional content > 4 mm | 35–50% weight |
| | General porosity | > 50% |
| | Maximum water capacity | 35–65% |
| | Air capacity at maximum water capacity | 10–20% |
| | Organic matter content | < 10 $g/dm^3$ |
| | Water permeability of the modified filtration coefficient | > 1–70 mm/min |
| | Compaction factor | ≤ 20% |
| | Settlement coefficient after mechanical compaction | ≤ 5% |
| | Dry weight | ≤ 1200 $kg/m^3$ |
| | Weight when fully saturated with water | ≤ 1650 $kg/m^3$ |
| Chemical properties: | pH value ($CaCl_2$) | 6–8.5 |
| | Value EC | 1–2 |
| | Salinity in g NaCl/l / g KCl/l | < 2.5 / < 2.5 |
| Pollution | Permissible amount of impurities | < 0.5% |

The lignite used in the experiment comes from lignite seams that are an associated (unmined) mineral, in the coal-bearing kaolinitic clays transitioning to grey and blue-grey clays found in the Rusko-Jaroszów refractory clay deposit (Halushak, 2007).

Sewage sludge was obtained from the solar sludge dryer at the municipal sewage treatment plant for the Strzelin agglomeration (equivalent population of 17,476 p.e.) (Resolution XXIX/376/20), in Chociwel, Strzelin municipality. Previous capacity of the treatment plant: maximum daily Q = 7,000.0 $m^3/d$; maximum hourly: 298.7 $m^3/h$; design capacity of the treatment plant 23,686 p.e. of mechanical-biological treatment. A sample of the material after drying was taken on the 28.07.2017 (test report No. 1207/07/2017/F/1, sampling according to (A) PB-167/P issue 2 dated 24.04.2015, (A) PN-ISO5567-13:2011). Test results made available by ZWiK in Strzelin sp. z o.o., performed by Jars sp. z o.o., are presented in Table 2.

The investigated formations, i.e. lignite and sewage sludge (25.86% organic matter, Table 3), were classified as organic formations due to organic matter content exceeding 20%, while volcanic soil substrate for green roofs (0.82% organic matter, Table 3) was classified as mineral formation due to organic matter content below 5% (SGP 2019). Organic carbon reserves were assessed as high (> 6%) (Terelak et al., 2001; Gonet, 2007; Kuś, 2015) for lignite and sewage sludge (C org. > 15%, Table 4), while volcanic mineral substrate (C org. < 0.3%, Table 3), was assessed as low (< 1%) (Terelak et al., 2001; Gonet, 2007; Kuś, 2015).

The nutrient content of the studied samples (Table 3) was evaluated taking into account the nature of the formation, i.e. a very light mineral formation (volcanic mineral substrate) and organic formations (lignite and sewage sludge). Very high abundance of $P_2O_5$ (Ochal, 2015) was exhibited by all the studied samples (Table 3). $K_2O$ content was assessed as very high, medium, and very low (Ochal, 2015) for sewage sludge, mineral volcanic substrate, and lignite samples, respectively (Table 3). As for magnesium (Table 3), very high content was noted in the mineral substrate sample, while medium content was found in the lignite and sewage sludge samples (Ochal, 2015). Sewage sludge met the minimum requirements for organic fertilizers (OJ 2024, item 1261) in terms of total nitrogen (> 0.3%), $P_2O_5$, (> 0.2%) and $K_2O$ (> 0.2%), permissible content of heavy metals (Cr, Cd, Ni,

**Table 2.** Test results of a sample of material of solar-stabilized sewage sludge, provided by ZWiK in Strzelin

| Tested parameter | Result | Uncertainty | Permissible content in the use of municipal sewage sludge (Journal of Laws 2023. item 23) | | unit |
|---|---|---|---|---|---|
| | | | Agriculture and recultivation for agricultural purposes | Recultivation for non-agricultural purposes | |
| pH | 7.4 | ±0.3 | | | - |
| Dry weight | 90.5 | ±4.5 | | | % |
| Loss on ignition (LOI) (organic matter) | 67.0 | ±10.1 | | | % |
| Total nitrogen according to Kjeldahl | 4.8 | ±1.0 | | | % |
| Ammonium nitrogen | 0.37 | ±0.07 | | | % |
| Total phosphorus | 1.5 | ±0.3 | | | % |
| Calcium | 2.8 | ±0.3 | | | % |
| Magnesium | 0.49 | ±0.07 | | | % |
| Lead | 37 | ±7 | 750 | 1000 | mg/kg |
| Cadmium | 0.86 | ±0.13 | 20 | 25 | mg/kg |
| Mercury | 0.36 | ±0.07 | 16 | 20 | mg/kg |
| Nickel | 14 | ±3 | 300 | 400 | mg/kg |
| Zinc | 703 | ±141 | 2500 | 3500 | mg/kg |
| Copper | 367 | ±73 | 1000 | 1200 | mg/kg |
| Chrome | 15 | ±3 | 500 | 1000 | mg/kg |
| The presence of *Salmonella spp.* | present in 100 g | | 0 | It does not specify | pcs/kg d.w. |
| Live eggs of intestinal parasites (*Ascaris sp.*, *Trichuris sp*, *Toxocara sp.*) | 0 | | 0 | 300 | pcs/kg d.w. |

Pb, Hg) for organic fertilizers and organic crop aids. In the case of lignite, they met the requirements in terms of total nitrogen, $P_2O_5$, while the value of $K_2O$ was lower than the requirements of the Ordinance. Both compositions did not meet the requirements of the Ordinance (Journal of Laws 2024. item 1261) in terms of organic matter content (> 30%) for organic fertilizers, but met the requirements for mineral-organic fertilizers (> 20% organic matter). The tested sewage sludge and lignite also met the requirements of the Regulation of the European Parliament and of the Council laying down rules for making EU fertilizer products available on the market (OJ L 170, 25.6.2019, as amended) for solid organic fertilizers and soil improvers regarding organic carbon content (> 15% C org. > 7.5% C org., respectively) and, in the case of sewage sludge, also total nitrogen (> 1% N total) for organic fertilizers and dry matter for soil improvers (> 20% dry matter). Sewage sludge met the requirements of the Regulation of the European Parliament and of the Council (OJ L 170, 25.6.2019, as amended) for organic fertilizers and soil improvers in terms of Cd, Ni, Pb, Hg, and Zn content, but it did not meet the requirements for copper content.

The sewage sludge used in the experiment was evaluated for applicability in accordance with the guidelines for the use of sewage sludge for non-agricultural purposes and reclamation for agricultural purposes, according to the Ordinance of the Minister of the Environment on the use of municipal sewage sludge (Journal of Laws 2023, item 23). The tested sludge met the standards when using municipal sewage sludge for non-agricultural land reclamation in terms of pH, content of Pb, Cd, Hg, Ni, Zn, Cu, Cr, presence of *Salmonella* spp. bacteria and live eggs of intestinal parasites (*Ascaris* sp., *Trichuris* sp., *Toxocara* sp.).

According to the classification of grain size of soils and mineral formations – PTG 2008, the mineral substrate used in the experiment was the strongly skeletal sandy gravel sample (SG), which is dominated by the fraction of medium gravel (MG), and within the earthy parts the sample shows the composition of loose sand (S). The permeability class of the tested mineral substrate was determined as good or very good.

The C:N ratio (27.85:1) in the tested mineral soil substrate for green roofs (Table 4) clearly exceeded the optimal values for soils (11-8:1) and their range (15-8:1, most often 12-10:1) (Bęś et al., 2005; Kuś, 2015; Malec and Borowski, 2017). However, it remained within the acceptable range for fertilizers and organic additives (30-20:1) (Palosz, 2009; Dach, 2010), while falling within the range of values (33.3-22.2:1) when transient immobilization of soil mineral nitrogen occurs (Brodowska, 2023). In contrast, the C:N ratio (7.37:1) recorded in sewage sludge (Table 4). was close to the lower limit of values presented in literature for sewage sludge, 13-6.5:1, (Bęś et al. 2005; Dach, 2010; Koch et al., 2016) and the lower values for the arable layer of soils of 8:1, and was within the range of the ratio when direct mineralization of organic forms of nitrogen occurs (Brodowska, 2023). The C:N ratio recorded in the lignite sample - 102.1:1 (Table 4). was in the middle of the C:N ratio range presented in the literature - 135-52:1 (Symanowicz and Kalembasa, 2001; Kalembasa et al., 2014), although it significantly exceeded the permissible upper limits for fertilizers and organic additives (Palosz, 2009; Dach, 2010), as well as the limit of the ratio above which organic matter decomposition slows down and mineral nitrogen is permanently immobilized (Palosz, 2009; Kuś, 2015; Kolacz, 2020; Kalembasa et al., 2014; Kolacz, 2020; Brodowska, 2023).

**Table 3.** Contents of macronutrients $P_2O_5$, $K_2O$, Mg, total nitrogen, and organic matter in the studied samples (studies performed by the District Chemical and Agricultural Station in Wroclaw (report GR/763/1-3/23 macronutrients) and the Centre for Environmental Quality Analysis of the WUELS (report 118/23/W))

| Sample | Assimilable forms of mineral nutrients [mg/100g soil] | | | | | | Total nitrogen [%] | C org./ organic substance [% p.s.m.] | |
|---|---|---|---|---|---|---|---|---|---|
| | Phosphorus | | Potassium | | Magnesium | | | | |
| | $P_2O_5$ content | Resourcefulness | $K_2O$ content | Resourcefulness | Mg content | Resourcefulness | | Content | Resourcefulness |
| Sewage sludge | >1755.0 | Very high | >209.0 | Very high | >73.5 | Average | 4.2 ± 0.8% | >15.0 /25.86 | High |
| Lignite | >221.3 | Very high | 11.6 | Very low | 66.8 | Average | 0.39 ± 0.08% | >15.0/25.86 | High |
| Mineral soil substrate | 23.8 | Very high | 9.8 | Average | 14.8 | Very high | <0.01 | < 0.3/0.82 | Very low |

The pH of the studied formations was assessed according to the range limits for assessing the acidity of soils in Poland (Pokojska, 2004; Gonet et al., 2015; Ochal, 2015; Ochal et al., 2017) where, based on the pH in KCl, mineral soil substrate (pH 5.7) and sewage sludge (pH 6.1) were classified as slightly acidic, while lignite (pH 3.8) was classified as strongly acidic. Soil is considered acidic when its pH is below 6.5. A drop in pH below 5.5 causes plants to start taking up ammonium ions, i.e. ammonium sulphate, urea, ammonia, and nutrients become unavailable to plants (Józefaciuk and Szatanik-Kloc; 2002). The lignite additive used in the experiment may have lowered the pH of the mineral soil substrate used in the experiment, which may have reduced the green matter yield of red fescue (*Festuca rubra* L. 'Dipper') as the addition of lignite to the mineral substrate increased. Sewage sludge, on the other hand, has a similar pH to the reference value, which may have been associated with higher yields of red fescue (*Festuca rubra* L. 'Dipper') in sludge-added samples.

## RESULTS AND DISCUSSION

During the study period, the average daily air temperature was in the range of 19.3–30.7 °C, averaging 22.6 °C (Figure 2). Meanwhile, the average daily relative humidity averaged 36%, ranging from 18.6–55.2% (Figure 2). On October 15, 2022, the heating season began.

On average, the green matter of red fescue (*Festuca rubra* L. 'Dipper') harvested from the control substrate was 93.933 g/m², while the dry matter was 14.205 g/m² (Table 5). In the variation

**Table 4.** Physicochemical properties of the tested samples

| Sample | pH | | C | N | C/N | EC | Kw | $Ca^{+2}$ | $Mg^{+2}$ | $K^+$ | $Na^+$ | gw | go |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $H_2O$ | KCl | g × kg$^{-1}$ | | | mg×kg$^{-1}$ | cmol(+) × kg$^{-1}$ | | | | | g × cm$^{-3}$ | |
| Mineral soil substrate | 6.5 | 5.7 | 0.286 | 0.01 | 27.85 | 167.4 | 0.25 | 3.06 | 2.43 | 0.17 | 0.1 | 2.62 | 1.5 |
| Sewage sludge | 6.4 | 6.1 | 27.82 | 3.77 | 7.37 | 10476 | 5.13 | 11.88 | 13.73 | 4.27 | 1.62 | 1.89 | 0.52 |
| Lignite | 4.5 | 3.8 | 36.35 | 0.36 | 102.1 | 510.3 | 3.23 | 5.88 | 6.18 | 0.16 | 0.14 | 1.65 | 0.3 |

**Note:** pH $H_2O$ – pH water, pH KCl – pH potassium chloride, C – carbon content, N – nitrogen content, Kw – exchangeable acidity, $Ca^{+2}$ – calcium ions, EC – salinity, C/N – carbon to nitrogen ratio, $Na^+$ - sodium ions, $K^+$ - potassium ions, $Mg^{+2}$ – magnesium ions, gw – specific density, go – bulk density. Test procedures/standards used in the study: pH in KCL PN-ISO 10390:1997; Mg / abundance - gl. Min. PN-R-04020:1994+Az1:2004; - withdrawn standard. No replacement; gl. Org. PN-R-04024:1997; pH and liming needs: Fertilizer recommendations, part 1, IUNG Puławy, 1990.

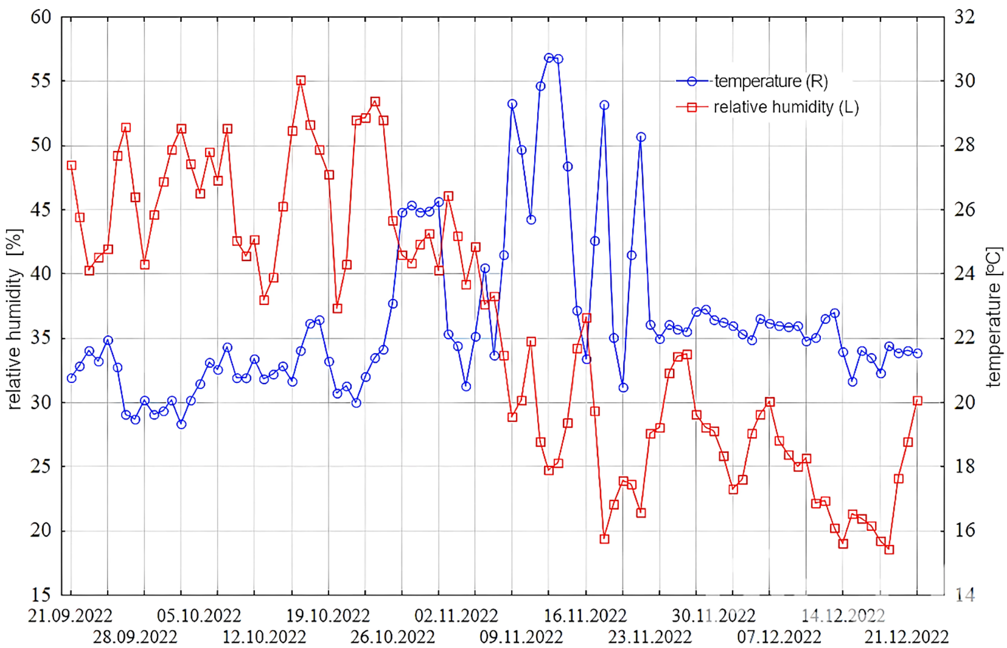


**Figure 2.** The course of average daily air temperature and average daily relative humidity during the study period

**Table 5.** Yield weight (green and dry matter) of red fescue (*Festuca rubra* L. 'Dipper') harvested in the tested variants of organic additives to the soil substrate for green roofs

| Type of additive | | Control (mineral soil substrate) | Sewage sludge | Lignite |
|---|---|---|---|---|
| | | Mean ± stand error.<br>Min-max | | |
| Variant of the additive | Yield | [g/m²] | | |
| Control | Green matter | 93.933 ± 7.838<br>80.692 – 107.820 | - | - |
| | Dry matter | 14.205 ± 1.116<br>12.221 – 16.083 | - | - |
| 10% | Green matter | 93.933 ± 7.838<br>80.692 – 107.820 | 173.149 ± 41.508<br>105.606 – 248.720 | 92.503 ± 2.356<br>87.899 – 95.640 |
| | Dry matter | 14.205 ± 1.116<br>12.221 – 16.083 | 27.636 ± 6.103<br>17.716 – 38.754 | 16.609 ± 0.320<br>16.055 – 17.163 |
| 20% | Green matter | 93.933 ± 7.838<br>80.692 – 107.820 | 141.961 ± 25.583<br>111.557 – 192.803 | 75.156 ± 0.160<br>74.879 – 75.433 |
| | Dry matter | 14.205 ± 1.116<br>12.221 – 16.083 | 23.299 ± 4.521<br>17.716 – 32.249 | 13.149 ± 0.400<br>12.457 – 13.841 |
| 30% | Green matter | 93.933 ± 7.838<br>80.692 – 107.820 | 62.099 ± 7.230<br>50.381 – 75.294 | 71.557 ± 4.538<br>62.561 – 77.093 |
| | Dry matter | 14.205 ± 1.116<br>12.221 – 16.083 | 9.873 ± 0.854<br>8.581 – 11.488 | 14.348 ± 0.919<br>12.734 – 15.917 |

with the addition of 10%, 20% and 30% sewage sludge, the green matter of red fescue (*Festuca rubra* L. 'Dipper') averaged 173.149 g/m$^2$, 141.961 g/m$^2$, and 62.099 g/m$^2$, respectively, and the dry matter was 27.636 g/m$^2$, 23.299 g/m$^2$, and 9.873 g/m$^2$, respectively (Table 5). The green matter of red fescue (*Festuca rubra* L. 'Dipper') harvested from the substrate with 10%, 20% and 30% lignite was 92.503 g/m$^2$, 75.063 g/m$^2$, and 71.557 g/m$^2$, respectively, and the dry matter was 16.609 g/m$^2$ 13.149 g/m$^2$, and 14.348 g/m$^2$, respectively (Table 5).

The highest average green matter yield of red fescue (*Festuca rubra* L. 'Dipper') was observed in the variant of volcanic mineral substrate mixtures with 10% and 20% sewage sludge, 173.149 g/m$^2$ and 141.961 g/m$^2$, respectively (Figure 3). On the other hand, the lowest average weight of green matter yield of red fescue (*Festuca rubra* L. 'Dipper') was observed in the variant of mixtures with the addition of 30% sewage sludge and 20% and 30% lignite, i.e. 62.099 g/m$^2$, 71.557 g/m$^2$ and 75.063 g/m$^2$, respectively. The highest average dry yield weight of red fescue (*Festuca rubra* L. 'Dipper') was noted in the variant of mineral substrate mixture with the addition of 10% and 20% sewage sludge and 10% lignite, i.e. 27.636 g/m$^2$, 23.299 g/m$^2$,

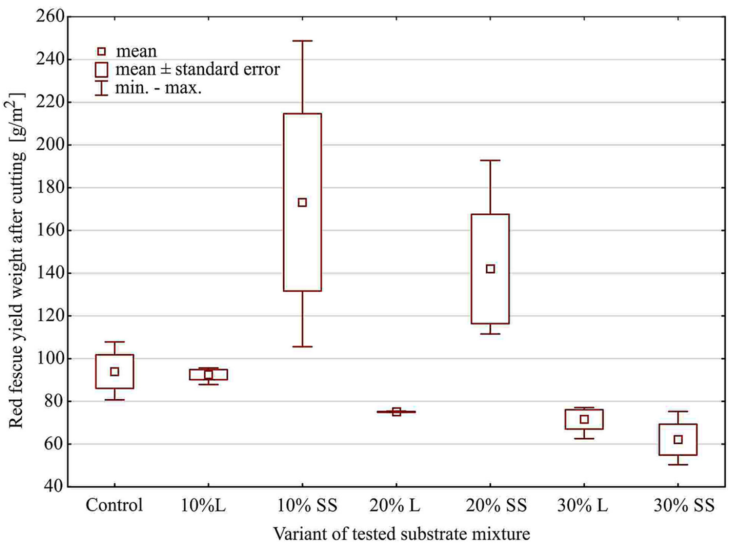


**Figure 3.** Yield (g/m$^2$) of green matter of red fescue (*Festuca rubra* L. 'Dipper'), directly after cutting

and 16.609 g/m$^2$, respectively (Figure 4). On the other hand, the lowest average dry matter yield of red fescue (*Festuca rubra* L. 'Dipper') was noted in the variant of mineral substrate mixture with the addition of 30% sewage sludge and 20% and 30% lignite, i.e. 9.873 g/m$^2$, 13.149 g/m$^2$, and 14.348 g/m$^2$, respectively.

Percentage differences between average green matter yield values of red fescue (*Festuca rubra* L. 'Dipper') in the tested variants of volcanic mineral substrate mixtures with additions of lignite and sewage sludge were calculated using the following equation (Equation 1):

$$x = \frac{b-a}{a} \times 100\% \quad (1)$$

where: $a$ – average yield for the first variant compared [g/m$^2$], $b$ – average yield for the second variant compared [g/m$^2$], $x$ – weight gain value [%].

Compared to the control samples, only the mineral substrate with the addition of sewage sludge showed an increase in the average green yield weight of red fescue (*Festuca rubra* L. 'Dipper'). Positive differences were noted in the sample with the addition of 10% and 20% sewage sludge, where the average green yield weight of red fescue (*Festuca rubra* L. 'Dipper') was higher than that of the control by 79.22 g/m$^2$ (84.3%) and 48.03 g/m$^2$ (51.1%), respectively (Table 6, Figure 5). On the other hand, the mineral substrate sample with the addition of 30% sewage sludge had a lower yield weight of red fescue (*Festuca rubra* L. 'Dipper') compared to the control sample, where the difference for green matter averaged 31.83 g/m$^2$ (33.89% less) (Table 6, Figure 5), as for the additions of 10%, 20%, and 30% lignite, where the difference was 1.43 g/m$^2$(1.52%) 18.87 g/m$^2$ (20.09%), and 22.38 g/m$^2$ (24.19% less), respectively. With the addition of lignite to the mineral substrate, there was a decrease in the average green yield weight of red fescue (*Festuca rubra* L. 'Dipper'), compared to the control sample, where the difference in yield weight increased as the proportion of lignite addition increased.

Compared to the control samples, the highest increase in the average dry matter of red fescue (*Festuca rubra* L. 'Dipper') was noted in the sample with 10% and 20% addition of sewage sludge, i.e. 13.43 g/m$^2$, respectively. (94.56% more) and 9.09 g/m$^2$ (64.02% more), respectively (Table 7, Figure 6). In contrast, the mineral substrate sample with the addition of 30% sewage sludge showed the smallest increase in yield weight of red fescue (*Festuca rubra* L. 'Dipper') compared to the control sample, where the difference for dry matter was 4.33 g/m$^2$ (30.50% less).

Table 8 shows the percentage differences between the average green matter of red fescue (*Festuca rubra* L. 'Dipper') yield in the tested variants of volcanic mineral substrate mixtures with lignite and sewage sludge additives. Relative to the average green matter of the grass crop

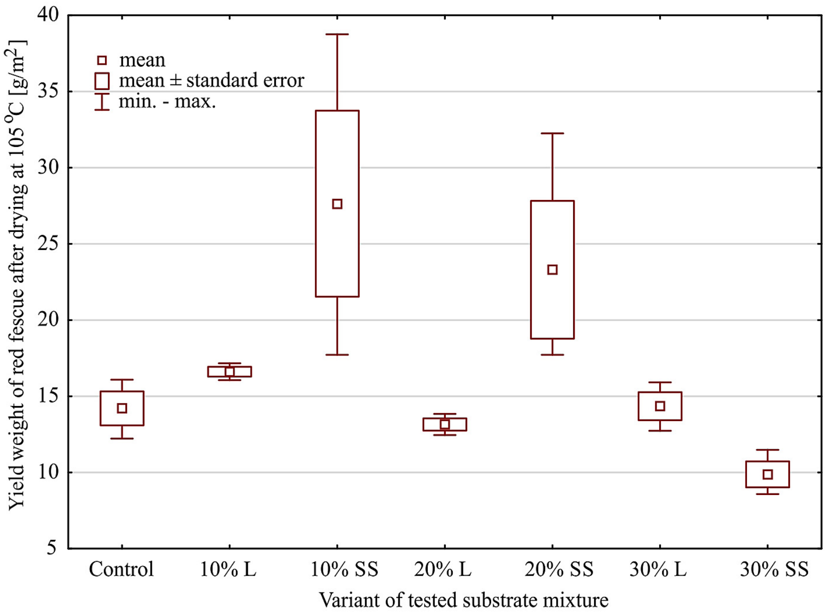


**Figure 4.** Yield dry matter (g/m$^2$) of red fescue (*Festuca rubra* L. 'Dipper') after drying at 105 °C

**Table 6.** Difference in grass green matter yield from control sample

| L | L 10 | L 20 | L 30 | SS 10 | SS 20 | SS 30 |
|---|---|---|---|---|---|---|
| Change in value [%] | -1.52 | -19.99 | -24.19 | 84.33 | 51.13 | -33.89 |
| Difference [g/m$^2$] | -1.43 | -18.78 | -22.38 | 79.22 | 48.03 | -31.83 |

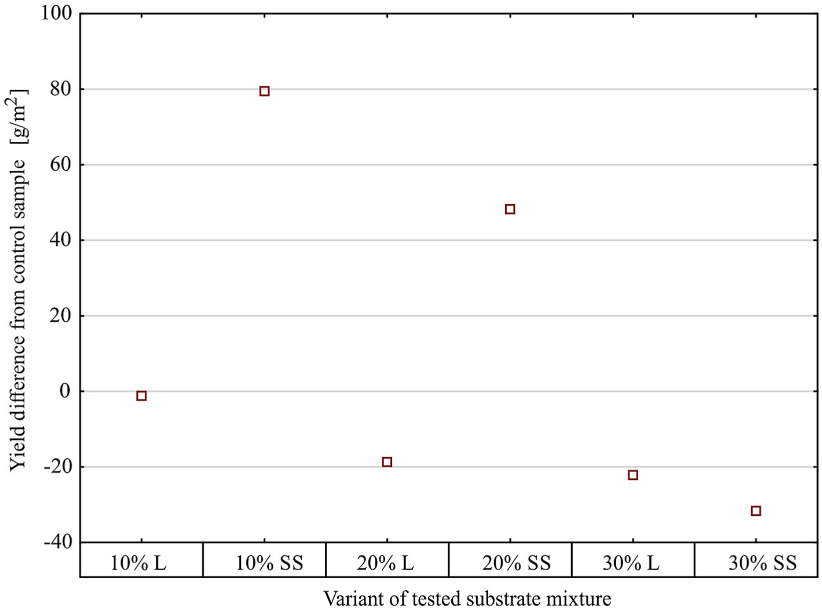


**Figure 5.** Difference in grass dry matter yield from control sample [g/m$^2$]

**Table 7.** Difference in grass dry matter yield from control sample

| L | L 10 | L 20 | L 30 | SS 10 | SS 20 | SS 30 |
|---|---|---|---|---|---|---|
| Change in value [%] | 16.92 | -7.44 | 0.86 | 94.56 | 64.02 | -30.50 |
| Difference [g/m$^2$] | 2.40 | -1.06 | 0.14 | 13.43 | 9.09 | -4.33 |

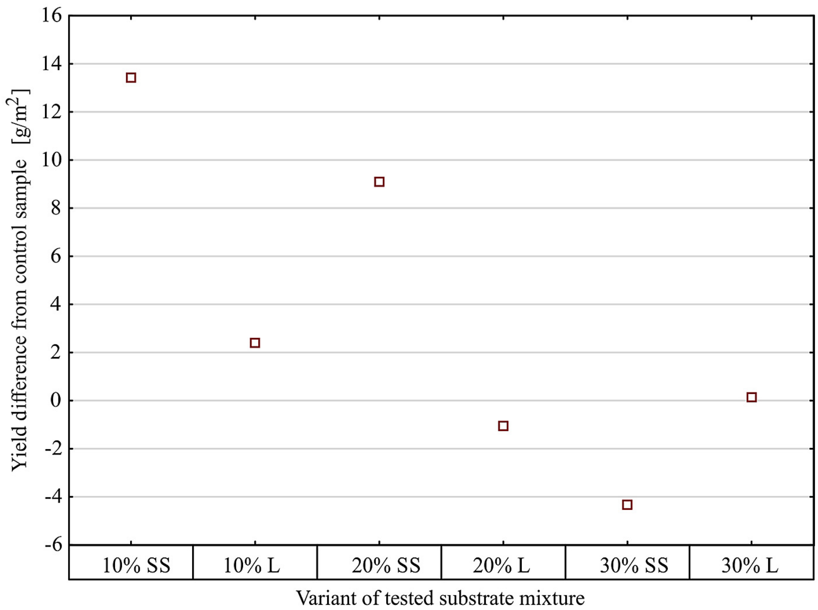


**Figure 6.** Difference in yield of grass dried at 105 $^o$C compared to control sample [g/m$^2$]

harvested from the substrate with the addition of 10% sewage sludge, the average weight of the harvested green matter was higher in all variants studied. For the variants with sewage sludge, the highest value (178.8% higher) was recorded for the substrate with the addition of 30% sewage sludge, and for the variants with lignite, the highest value (142.0% higher) was recorded for the addition of 30% lignite. Relative to the average green yield weight of red fescue (*Festuca rubra* L. 'Dipper') harvested from the variant with the addition of 20% sewage sludge, the average weight of the harvested green yield was higher in most of the variants tested, where the biggest differences were recorded for the variants with the addition of 30% sewage sludge and lignite, 128.6% and 98.4% higher, respectively. In the variant with the addition of 20% sewage sludge only compared to the variant of the substrate with the addition of 10% sewage sludge, the average green yield of grass was lower by 18.0%. In relation to the average weight of the green yield of red fescue (*Festuca rubra* L. 'Dipper') harvested from the substrate with the addition of 30% sewage sludge, the average weight of the harvested green yield was lower in all the analysed variants, where the greatest differences were observed in the variants with the addition of 10% sewage sludge and lignite, 64.1% and 32.9% lower, respectively, than the variant of the substrate with the addition of 30% sewage sludge.

Relative to the average green matter of grass yield harvested from the substrate with 10% lignite, the average weight of harvested green yield was higher in the lignite substrate variants tested, where the greatest difference (by 29.3%) was recorded for the yield from the substrate variant with 30% lignite. In contrast, the average green yield of red fescue (*Festuca rubra* L. 'Dipper') was higher only for the variant with 30% sewage sludge (by 49.0%), and was lower in relation to the other variants, with a maximum of 46.6% for the variant of the substrate with 10% sewage sludge. In relation to the average weight of the green yield of red fescue (*Festuca rubra* L. 'Dipper') harvested from the variant of the substrate with the addition of 20% lignite, the average weight of the harvested green yield was lower in most of the variants studied, where the greatest differences (lower by 56.59%) were recorded in the variant with the addition of 10% sewage sludge. A higher average green grass yield was recorded for the variants of the substrate with the addition of 30% sewage sludge and lignite, higher by 21.03% and 5.03%, respectively. In relation to the average weight of the green grass yield harvested from the substrate with the addition of 30% lignite, the average weight of the harvested green yield was lower in all the analysed variants, where the greatest differences were recorded in the variants with the addition of 10% sewage sludge and lignite, lower by 58.7% and 22.6%, respectively.

Table 9 shows the percentage differences between the average dry matter values of the red fescue (*Festuca rubra* L. 'Dipper') yield in the tested variants of mineral substrate mixtures with additions of lignite and sewage sludge. Relative to the average weight of the dry grass crop harvested from the substrate with the addition of 10% sewage sludge, the average weight of the harvested dry crop was higher in all analysed variants. For the variants with sewage sludge, the highest value (higher by 179.91%) was recorded for the substrate with the addition of 30% sewage sludge, and for the variants with lignite, the highest value (higher by 110.18%) was recorded for the addition of 20% lignite. In relation to the average dry matter of the red fescue (*Festuca rubra* L. 'Dipper') harvested from the variant with the addition of 20% sewage sludge, the average weight of the harvested green crop was higher in

**Table 8.** Percentage differences between the average values of the green yield weight of red fescue (*Festuca rubra* L. 'Dipper') in the tested variants of mixtures of mineral substrate with additions of lignite and sewage sludge (%)

| Parameter | 10% SS | 20% SS | 30% SS | 10% L | 20% L | 30% L |
|---|---|---|---|---|---|---|
| 10% SS | 0.00 | -18.0 | -64.1 | -46.6 | -56.59 | -58.7 |
| 20% SS | 22.0 | 0.00 | -56.3 | -34.84 | -47.06 | -49.6 |
| 30% SS | 178.8 | 128.6 | 0.0 | 49.0 | 21.03 | -13.2 |
| 10% L | 87.2 | 53.5 | -32.9 | 0.0 | -18.75 | -22.6 |
| 20% L | 130.39 | 88.89 | -17.37 | 23.08 | 0.0 | -4.79 |
| 30% L | 142.0 | 98.4 | -13.2 | 29.3 | 5.03 | 0.0 |

**Note:** The values of the variants given in the columns are related to the values given in the rows.

most of the analysed variants, where the greatest differences were recorded for the variants with the addition of 30% sewage sludge and 20% lignite, 135.98%, and 77.19% higher, respectively. Only in relation to the variant of the substrate with the addition of 10% sewage sludge, the average dry yield of grass was lower by 15.69%. In relation to the average weight of the dry yield of red fescue grass (*Festuca rubra* L. 'Dipper') harvested from the substrate with the addition of 30% sewage sludge, the average weight of the harvested dry yield was lower in all the variants studied, where the greatest differences were observed in the variants with the addition of 10% sewage sludge and lignite, 64.27% and 40.56% lower, respectively, than in the variant of the substrate with the addition of 30% sewage sludge.

Relative to the average weight of dry grass yield harvested from the substrate with 10% lignite, the average weight of harvested dry yield was higher in the lignite substrate variants tested, where the greatest difference (by 26.32%) was recorded for the yield from the substrate variant with 20% lignite. In contrast, the average dry yield of red fescue (*Festuca rubra* L. 'Dipper') was higher only for the variant with 30% sewage sludge (by 68.22%), and was lower in relation to the other variants, with a maximum of 39.9% for the variant of the substrate with 10% sewage sludge. In relation to the average weight of the dry yield of red fescue (*Festuca rubra* L. 'Dipper') harvested from the variant of the substrate with the addition of 20% lignite, the average weight of the harvested dry yield was lower in most of the variants studied, where the greatest differences (lower by 52.42%) were recorded in the variant with the addition of 10% sewage sludge. A higher average dry grass yield was recorded for the variants of the substrate with the addition of 30% sludge greater by 33.18%, respectively. In relation to the average weight of the dry grass yield harvested from the substrate with the addition of 30% lignite, the average weight of the harvested dry yield was lower in most of the variants studied, where the greatest differences were recorded in the variants with the addition of 10% sludge and lignite, lower by 48.08% and 13.61%, respectively. The average weight of the harvested dry yield was higher only for the 20% L variant (higher by 9.12%).

In order to check whether the differences between the samples in the analysed variants and the control sample are statistically significant, a T-student test (significance level $\alpha = 0.05$) was used for independent samples versus groups for each variant (Table 10) (Zawadzki, 2011). The variables have a normal distribution, as tested by the Shapiro Wilk test (null hypothesis - the distributions are not statistically significantly different from the normal distribution) (Domanski and Wagner, 1992). The minimum sample size for the Shapiro Wilk test is 3 observations (Domanski and Wagner, 1992).

The results show the effect of 10%SS and 20%SS sludge addition on higher biomass growth of red fescue (*Festuca rubra* L. 'Dipper') compared to the control sample (Tables 6 and 7), by 84.3% and 51.1% of green matter and 94.6% and 64.0% of dry matter, respectively. However, the sample with the addition of 30% sewage sludge showed a lower biomass increase of red fescue (*Festuca rubra* L. 'Dipper') compared to the control sample by 33.9% for green matter and 30.5% for dry matter. The obtained results partially confirm literature reports, where the appropriate fertilization of plants with sewage sludge can affect increased biomass yield, and plant growth depends on the applied dose and can increase with it, contributing to an even several times higher biomass yield compared to the control (Kiryluk, 2003; Krzywy et al., 2003; Kalembasa and Malinowska, 2008; Kacprzak and Grobelak, 2011;

**Table 9.** Percentage differences between average green matter yield values of red fescue (*Festuca rubra* L. 'Dipper') in the tested variants of volcanic mineral substrate mixtures with additions of lignite and sewage sludge (%)

| Parameter | 10% SS | 20% SS | 30% SS | 10% L | 20% L | 30% L |
|---|---|---|---|---|---|---|
| 10% SS | 0.00 | -15.69 | -64.27 | -39.90 | -52.42 | -48.08 |
| 20% SS | 18.61 | 0.00 | -57.62 | -28.71 | -43.56 | -38.42 |
| 30% SS | 179.91 | 135.98 | 0.0 | 68.22 | 33.18 | -31.19 |
| 10% L | 66.39 | 40.28 | -40.56 | 0.0 | -20.83 | -13.61 |
| 20% L | 110.18 | 77.19 | -24.91 | 26.32 | 0.0 | 9.12 |
| 30% L | 92.60 | 62.38 | -31.19 | 15.76 | -8.36 | 0.0 |

**Note:** The values of the variants given in the columns are related to the values given in the rows.

**Table 10.** results of Student's t-test for independent samples against groups for individual variants of green and dry matter yield of cut grass (p-value for significance level 0.05)

| Parameter | 10% L | 20% L | 30% L | 10% SS | 20% SS | 30% SS |
|---|---|---|---|---|---|---|
| Green matter | 0.869764 | 0.073807 | 0.068900 | 0.134007 | 0.147099 | 0.040520 |
| Dry matter | 0.107160 | 0.423140 | 0.925962 | 0.096370 | 0.12547 | 0.036853 |

**Note:** If $p < 0.05$ then the variable is statistically significant.

Rosikoń, 2014; Antonkiewicz et al., 2018). The obtained results indicate that when sewage sludge was used as an additive to the mineral soil substrate for green roofs, higher yields compared to the control were achieved with the addition of 10% of the sludge (~5% by weight) and 20% of the sludge (~10% by weight), and lower yields were obtained with the addition of 30% of the sludge (~16% by weight), where according to the literature, higher yield increases were obtained for the addition of more than 15% (by weight) of sewage sludge (Krzywy et al., 2003; Kacprzak and Grobelak, 2011). However, the referenced studies were conducted using soil, not soil substrates for green roofs. It is likely that the low yield of red fescue (*Festuca rubra* L. 'Dipper') may be due to the threefold higher dose of high-salinity sewage sludge (10.5 $g \times kg^{-1}$) or the amount of heavy metals introduced into the substrate for green roofs with sewage sludge in the 30%SS variant compared to the control. This supposition is supported by the literature, where salinity or heavy metal contamination of sewage sludge may be a limiting factor in biomass growth (Rosik-Dulewska et al., 2007; Małuszyńska and Małuszyński, 2009; Kabala et al., 2010; Hadam and Karaczun, 2011; Rosikoń, 2014; Dudley et al., 2014; Możdżeń et al., 2018). Therefore, due to the microscale of the experiment, it is advisable to continue research on the effect of the amount of sewage sludge addition to green roof substrates on the biomass production of the sown plants. The results obtained from the present experiment indicate that the use of sewage sludge as a substrate additive for green roofs can clearly increase the biomass yield on a green roof. These results are similar to those of other researchers working on the effect of sewage sludge on increasing plant yields (including Gondek and Filipek-Mazur, 2006; Sobczyk et al., 2015; Grobelak et al., 2016).

The test of differences between means showed the absence of significance of differences in most of the analysed cases. It is likely that the result of the test of significance of differences between means may have been influenced by the micro-scale of the experiment (the size of the pots) and the number of samples. Despite the lack of significance of differences between means, it is interesting to note the relatively high difference in green and dry matter yield of red fescue (*Festuca rubra* L. 'Dipper') in variants with 10% and 20% sewage sludge added to the sample. This may be a rationale for continuing studies on a larger scale, both of pot dimensions and sample sizes of individual variants.

The results of the study of the effect of the addition of 10%, 20% and 30% lignite to the soil substrate on the biomass growth of red fescue (*Festuca rubra* L. 'Dipper') are inconclusive (Tables 6 and 7). In the case of the green matter of the grass tested, all samples with lignite addition show lower values than the green matter of the control sample, where the difference increases with lignite addition, by -1.5% (at 10%L, ~3% by weight), -20.0% (at 20%L, ~5% by weight), -24.2% (at 30%L, ~9% by weight), respectively. On the other hand, analysis of the dry matter yield of red fescue (*Festuca rubra* L. 'Dipper') showed greater variation, respectively +16.9% (at 10%L), -7.4% (at 20%L), +0.9% (at 30%L). At the same time, the test of differences between means showed no statistically significant differences. These results differ from the data provided in literature that indicate that with the addition of 5% (by weight) of lignite, yield increases were observed on light soil, while the addition of 7.5% (by weight) of lignite significantly increased the dry matter yield of perennial ryegrass (*Lolium multiflorum* Lam.); it also remained without significant effect on the biomass yield of cocksfoot (*Dactylis glomerata*) compared to the control trial, (Symanowicz and Kalembasa, 2006; Kwiatkowska, 2007; Kalembasa et al., 2014). However, this research was conducted using soil, not soil substrate for green roofs. The decrease in green matter yield, as well as the high heterogeneity of the obtained results of dry matter of red fescue (*Festuca rubra* L. 'Dipper') sown on soil substrate for green roofs, can probably be attributed to the strongly acidic reaction of the addition of lignite increasing the mobility of heavy metals, low potassium content and unfavourable C:N ratio. The lower yield of red fescue (*Festuca rubra* L. 'Dipper') in successive variants of samples with higher lignite addition (where the relatively wide C:N ratio in lignite was 102.1:1) can be explained by the predominance of biological sorption processes of nitrogen and permanent immobilization of mineral nitrogen (Kwiatkowska, 2007; Kalembasa et al., 2014; Brodowska, 2023). This coincides with the negative effects of introducing lignite into soils presented in literature, such as the introduction of toxic substances, sorption of micronutrients essential for plant life, and/or sorption stability of heavy metals when present in soils (Kwiatkowska, 2007), as well as unfavourable processes for plants observed at wide C:N ratios (exceeding 33: 1), such as slowing down the decomposition of organic matter, uptake of nitrogen from the soil by the microorganisms carrying out this decomposition, and permanent immobilization of mineral nitrogen (ubiquitination, nitrogen-proteinization), which leads to a nitrogen deficit for plants (Pałosz, 2009; Kuś, 2015; Kołacz, 2020; Kalembasa et al., 2014; Kus, 2015; Kolacz, 2020; Brodowska, 2023).

On average, sewage sludge can contain ~3–5% nitrogen (Siuta, 2014; Wiater and Butarewicz, 2014; Dusza et al., 2017; Bartkowska and Dzienis, 2019; Bartkowska et al., 2019; Czarnota et al., 2020) and organic carbon ~15–35% (Mazur and Mokra, 2011; Siuta and Dyguś, 2013; Wiater and Butarewicz, 2014; Dusza et al., 2017; Bartkowska and Dzienis, 2019; Bartkowska et al., 2019) which can affect a narrow C:N ratio of less than 10 (in this study it was 7.37). To improve the C:N ratio to limits close to the optimal ratio, high-carbon and low-nitrogen materials, such as straw, leaves, and sawdust may be added to sewage sludge (Palosz, 2009; Dach, 2010; Kuś, 2015). After the introduction of organic additives into the soil or soil substrates, C:N ratios close to the optimum were obtained for about 1–2 years (Bęś et al., 2005; Wiater, 2020). Moreover, soils with higher organic carbon content have a higher potential for nutrient mobilization. Based on the obtained results of the C:N ratio in the tested samples (sewage sludge – 7.37:1, lignite – 102.1:1), it seems appropriate to continue experiments in which the effect of the addition of a mixture of sewage sludge and lignite to the volcanic mineral soil substrate for green roofs on the yield of, for example, red fescue (*Festuca rubra* L. 'Dipper') will be analysed, and the duration of the experiment will be extended.

## CONCLUSIONS

The results obtained in the present experiment indicate that the use of sewage sludge as a green roof substrate additive can clearly increase the green roof biomass yield by 94.6% and 64.0% of red fescue (*Festuca rubra* L. 'Dipper') dry matter (in the 10%SS and 20%SS variants, respectively) compared to the control sample, although the relationship was statistically insignificant. However, a clear (by 30.5%) and statistically significant decrease in dry matter yield of red fescue (*Festuca rubra* L. 'Dipper') was observed for the highest addition of sewage sludge (30%SS). The decrease in yield in this variant may have been caused by increased salinity of the samples associated with the application of a triple dose of sewage sludge (sewage sludge salinity Table 5), which may have impeded the uptake of water by the plant by and reduced biomass growth.

With the addition of lignite, there was a decrease in the green matter yield of red fescue (*Festuca rubra* L. 'Dipper') compared to the control sample by 1.5% (at 10%L), 20.0% (at 20%L,), and 24.2% (at 30%L). This may be due to the highly acidic reaction of lignite (pH KCl 3.8, pH $H_2O$ 4.5), the addition of which may have contributed to lowering the reaction of the volcanic mineral substrate for green roofs to values unfavourable to plants as well as to the wide C:N ratio of lignite (102.1:1) contributing to the occurrence of processes unfavourable to plants, such as slowing down the decomposition of organic matter, the uptake of nitrogen from the soil by microorganisms carrying out this decomposition, and the permanent immobilization of mineral nitrogen (ubiquitination, nitrogen clumping), leading to a nitrogen deficit for plants.

The research hypothesis was confirmed for the variants with the addition of 10% and 20% sewage sludge to the volcanic soil substrate, where an increase in biomass yield was obtained. In the variants with the addition of 30% sewage sludge, and 20% and 30% lignite, the research hypothesis should be rejected, as a clear decrease in biomass yield was recorded compared to the control sample. Undoubtedly, the limitations of the experiment carried out were its laboratory scale, which may have influenced the lack of statistical significance of some correlations, or the discrepancy of some of the results obtained. Therefore, the results obtained at the laboratory microscale need to be verified at the meso- or macro-field scale, the period of the experiment should be extended to a minimum of 2 years, and a variant of the addition to the volcanic mineral substrate for green roofs in the form of a mixture of sewage sludge and lignite should be introduced. The literature review shows that few similar studies have been conducted on green roofs. The attention of researchers has focused on the impact of sewage sludge additives or biocarbon in agricultural crops. Therefore, this may be a reason to continue research in the context of green roofs.

The use of sewage sludge as an additive to improve the macronutrient content of soil substrates for green roofs can be one of the elements of sustainable resource management and waste management, especially in industrialized and urbanized areas. In addition, more frequent use of green roof technology in urban areas is one way to reduce the negative effects of global climate change, manifested, among other things, by the urban heat island phenomenon. Developing the optimal soil substrate mixes may be of interest to green roof designers and contractors, substrate manufacturing companies, as well as wastewater treatment plant managers. Therefore, one may conclude that further research in this area carries high application potential.

The conducted research allowed the authors to formulate the following detailed conclusions:

1. The enrichment of the tested volcanic mineral substrate for green roofs with a 10% and 20% addition of sewage sludge contributed to an increase in the biomass yield of red fescue (*Festuca rubra* L. ‘Dipper’) by 84.3% and 51.1% of green matter and 94.6% and 64.0% of dry matter, respectively, compared to the control sample, but increasing the dose of sewage sludge to 30% resulted in a decrease in the biomass yield of fescue by 33.9% of green matter and 30.5% of dry matter.
2. The addition of lignite to the volcanic mineral substrate for green roofs contributed to a decrease in the yield of red fescue (*Festuca rubra* L. ‘Dipper’), particularly evident in the green roof, where, as the dose of lignite increased, the yield decreased relative to the control (by -1.5% (10%L), -20.0% (20%L), -24.2% (30%L)), most likely due to the unfavourable ratio of C:N recorded in the applied lignite (102.1:1), contributing to permanent immobilization of mineral nitrogen, which, in turn, led to a nitrogen deficit for plants, and the low pH of the lignite (pH KCl 3.8).
3. The unfavourable C:N ratio, in the case of lignite (102.1:1) resulting from high carbon content (36.35 g × $kg^{-1}$) with nitrogen content (0.36 g × $kg^{-1}$), and in the case of sewage sludge (7.37:1) resulting from high nitrogen content (3.77 g × $kg^{-1}$) with carbon content (27.82 g × $kg^{-1}$), can be improved by creating a mixture of lignite and sewage sludge in empirically or experimentally determined ratios. On the other hand, the effect of low lignite reaction can be reduced, for example, by liming.


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