

## Article

# From Wastewater to Soil Amendment: A Case Study on Sewage Sludge Composting and the Agricultural Application of the Compost

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## Abstract

The treatment of wastewater and the utilization of the by-products of these processes are an important part of the circular economy. The sewage sludge, a result of wastewater treatment, could be used as a material for plant nutrient supply and/or soil-improving products. The city of Nyíregyháza, Hungary, with 120,000 citizens, has a well-planned water treatment plant operated by Nyírségvíz Ltd., which, in cooperation with the Research Institute of Nyíregyháza, developed a municipal sewage sludge compost (SSC). The closed loop of sewage water treatment and the agricultural utilization of its by-product has been developed and managed. The compost product called Nyírkomposzt was planned for acidic sandy soils. Beyond the agronomic benefits, the sustainable and environmentally sound utilization of SSC reduces sewage sludge disposal. This active involvement of a water utility company demonstrates the potential of cross-sectoral cooperation in solving environmental problems. The quality of the compost fits the Hungarian legislation. To study the effects of 0, 9, 18, and 27 t ha<sup>-1</sup> doses of compost on acidic sandy soil, a long-term small plot experiment was started in 2003. The cumulative effects of the regular (every third year, last treatment before sampling in 2021) application of the SSC showed positive changes in basic soil properties, depending on the doses used. Increasing values were found in the case of pH from 4.5 to 6, plant available P<sub>2</sub>O<sub>5</sub> from 240 to 690 ppm, and plant available K<sub>2</sub>O from 180 to 200 ppm. The plant-available zinc and copper content also increased. Soil organic matter and total N content stabilized at around 0.9% and 0.08%, respectively. The grain yields of winter rye also increased in both investigated years. The yields of 18 t ha<sup>-1</sup> treatment were about two times higher compared to the control, but only in 2022 was the difference significant. Our findings underscore the potential of well-planned SSC applications to improve the fertility of ploughed, acidic sandy soil, taking into account the theory of the circular economy by utilizing wastes and decreasing landfilling.

**Keywords:** wastewater treatment; sludge valorisation; acidic sandy soil; nutrient source; soil improvement; long-term experiment; sustainable agriculture; circular wastewater management



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## 1. Introduction

Due to circular farming, efficient energy management, nutrient supply, reduction in fertilizer dependence, and mitigating the effects of climate change, the use of sludge produced in urban wastewater treatment plants is becoming more and more important. In Hungary, a reduction in the number of settlements without a public wastewater collection system results in a larger amount of sewage sludge, the disposal of which causes serious problems for the operators. In 2023, the amount of treated wastewater (571 million m<sup>3</sup>) was more than a quarter of the water mass of Hungary's largest lake, Lake Balaton. Hungary supports the recycling of useful substances available in sewage sludge as nutrients under strict criteria in order to protect the environment, mainly the soils. The safe use of sewage sludge and controlling the quality of the final compost product are essential.

According to the latest Eurostat data for 2022, 248.08 thousand tons (in dry substance) of sludge were produced in urban wastewater treatment plants in Hungary, which is 45.5% more than the 2013 data. In 2022, 88% of the generated sludge were disposed of, 10.82 thousand tons of sludge was used for agricultural purposes, 193.34 thousand tons of sludge were used as compost and for other applications, while 2.76 thousand tons were landfilled [1].

In Hungary, during the year 2023, out of the total treated wastewater exceeding 500 million m<sup>3</sup>, 0.06% underwent mechanical treatment only, 7.83% received secondary biological treatment, while the majority, accounting for 92.11%, was subjected to a tertiary level of treatment [2].

In the city of Nyíregyháza, 100% of the generated municipal sewage is treated at a tertiary level. Annually, 16 thousand tons of dewatered sludge occur, of which, along with the added straw, 33% shrinks to its original volume. This amount is treated as the initial sequence of the compost product called Nyírkomposzt, which can be utilized in agriculture according to an easier permitting process because of its composition. This material is optimal for recultivation purposes as well.

A large number of settlements with less than 2000 inhabitants lack sufficient public urban utilities due to the unfavourable structure. An intense development of municipal wastewater drainage and treatment began in the early 1990s, targeting these support systems. The key indicator of this process is the so-called wastewater treatment index. In Hungary, this index decreased from 79.8% in 2000 to 21.4% by 2020. This trend positioned the country in the mid-range within the European Union member states [3], hence suggesting a high level of municipal wastewater treatment plant operations. Various methods are known for utilizing the large amount of sludge generated at wastewater treatment plants, keeping in mind the principles of the waste minimization and waste management. Each country applies its own strategy based on costs and opportunities.

Due to the deterioration of soil quality, agriculture increasingly needs materials that improve, restore, or maintain soil structure, water balance, and organic matter content [4]. Soil organic matter has great importance in the formation of buffer capacity, nutrient supply, soil structure, water dynamics, and biological properties of the soil. Soils with inherently low organic matter content, such as sandy soils, are often confronted with poor soil structure, low nutrient-holding capacity, decreased microbial activity, lower input efficiency, and reduced soil resilience [5]. According to numerous studies, sludge application is a useful strategy to increase soil carbon sequestration among the existing soil and nutrient management practices and cover crop utilization [6,7].

Through rising fertilizer prices and the Green Deal policy of the European Union, the circular economy encourages the reduction in mineral fertilizer use and its replacement with nutrients from organic sources [8]. The decrease in Hungary's cattle industry reflects political transitions, adaptation to European Union policies, and recent global market

shocks affecting fertilizer prices and, consequently, the cost of animal feed; therefore, sewage sludge appears to be a viable alternative to farmyard manure. Over the past two decades, Hungary's cattle herd changed year by year. According to the report of the Hungarian Statistical Office, there was a decline in the number of animals from 805,000 in 2000 to 682,000 in 2010, which means a 15% decrease within a decade, but after that time, the number continuously increased to 2024 with 861,000 [9]. The sewage sludge compost (SSC) utilization is also supported by increasing costs of fertilizers. The SSC can be a potential substitute for mineral fertilizers due to its rich macro- and micronutrient content and organic matter [10].

Concerns regarding the long-term use of SSC due to heavy metal accumulation, microplastics, pharmaceutical residues, and possible pathogenic contamination hinder its widespread acceptance [11,12].

The landfilling and disposal of biosolid waste, which is generated in significant quantities at sewage treatment plants, is causing an increasing problem. Apart from incineration, deponation, or energy recovery, one of the ways is to apply it to the soil for agricultural purposes after proper stabilization [13], which is the most favourable solution from a social point of view. To produce a high-quality, beneficial compost product, the method used should be carefully optimized and managed to control the fundamental factors like the adequate nutrient content, carbon-to-nitrogen ratio, temperature, oxygen supply, moisture content, particle size of the compost, microbial activity, and time [14]. The material produced in this way contributes to improving and maintaining the physical, chemical, and microbiological properties of the soil.

Product-classified compost is a useful resource in circular agronomy [15]. The sewage sludge produced during sewage treatment contains useful substances—apart from the factors preventing its utilization—such as sludge water, crushed mineral particles, organic substances, nutrients, and trace elements [16]. The agricultural use of stabilized sewage sludge has already been regulated, and it is used as part of an economical agricultural practice in many countries [17]. In Hungary, several regulations provide the legal background for the agricultural utilization of sewage sludge, including the upper limit of potentially toxic elements in the soil and the treatment of wastewater and sewage sludge. Moreover, some other micropollutants could be present in the sewage sludge and its compost, like pharmaceuticals, hormone-like materials, and microplastics, but for these pollutants, there are no limit values in the Hungarian rules.

Humic substances formed during composting have a positive effect on root growth and the nutrient uptake of plants [18,19]. Organic nutrient supplements obtained from sewage sludge are among the products with a slow release of nutrients [20]. The compost application has long-term beneficial effects; the nutrients are released from it gradually and slowly [21].

In Hungary, the area of sandy soils is 1.2 million hectares. About half of it is calcareous sandy soil, while the other part is acidic sandy soil. In the Nyírség region, 400,000 hectares of acidic sandy soils are located with unfavourable heat, water, air, and nutrient management. These soils dry out quickly; their ability to retain water and nutrients is also inadequate, and their availability of phosphorus is determined by  $\text{Al}^{3+}$  and  $\text{Fe}^{3+}$  ions [22]. Previously, the mineral fertilizer was applied in high quantities in Hungary because of its easy access at low prices, resulting in the continuous decrease in the originally acidic pH of the soil. Poor sandy soils need improvements to enhance their physical, chemical, and biological properties [23]. The SSC seems to be a good possibility for this purpose, but its effect highly depends on its quality as well as the soil type [24].

The SSC has a particularly favourable effect on soils with low plant available phosphorus (P) content, as they play a role in mobilizing nutrients as a functional microbial resource [25]. Other study reported increases in crop yield, soil respiration, and microbial activity after the application of SSC [26]. Municipal sewage sludges treated in different ways have favourable effects on soil enzyme activity due to the extra- and intracellular enzyme content of the added substance and owing to the increased colloidal, mineral, and organic components [27]. Moreover, the SSC has a dose-dependent effect on soil P-cycle related enzyme activity [28]. Da Silva et al. (2021) [29] conducted experiments with chemically stabilized and composted sludge. Their findings showed their beneficial effect on soil and plant nutrient supply, despite their different effects on soil characteristics, mineral composition, and corn yield. The short-term application of SSC enhanced the availability of essential nutrients, changed microbial abundance and diversity, and improved soil fertility [30]. Moreover, the SSC contains all the micro-elements necessary for plant growth [31]. Our earlier results proved the favourable effects of SSC on soil structure and water balance [32]. Despite the positive effects of using SSC in agriculture, the possible negative impact on soil and plants must be considered and monitored when determining the dosage and duration [33], and the local regulations must be followed.

The aims of this article were to describe the sewage water treatment process of a Hungarian city and the applied methods of sewage sludge composting and to present the agricultural utilization of the produced compost. The soil texture of the Nyírség region results in high physical degradation processes of acidic sandy soil with low water storage capacity. These properties decrease the agronomic value of sandy soil which needs improvements. We hypothesized that the applied compost product has positive effects on the nutrient and organic matter content of acidic sandy soil, and on winter rye yield after its long-term application. Therefore, our objectives were to (i) present the sewage treatment and composting processes, (ii) study the changes in some soil chemical properties in a long-term SSC experiment, (iii) measure the yield of rye as a test plant in the long-term SSC experiment, and (iv) analyze the soil-plant results of two different years after the sixth application of the SSC.

## 2. Materials and Methods

### 2.1. Wastewater Quality and Quantity in the City of Nyíregyháza

The city of Nyíregyháza has approximately 120,000 residents. Two major wastewater treatment plants co-exist: Plant Number 1 and Plant Number 2, with a 133,000 and 90,000 population equivalent (PE) theoretical maximum capacity, respectively. The compost manufacturing process takes place at a nearby site of Plant No. 1. This is located in the vicinity of the agricultural test field, precisely on the other side of the road. Both treatment plant sludge are transferred to this composting site (Figure 1).

Both Plant No. 1 and No. 2 have anaerobic digestion for sludge stabilization and produce biogas that feed engines in order to generate green electricity. The later dewatered sludge functions as a primary source for composting material. The two plants function as conventional activated sludge technology. The utility company of Nyírségvíz Ltd. operates region-wide; hence, occasionally, smaller treatment plants with similarly dewatered sludge may transfer their products to the composting site. Proportionally, the quantity of this input material is comparably low. To clarify, for scientific purposes, we always create separate prisms, and these are only formed from the dewatered sludge of Plant No. 1. Hence, we avoid principal constitution differences between the Plants' sludges.



**Figure 1.** Locations of the Wastewater Treatment Plant No. 1, the Composting Facility, the long-term sewage sludge compost experiment, and the UD, IAREF, Research Institute of Nyíregyháza. Google Earth Nyíregyháza region satellite image, <https://earth.google.com> (accessed on 20 May 2025).

## 2.2. Quality and Quantity of the Wastewater in the Plant No. 1 Nyíregyháza Treatment Procedure

Plant No. 1 is located in the northern part of the city of Nyíregyháza. The main characteristics of the sewage are based on the year 2021. In that year, the last compost application occurred before the discussed results from the long-term experiment. The daily average influent quantity in Plant No. 1 was 13,250 m<sup>3</sup>. The general parameters averaged according to the following conditions: NH<sub>4</sub>-N: 79.2 mg L<sup>-1</sup>, total nitrogen (TN): 96.1 mg L<sup>-1</sup>, chemical oxygen demand (COD): 836 mg L<sup>-1</sup>, 5 days biological oxygen demand (BOD<sub>5</sub>): 530 mg L<sup>-1</sup>, total suspended solids (TSS): 358 mg L<sup>-1</sup>, total phosphorus (TP): 14.4 mg L<sup>-1</sup>, and pH: 7.47.

The secondary sludge, along with the digester reject water, is fed into the raw sewage recipient shaft and the liquid municipal waste, which also connects to this point. From here, the sewage travels through a grit chamber and is latter lifted onto the sand filter. After removing the artificial solid matter, the primary settling with three parallel-operated Dorr-designed settlers starts. The primary and secondary sludge are removed in this single event. The effluent raw sewage is then transported to a single large, track-shaped denitrification reactor with a nominal volume of 6000 m<sup>3</sup>. Afterwards, the sewage is split into three parallel-operated aerating reactors, each with a capacity of 2000 m<sup>3</sup>. At the end of these reactors, the desired amount of treated water, functioning as an internal small recirculation, is relocated to the denitrification reactor. The rest of the treated water is coursed to the four secondary final settling reactors

## 2.3. Sludge Treatment and Composting

The primary and secondary sludge are mixed and pre-thickened with polymers to enter the two digester towers, each with a volume of 1800 m<sup>3</sup>, in the form of 6% dry matter content. The organic content is effectively converted into biogas within 22 days of residence at 33 °C in a mesophilic environment. Finally, the excess sludge was partially degassed and dewatered through high-performance centrifuges utilizing polymers. The final form of sludge, with around 20% dry matter content, is collected into four m<sup>3</sup> volume containers and transported to the compost manufacturing site. Since 2006, the plant has been augmented with additional sludge feed intake. This allows us to balance the amount of sludge in the digestion process. From region-wide to small municipal wastewater treatment plants with low dry matter content dewatered sludge is involved throughout

the pre-thickening process. The tower feed proportion is around 75% internal source (Nyíregyháza) and 25% external source.

The composting process involves 200 kg of dry winter wheat straw for every ton of dewatered sludge. The transformation occurs while the prisms are mixed in every interval throughout the optimal 28 days.

The entire process consists of four phases. In Phase I, the initial dewatered sludge is covered with straw and starts at a mesophilic temperature of 35 °C. It lasts around 1–2 days and is mixed regularly with BACKHUS 17.55 heavy-duty machinery (Eggersmann GmbH, Wardenburg, Germany). In Phase II, the temperature gradually increases to 70–75 °C; as a consequence, the process enters a thermophilic range. Depending on the quality of sewage and sludge, this stage can last from two to five weeks. Mixing occurs twice a week. In Phase III, as the available organic content starts to limit bacterial growth, the process falls back to the mesophilic range of 40–45 °C, and mixing occurs only once a week. Depending on the transformation rate, this stage can last from two to four weeks. In the final Phase IV, an active cooldown period starts and lasts for two to three weeks. Microfauna appears as the stabilizing process is nearly finished.

#### 2.4. The Quality of Compost Used in the SSC Experiment

The used composted sewage sludge was developed jointly by the Soil Biological Laboratory of the Research Institute of Nyíregyháza and the local water utility company, Nyírségvíz Ltd. The quality of the produced compost meets all standards for commercial agricultural use, marketed under the brand name Nyírkomposzt. The compost contains 40% (m/m) sewage sludge, 20% (m/m) winter wheat straw, 35% (m/m) rhyolite, and 5% (m/m) bentonite.

The 6th SSC application in the long-term experiment was conducted in the autumn of 2021. The main parameters of the SSC applied in 2021 were as follows: pH 6.9, total organic matter 24.6%, total nitrogen 16,000 mg kg<sup>−1</sup> (dry matter, d.m.), total phosphorus 26,800 mg kg<sup>−1</sup> (d.m.), total potassium 3994 mg kg<sup>−1</sup> (d.m.), zinc 184 mg kg<sup>−1</sup> (d.m.), and copper 41 mg kg<sup>−1</sup> (d.m.). The measured values met the requirements of Hungarian and European regulations of product composts. The wastewater treatment plant, composting, and compost utilization are shown in Figure 2.



**Figure 2.** Steps of wastewater treatment and compost utilization. Wastewater treatment Plant No. 1 (a), Composting Facility (b–e), sewage sludge compost application (f), control and 27 t ha<sup>−1</sup> treated plots (g), rye biomass (T1: 0 t ha<sup>−1</sup>, T2: 9 t ha<sup>−1</sup>, T3: 18 t ha<sup>−1</sup>, and T4: 27 t ha<sup>−1</sup>), and root biomass (h,i).

## 2.5. Long-Term Field Experiment

The basic goals of the experiment were to (1) model whether municipal SSC can be used to replace the decreasing amount of farmyard manure or the mineral fertilizers, which would be relevant for farms using conventional tillage management techniques, and (2) monitor the change and progress of the impact of long-term, regular compost application.

The long-term SSC field experiment was established in 2003 and rearranged in 2006, at the experimental research farm of the Research Institute of Nyíregyháza of the University of Debrecen, Nyíregyháza, Szabolcs-Szatmár-Bereg County, on soil type Dystric Arenosol, Aric, Cordic, according to the World Reference Base for Soil Resources [34]. The experiment geographical coordinates are 47°59′19.4″, 21°42′10.3″ E, 106 m above sea level.

The soil texture of the experimental site is sandy, containing 87.7% sand, 2.8% silt, and 9.6% clay. The regular SSC application improved the soil water infiltration capacity and decreased the surface erosion of treated plots [32].

Based on the nitrogen (N) content of the SSC, the applied doses were 0, 9, 18, and 27 t ha<sup>-1</sup>. In 2021, the SSC treatment was conducted on October 7th, after the maize harvest. Other nutrient supply was not applied in the studied 2022–2024 period. The control plots received neither SSC nor chemical fertilizer. The SSC doses were ploughed into the 0–25 cm soil layer every 3<sup>rd</sup> year, in five replications (blocks). The experiment includes 60 plots (twelve in each block), and the size of each plot is 12 m × 19 m. The gross area of the experiment is 1.4 ha, which is a big area and results in the relatively high standard deviations of the studied parameters because of the natural heterogeneity of the soil. Three test crops were sown annually in crop rotation from the beginning of the experiment. Plants included in the rotation were triticale (*Triticosecale* Wittm.), green pea (*Pisum sativum* L.), and maize (*Zea mays* L.) until 2017, while winter rye (*Secale cereale* L. ‘Varda’), winter rye with hairy vetch (*Secale cereale* L. ‘Varda’ and *Vicia villosa* L. ‘Hungvillosa’), and maize (*Zea mays* L. ‘Torino’ F1) were from 2018. Winter rye was sown on 12 October 2021 and 5 October 2023, while harvests took place on 7 July 2022 and 8 July 2024. Sowing was performed with a Pöttinger Vitasem 302 seed drill, using a row spacing of 120 mm and a seeding rate of 200 kg ha<sup>-1</sup> (PÖTTINGER Landtechnik GmbH, Grieskirchen, Austria). The location and experimental design are shown in Figure 3.

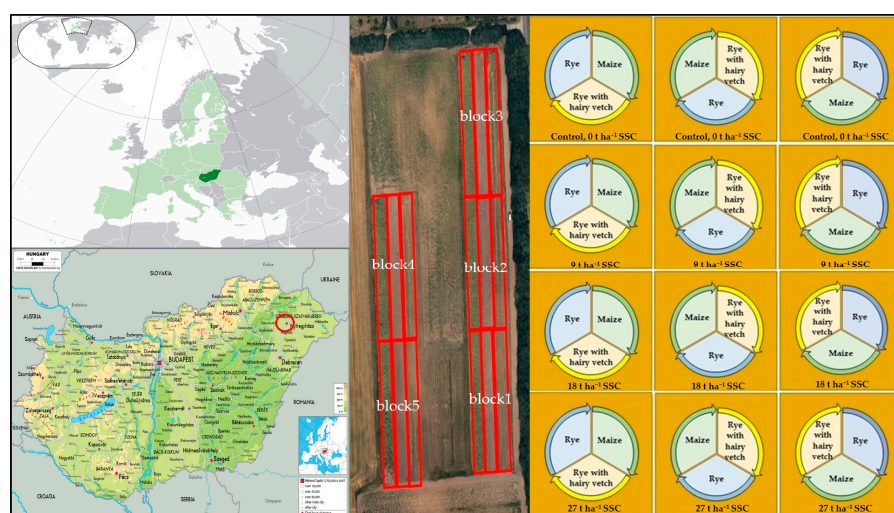


**Figure 3.** Location of the sewage sludge compost long-term experiment, the experimental setup, and block layout. In the red circle (bottom left), Nyíregyháza is highlighted, located in North-East Hungary. Squares in the landscape view (centre) represent the five blocks of the SSC experiment. One block is a 36 × 19 m, 36 × 7 m path with crops between each block. Block layout map illustrated with yearly crop rotation (right).

The basic information (history, design, soil type and properties, climate type and properties, crops, and designed periods) about the long-term SSC experiment of the Research Institute of Nyíregyháza, IAREF, University of Debrecen, can be found on the website of Global Long-Term Agricultural Experiment Network of Rothamsted Research (<https://glten.org/experiments/166>, accessed on 20 May 2025).

## 2.6. Meteorological Conditions

The meteorological data of the investigated area were recorded every two minutes by a  $\mu$ -Metos meteorological station (Pessl Instruments GmbH, Weiz, Austria) in the area of the Research Institute.

Figure 4 illustrates that the year 2023 recorded the highest annual precipitation within the observed period, with a total of 716 mm, compared to only 466 mm in 2022. An analysis of the monthly precipitation distribution reveals that June was the rainiest month in both 2023 and 2024, followed by the autumn months. In contrast, during the drier year of 2022, the highest monthly precipitation occurred in September and December.

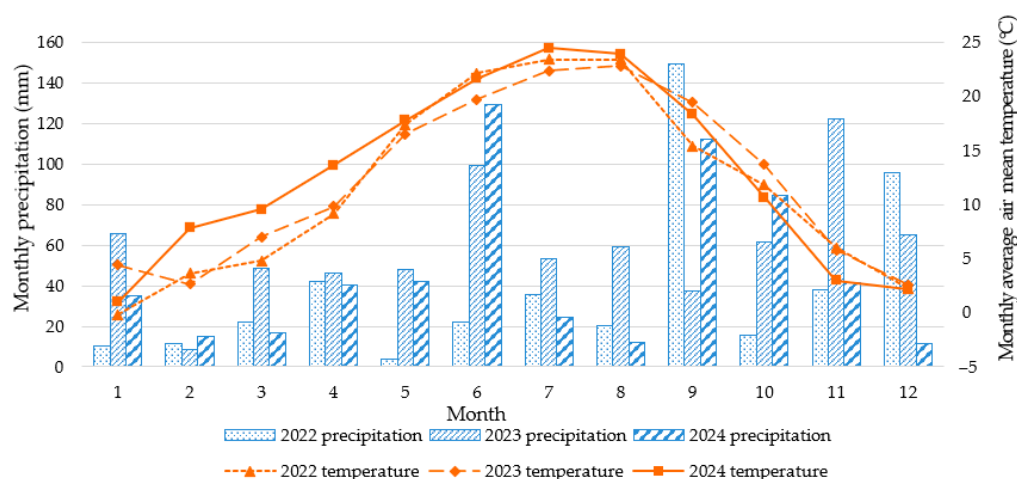


**Figure 4.** Changes in monthly precipitation and monthly average air temperature of the investigated region in 2022–2024.

Regarding air temperature, the annual mean temperature showed a continuous increase from 2022 to 2024. While the mean temperature was 11.6 °C in 2022, it rose to 12.8 °C by 2024. In all three years, the period from June to September was consistently warm.

## 2.7. Soil and Plant Sampling

Soil samples were taken after the rye harvest in 2022 and 2024, following the 6th SSC application in 2021. Composite soil samples from each plot were collected from the 0–20 cm soil layer. Samples for chemical analysis were air-dried and stored at room temperature. Before the measurements, samples were sieved ( $\varnothing$  2 mm). Plant samples were collected from four separate 1 m<sup>2</sup> sampling areas from each plot for yield measurement. The collected plant samples were threshed using a WINTERSTEIGER LD 180 laboratory thresher designed for small plant samples (Wintersteiger Holding AG, Ried im Innkreis, Austria). The measured grain yield was calculated for t ha<sup>−1</sup>.

## 2.8. Soil Chemical Analysis

Soil pH was measured in a 1:2.5 soil:1 M KCl suspension [35] with a WTW inoLab pH 7310P digital pH meter (Xylem Analytics Germany Sales GmbH & Co. KG., Weilheim in Oberbayern, Germany). During the determination of the total water-soluble salt content, we measured the electrical conductivity of the soil paste saturated with water using a WTW

inoLab Cond 7310P conductometer (Xylem Analytics Germany Sales GmbH & Co. KG., Weilheim in Oberbayern, Germany) [35]. Soil organic matter (SOM) content was measured according to the Tyurin method [35]. The  $\text{NO}_3\text{-NO}_2\text{-N}$  content was determined according to the Griess–Ilosvay reaction, using an MLE5134G flow injection analyser (Medizin- und Labortechnik Engineering GmbH Dresden, Radebeul, Germany) [36]. The plant available phosphorus (P, presented as  $\text{AL-P}_2\text{O}_5$ ) and potassium (K, presented as  $\text{AL-K}_2\text{O}$ ) were determined according to the Hungarian National Standard No. 20135:1999 [37]. The samples were extracted for two hours using ammonium acetate lactate (AL) solution (0.1M ammonium lactate, 0.4M acetic acid, and pH 3.70) with a ratio of 1:20 soil to solution. Then, the extracted P was determined photometrically by the molybdenum blue method according to [38]. The K content was determined in the AL solution with a PerkinElmer PinAAcle 900H atomic absorption spectrometer (PerkinElmer Inc., Waltham, MA, USA) according to the Hungarian National Standard No. 20135:1999, sections 4.2.1. and 5.3 [37]. For the determination of the plant available zinc (Zn) and copper (Cu) content of the soil samples, the soil samples were extracted using a solution containing 0.05M ethylenediaminetetraacetic acid (EDTA) and 0.1M potassium chloride. The soil extractant ratio was 25 g to 50 mL, while the extraction time was two hours. After filtration, the Zn and Cu concentration was measured by a PerkinElmer PinAAcle 900H atomic absorption spectrometer (PerkinElmer Inc., Waltham, MA, USA) [37].

## 2.9. Statistical Analysis

Microsoft Excel 2023 software was used for datasheet preparation. Data were evaluated with the IBM SPSS v29 statistical package (IBM Inc., Armonk, NY, USA). Outlier data were removed before the statistical analysis. One-way ANOVA analysis was performed to study the effects of treatments, while the means of parameters were compared with Tukey's test. An independent sample *T*-test was used to compare the two studied years. The relationship among measured parameters was calculated with Pearson's correlation, performed using Past software v4.03 (Natural History Museum—University of Oslo, Oslo, Norway). All statistics were performed at the 0.05 level of significance.

## 2.10. Quality Control and Assurance

All chemicals and reagents used for the preparation as well as for the calibration of equipment were purchased from Merck Life Science Ltd., Budapest, Hungary. The purity of used reagents was puriss. or a.r. The electrode used for pH measurement was calibrated by two standard buffer solutions before the measurements at 20 °C:  $\text{C}_6\text{H}_8\text{O}_7/\text{NaOH}/\text{HCl}$  (pH 4) and  $\text{Na}_2\text{HPO}_4/\text{KH}_2\text{PO}_4$  (pH 7), with both of them directly traceable to primary SRM from NIST/PTB. The phosphorus estimation was measured using a PerkinElmer Lambda 25 UV/VIS Spectrophotometer (PerkinElmer Inc., Waltham, MA, USA) using the calibration curves of the standard solution ( $\text{KH}_2\text{PO}_4$ ). For the accuracy verification of multi-element (K, Cu, and Zn) determination by a PerkinElmer PinAAcle 900H atomic absorption spectrometer (PerkinElmer Inc., Waltham, MA, USA), the calibration curves of a standard solution were prepared and recorded ( $R^2 \geq 0.99$ ), and the average recovery was adjusted between 98.11 and 101.90%. The precision of the analytical methods was performed by repeating the samples five times (repeatability test) and expressed as the standard deviation (SD). In addition, precision specification was determined by calculating the relative standard deviation (RSD); the measurement set is considered to be precise if the RSD from the average of the set does not exceed 2%. Furthermore, all analyses were subjected to a laboratory control sample (LCS) for validation and were checked by the quality control charts.

### 3. Results

#### 3.1. Efficiency of the Wastewater Treatment

The operational status complies with the regulatory standards. The treated effluent water results can be summarized as follows:  $\text{NH}_4\text{-N}$ :  $1.76 \text{ mg L}^{-1}$ , TN:  $24.8 \text{ mg L}^{-1}$ , COD:  $29.6 \text{ mg L}^{-1}$ ,  $\text{BOD}_5$ :  $10.6 \text{ mg L}^{-1}$ , SS:  $11.5 \text{ mg L}^{-1}$ , TP:  $3.07 \text{ mg L}^{-1}$ , and pH: 7.45. Ferric (III)-chloride ( $\text{FeCl}_3$ ) is only added to enhance phosphorus (P) removal from October to June. In the summer season, the local Food Processing Facility (EKO Ltd., Nyíregyháza, Hungary) contributes enough surplus of easily degradable organic matter that can fuel excess biological P uptake in the aerobic reactors. As the organic matter load is the key factor for biological nitrate reduction and additional P uptake, removing unintended amounts with the primary settlers is compulsory to monitor. On the other hand, biogas yields are better from the primary sludge compared to the secondary. It is cardinal to find the proper adjustment to satisfy both demands.

#### 3.2. Sewage Sludge Compost Quality Requirements in Hungary

In Hungary, a fertilizer and/or an amendment product can be licensed and placed on the market. The licensing authority is currently the National Food Safety Authority, Plant, Soil, and Agri-Environmental Directorate. The Hungarian licensing system is the strictest one in Europe. The licensing procedure requires the results of physical and chemical properties, toxic elements and organic pollutants content, anti-germination and weed control effects, free from plant pathogens and pests, test of biological effect, hygienic microbiological tests, radiation biological test, or other ecotoxicological tests, depending on the nature of the used waste. All required tests must be carried out by an accredited laboratory. Since a yield-enhancing substance is introduced into the soil, it must be ensured that it is not harmful to human and animal health or to the environment. In Hungary, this compliance is ensured by Decree 36/2006 (V.18.) of the Ministry of Agriculture and Rural Development on the licensing, storage, distribution, and use of crop-enhancing substances [39]. This regulation classifies the yield enhancers into 11 categories, which differ in the materials used and quality standards.

The applied composted sewage sludge meets the requirements but is not authorized for use in organic farming (Table 1).

**Table 1.** Quality requirements for the applied product compost produced in Hungary, according to the Decree of 36/2006 (V.18.) of the Ministry of Agriculture and Rural Development, on the licensing, storage, distribution, and use of crop-enhancing substances. (d.m.—dry matter; CFU—Colony Forming Unit).

| Parameter                                     | Value      |
|-----------------------------------------------|------------|
| Bulk density ( $\text{kg dm}^{-3}$ )          | min. 0.9   |
| Dry matter (m/m%)                             | min. 50.0  |
| Organic matter (m/m%) in d.m.                 | min. 25    |
| pH ( $\text{H}_2\text{O}$ 10%)                | 6.5–8.5    |
| Water soluble salt content (m/m%) in d.m.     | max. 4.0   |
| Particle size composition <25 mm (m/m%)       | min. 100.0 |
| N content (m/m%) in d.m.                      | min. 1.0   |
| $\text{P}_2\text{O}_5$ content (m/m%) in d.m. | min. 0.5   |
| $\text{K}_2\text{O}$ content (m/m%) in d.m.   | min. 0.5   |
| Ca content (m/m%) in d.m.                     | min. 1.2   |
| Mg content (m/m%) in d.m.                     | min. 0.5   |

**Table 1.** *Cont.*

| Parameter                                                                                                                                                                                                                                                                                                                 | Value      |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| As content (m/m%) in d.m.                                                                                                                                                                                                                                                                                                 | max. 10.0  |
| Cd content (m/m%) in d.m.                                                                                                                                                                                                                                                                                                 | max. 2.0   |
| Co content (m/m%) in d.m.                                                                                                                                                                                                                                                                                                 | max. 50.0  |
| Cr content (m/m%) in d.m.                                                                                                                                                                                                                                                                                                 | max. 100.0 |
| Cu content (m/m%) in d.m.                                                                                                                                                                                                                                                                                                 | max. 100.0 |
| Hg content (m/m%) in d.m.                                                                                                                                                                                                                                                                                                 | max. 1.0   |
| Ni content (m/m%) in d.m.                                                                                                                                                                                                                                                                                                 | max. 50.0  |
| Pb content (m/m%) in d.m.                                                                                                                                                                                                                                                                                                 | max. 100.0 |
| Se content (m/m%) in d.m.                                                                                                                                                                                                                                                                                                 | max. 5.0   |
| Total polycyclic aromatic hydrocarbons (PAH) content (19 elements) (mg kg <sup>−1</sup> ) in d.m.                                                                                                                                                                                                                         | <1.0       |
| Benzopyrene content (mg kg <sup>−1</sup> ) in d.m.                                                                                                                                                                                                                                                                        | <0.1       |
| Aliphatic and aromatic petroleum hydrocarbon (TPH) (C5–C40) content (mg kg <sup>−1</sup> ) in d.m.                                                                                                                                                                                                                        | <100.0     |
| Total polychlorinated biphenyls (PCB) content (amount of PCB–28, 52, 101, 118, 138, 153, 180) (mg kg <sup>−1</sup> ) in d.m.                                                                                                                                                                                              | <0.1       |
| Total polychlorodibenzo-p-dioxins and polychlorodibenzofurans (PCDD/F) content (ng kg <sup>−1</sup> ) in d.m. T.E.Q.                                                                                                                                                                                                      | <5.0       |
| Fecal Coliform (CFU g <sup>−1</sup> or CFU mL <sup>−1</sup> )                                                                                                                                                                                                                                                             | <10        |
| Fecal Streptococcus (CFU g <sup>−1</sup> or CFU mL <sup>−1</sup> )                                                                                                                                                                                                                                                        | <10        |
| Salmonella sp. (in 2 × 10 g or mL)                                                                                                                                                                                                                                                                                        | negative   |
| Human parasitic worm (in 100 g or mL)                                                                                                                                                                                                                                                                                     | negative   |
| Free from foreign matter that cannot be introduced into the biological cycle, substances that inhibit germination or growth, seeds of quarantine weeds or their vegetative parts, infectious macro- and microorganisms that are harmful to human, animal, and plant health, toxic, polluting, and radioactive substances. |            |
| The biological efficiency should correspond to the effect guaranteed by the manufacturer.                                                                                                                                                                                                                                 |            |

### 3.3. Changes in Soil Quality

Chemical parameters of the first and last years of the three-year period of compost application are presented in Table 2. Both sampling time and the pH<sub>KCl</sub> of SSC-treated plots, which determines the availability of nutrients, increased to 5.49–5.97, which were higher by 19.9, 30.1, and 30.4%, respectively, than in the control plots in 2022 and increased to 5.59–6.24 in 2024 (26.2, 37.7, and 40.9% increase, respectively). The water soluble salt content was under the detection limit of 0.02% (m/m) in both sampling years, indicating that after 20 years of SSC application, the salt content of the soil had not increased. Soil organic matter content increased with the SSC rates to 0.65–0.77 (12.1, 27.6, and 32.8% increase comparing to the control) in 2022, while the SOM values of the treated plots were 0.65, 0.67, and 0.82, which were higher by 1.6, 4.7, and 28.1%, compared to the control in 2024. The plant available nitrogen concentrations varied in both years; their increase in the SSC-treated plots was not significant. Plant available phosphorus in soil strongly increased by three to seven times compared to the untreated plots, while the plant available K<sub>2</sub>O level of the soil changed modestly and was more pronounced in the highest rate (27 t ha<sup>−1</sup>). The study area was characterized by increased Zn and Cu content. These elements are

essential micronutrients for plants but can become toxic at high rates. The measured Zn and Cu values remained below the toxicity threshold after 21 years of SSC treatment.

**Table 2.** Chemical properties (mean  $\pm$  Standard Deviation) of sewage sludge compost (SSC)- treated soil in 0–20 cm soil depth in 2022 and 2024. Different letters indicate significant differences among treatments according to Tukey’s test ( $p < 0.05$ ).

| Parameter                                                  | 0 t ha <sup>−1</sup> SSC | 9 t ha <sup>−1</sup> SSC | 18 t ha <sup>−1</sup> SSC | 27 t ha <sup>−1</sup> SSC |
|------------------------------------------------------------|--------------------------|--------------------------|---------------------------|---------------------------|
| <b>2022</b>                                                |                          |                          |                           |                           |
| pH <sub>KCl</sub>                                          | 4.58 $\pm$ 0.10 a        | 5.49 $\pm$ 0.38 b        | 5.96 $\pm$ 0.16 b         | 5.97 $\pm$ 0.33 b         |
| Water soluble salt content (% m/m)                         | <0.02                    | <0.02                    | <0.02                     | <0.02                     |
| SOM (%)                                                    | 0.58 $\pm$ 0.19 a        | 0.65 $\pm$ 0.18 a        | 0.74 $\pm$ 0.04 a         | 0.77 $\pm$ 0.11 a         |
| NO <sub>3</sub> -NO <sub>2</sub> -N (mg kg <sup>−1</sup> ) | 5.25 $\pm$ 2.08 a        | 4.26 $\pm$ 0.38 a        | 5.99 $\pm$ 2.92 a         | 6.17 $\pm$ 2.60 a         |
| P <sub>2</sub> O <sub>5</sub> (mg kg <sup>−1</sup> )       | 94 $\pm$ 23.48 a         | 400 $\pm$ 29.83 b        | 455 $\pm$ 177.02 b        | 741 $\pm$ 62.27 c         |
| K <sub>2</sub> O (mg kg <sup>−1</sup> )                    | 122 $\pm$ 27.54 ab       | 112 $\pm$ 12.48 a        | 145 $\pm$ 34.48 ab        | 166 $\pm$ 32.34 b         |
| Zn (mg kg <sup>−1</sup> )                                  | 0.78 $\pm$ 0.79 a        | 5.14 $\pm$ 0.53 b        | 8.79 $\pm$ 2.33 c         | 11.40 $\pm$ 1.97 c        |
| Cu (mg kg <sup>−1</sup> )                                  | 1.02 $\pm$ 0.64 a        | 1.58 $\pm$ 0.50 ab       | 2.17 $\pm$ 0.37 bc        | 2.65 $\pm$ 0.29 c         |
| <b>2024</b>                                                |                          |                          |                           |                           |
| pH <sub>KCl</sub>                                          | 4.43 $\pm$ 0.22 a        | 5.59 $\pm$ 0.42 b        | 6.10 $\pm$ 0.32 bc        | 6.24 $\pm$ 0.36 c         |
| Water soluble salt content (% m/m)                         | <0.02                    | <0.02                    | <0.02                     | <0.02                     |
| SOM (%)                                                    | 0.64 $\pm$ 0.27 a        | 0.65 $\pm$ 0.04 a        | 0.67 $\pm$ 0.03 a         | 0.82 $\pm$ 0.21 a         |
| NO <sub>3</sub> -NO <sub>2</sub> -N (mg kg <sup>−1</sup> ) | 1.57 $\pm$ 0.28 a        | 5.02 $\pm$ 3.18 a        | 4.09 $\pm$ 2.06 a         | 5.83 $\pm$ 1.99 a         |
| P <sub>2</sub> O <sub>5</sub> (mg kg <sup>−1</sup> )       | 91 $\pm$ 32.29 a         | 263 $\pm$ 53.34 a        | 582 $\pm$ 83.34 b         | 737 $\pm$ 164.44 b        |
| K <sub>2</sub> O (mg kg <sup>−1</sup> )                    | 117 $\pm$ 7.23 a         | 111 $\pm$ 4.72 a         | 115 $\pm$ 11.39 a         | 174 $\pm$ 71.90 a         |
| Zn (mg kg <sup>−1</sup> )                                  | 0.84 $\pm$ 0.57 a        | 3.98 $\pm$ 0.24 a        | 8.68 $\pm$ 1.77 b         | 13.12 $\pm$ 2.78 c        |
| Cu (mg kg <sup>−1</sup> )                                  | 1.32 $\pm$ 0.72 a        | 1.73 $\pm$ 0.30 a        | 2.36 $\pm$ 0.27 ab        | 3.12 $\pm$ 0.67 b         |

Comparing the soil chemical parameters of the two studied years, the changes between 2022 and 2024 were not statistically proved according to the independent sample *T*-test (Table 3).

**Table 3.** Significance values of the *T*-test regarding the soil chemical parameters of the samples collected in 2022 and 2024 ( $p < 0.05$ ).

|                                                            | Levene Test<br><i>p</i> Value | <i>T</i> -Test<br><i>p</i> Value<br>(Two-Sided) |
|------------------------------------------------------------|-------------------------------|-------------------------------------------------|
| pH <sub>KCl</sub>                                          | 0.191                         | 0.781                                           |
| SOM (%)                                                    | 0.837                         | 0.685                                           |
| NO <sub>3</sub> -NO <sub>2</sub> -N (mg kg <sup>−1</sup> ) | 0.201                         | 0.113                                           |
| P <sub>2</sub> O <sub>5</sub> (mg kg <sup>−1</sup> )       | 0.236                         | 0.957                                           |
| K <sub>2</sub> O (mg kg <sup>−1</sup> )                    | 0.903                         | 0.717                                           |
| Zn (mg kg <sup>−1</sup> )                                  | 0.389                         | 0.936                                           |
| Cu (mg kg <sup>−1</sup> )                                  | 0.588                         | 0.231                                           |
| Grain yield                                                | 0.384                         | 0.694                                           |

### 3.4. Grain Yield of Rye

The crop yield changed from 1.01 t ha<sup>−1</sup> in control plots to 2.10, 2.50, and 2.44 t ha<sup>−1</sup> in the compost treatments, respectively, meaning 107.9, 147.5, and 141.6% increase in the treated plots in 2022. In 2024, the yield of control plots was 1.55 t ha<sup>−1</sup> while the treatments resulted in 1.57, 2.24, and 2.20 t ha<sup>−1</sup> yield, which means 101.3, 144.5, and 141.9% increases, respectively, compared to the control (Table 4). The highest values were obtained in both years in the treatment of 18 t ha<sup>−1</sup>, then a slight decrease was observed at the highest dose (27 t ha<sup>−1</sup>), suggesting a threshold of optimal use of the SSC.

**Table 4.** Grain yield of rye (mean  $\pm$  Standard Deviation) in a long-term sewage sludge compost (SSC) experiment in the sampling years of 2022 and 2024. SD means Standard Deviation. Letters indicate significant differences between treatments according to Tukey's test ( $p < 0.05$ ).

| Treatments                  | 0 t ha <sup>-1</sup> SSC | 9 t ha <sup>-1</sup> SSC | 18 t ha <sup>-1</sup> SSC | 27 t ha <sup>-1</sup> SSC |
|-----------------------------|--------------------------|--------------------------|---------------------------|---------------------------|
| <b>2022</b>                 |                          |                          |                           |                           |
| Yield (t ha <sup>-1</sup> ) | 1.01 $\pm$ 0.63 a        | 2.10 $\pm$ 0.70 b        | 2.50 $\pm$ 0.42 b         | 2.44 $\pm$ 0.33 b         |
| <b>2024</b>                 |                          |                          |                           |                           |
| Yield (t ha <sup>-1</sup> ) | 1.55 $\pm$ 0.50 a        | 1.57 $\pm$ 0.79 a        | 2.24 $\pm$ 0.66 a         | 2.20 $\pm$ 0.80 a         |

### 3.5. Relationships Between Soil Chemical Parameters and Rye Yield

Soil pH had a positive correlation with plant available phosphorus (0.76 in 2022; 0.84 in 2024), Zn (0.82 in 2022; 0.82 in 2024), and Cu (0.73 in 2022; 0.76 in 2024) in both studied years, while correlations with other soil parameters were not significant (Figure 5, Table S1). The organic matter content of soil also has a strong positive correlation with Cu (0.85 in 2022; 0.75 in 2024) and K<sub>2</sub>O (0.78 in 2022; 0.68 in 2024) in the two years studied. SOM had weak, significant, or non-significant correlations with other soil chemical parameters. The plant available nitrogen content had a weak, significant correlation with SOM in both years (0.59 and 0.57, respectively). Moreover, it had a positive relationship with the plant available potassium (0.75) and Cu (0.55) content in 2022 and with Zn content (0.75) in 2024. Strong positive correlations were identified between the plant available phosphorus content and soil pH in both years (0.76 and 0.84), and AL-P<sub>2</sub>O<sub>5</sub> had a positive correlation with the available potassium (0.74), Zn (0.94), and Cu (0.84) content of soil in 2022 while it correlated with 0.60, 0.98, and 0.89 in 2024, respectively. AL-P<sub>2</sub>O<sub>5</sub> and SOM were correlated only in the first year after the SSC application with a value of 0.56. Cu and Zn correlated positively with all the measured soil chemical parameters in the first year after the SSC application. In the third year after the treatment, the correlations between Zn and SOM and Cu and available N were not significant. Crop yield in 2022 was most strongly determined by soil organic matter (0.78) and copper content (0.86), while in 2024, it was the available nitrogen content (0.80). However, the crop yield was significantly positively correlated with almost all of the measured soil chemical parameters.

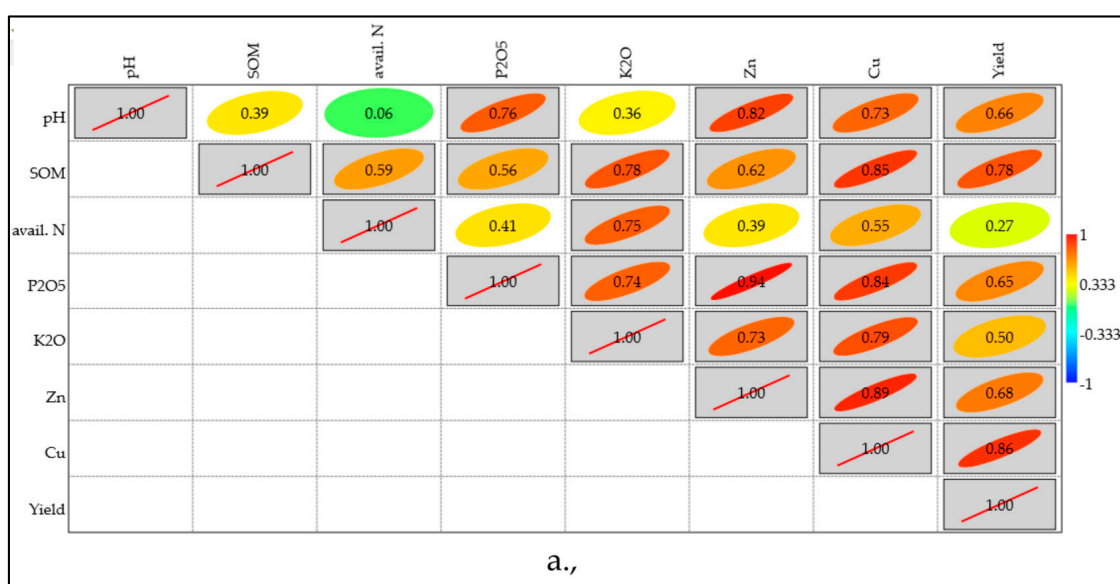


**Figure 5.** Cont.

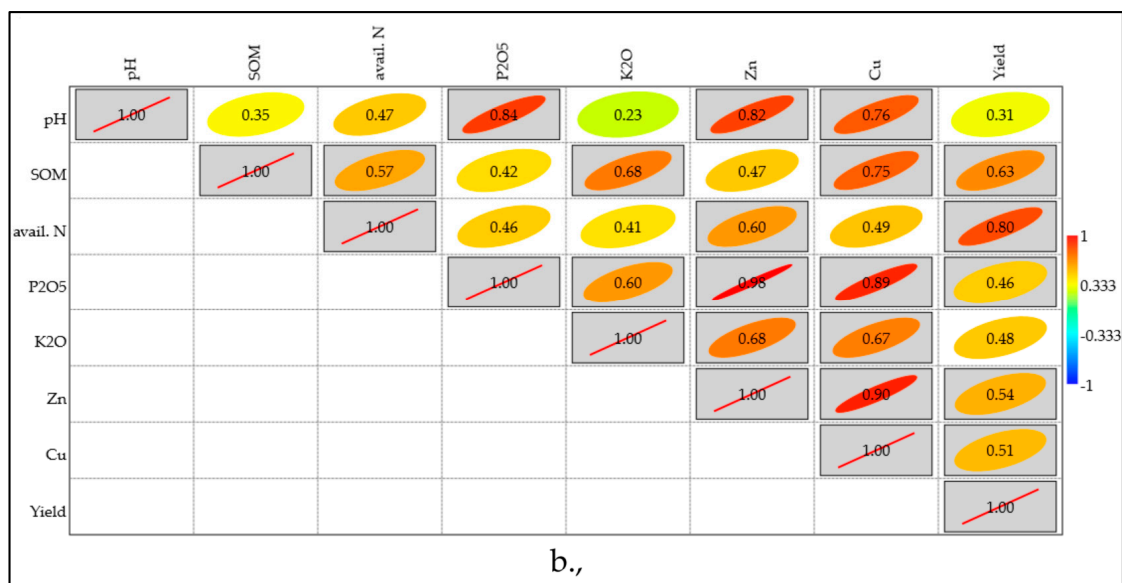


**Figure 5.** Pearson's correlation ( $r$  values) matrix between soil chemical parameters and grain yield of rye in 2022 (a) and in 2024 (b) after harvest. Numbers in the ellipses indicate the correlation coefficients. The shape of the ellipses and the different colours according to the colour scale indicate the strength of the variables' relationships. The angle of the ellipses indicates the direction of the correlation from the major axis. Boxed squares indicate the significance at  $p < 0.05$ . The numerical correlation matrix is provided as Supplementary Material.

#### 4. Discussion

The treatment of used and polluted water of settlements is a basic service for residents. This process could be managed in different ways depending on the local financial and environmental opportunities and on the knowledge/technological level of the provider. This study presented the integrated processes of wastewater treatment, sewage sludge treatment, and composting in the seventh largest city of Hungary, along with the subsequent agricultural utilization of the compost product.

##### 4.1. Water Treatment and and Composting Process

Conventional activated sludge technology is the most common process in Hungary to treat municipal sewage [40].

While this prevalence is consistent nationwide, sludge treatment and utilization practices vary. Although the National Sludge Guideline [41] recommends alternative disposal methods—such as incineration and recultivation—agricultural application remains dominant, making composting the most advantageous waste treatment approach. The guideline also highlights sludge digestion and energy recovery, particularly methane production, as a sustainable energy source.

Currently, the county has two sewage sludge digestion facilities, both operated by water utility companies in Nyíregyháza. Although initial plans proposed additional centralized digestion infrastructure across the county, these efforts were unsuccessful. The proposal also sought to improve the composting capacity. However, in the absence of such developments, treatment plants are compelled to meet regulatory requirements, with composting remaining the most feasible option.

The proposal for centralized digestion and composting infrastructure was not arbitrary. Water utility companies—whether governmental or private—typically site such facilities within a carefully selected radius, preferably under 50 kilometers. Meanwhile, the population equivalent (PE) serves as the second key determinant in sludge digestion implementation. However, the underlying material and financial calculations face numerous

constraints, often leading to overestimated requirements and unreliable projections. The literature suggests an optimal range of 30,000–50,000 PE [42], though significant exceptions and local contingencies frequently arise [43].

Composting methods vary significantly by technology, depending on operational inputs and desired product quality—examples include vermicomposting and solar pre-thickening [44]. The most desirable output is compost suitable for unrestricted agricultural use; any material failing to meet this standard is classified as regulated waste. Although Nakatsuka et al. (2010) propose a relevant waste recovery solution involving co-incineration with selected municipal waste—particularly applicable in industrialized regions [45]—both agricultural reuse and waste-to-energy approaches remain optimal only when source and application sites are geographically nearby.

#### 4.2. Agricultural Utilization of the Sewage Sludge Compost Product

The agricultural utilization of sewage sludge compost (SSC) has some pros [30,46,47] and cons [48]. The sewage sludge compost was specifically designed for application on the acidic sandy soils prevalent in Hungary's Nyírség region. To test the effects of the SSC, a long-term experiment was established in 2003, where the processes of soil taking place and the variations in plant development and yield can be studied after regular SSC application.

Soil pH is the central property of soil that determines the chemical and biological processes. Its most favourable value is around pH 7 [49]. The long-term application of SSC increased the pH of sandy soil from pH 4.5 to around pH 6 after 20 years of regular SSC application, indicating that this compost is suitable for the chemical improvement in the main soil type in the Nyírség region. The increase in soil pH in each treatment and year is especially beneficial in acidic sandy soils, where inadequate pH limits nutrient solubility and uptake. Moreover, it also affects the dissolution of toxic elements. The increased pH had a positive effect on the availability of several macro- and microelements to plants (P, Zn, and Cu), indicated by the strong positive correlation found, thereby improving plant nutrition.

Increased soil salt content destroys the soil structure [50], resulting in problems in aggregation and hydraulic properties. High salt content in the soil is an osmotic stress that has a detrimental effect on seed germination, plant water, nutrient uptake, and thus on their growth and their yield [51]. Our test results showed that the applied doses of sewage sludge compost did not cause any changes in the salt content of the soil (Table 2).

Soil organic matter (SOM) is the storage of plant nutrients, a habitat for soil microbes [52], and has an important role in good soil structure and water holding capacity [53]. Our long-term experiment proved that regular SSC application effectively maintained the SOM content in a ploughed agrotechnical system (Table 2). This is a very important effect because the main threat against soils is the decrease in organic matter, mainly in ploughed soils [54,55]. The correlation analysis showed that the compost was a good source of macro- and microelements (N, P, K, Cu, Zn) in the soil. However, in the third year after the last SSC application, its effect on P and Zn content was weaker than one year after the application (Figure 5). This correlation can be explained by the ability of SOM and micronutrients to form a chelate complex, preventing their leaching and increasing their utilization, affecting crop yield [56]. SOM increases the soil cation exchange capacity [57], determining the adsorption capacity of the soil and promoting slow release of nutrients. Formation of the SOM content is a long-term process; therefore, it is important to support its building and maintenance because it increases soil fertility and, therefore, crop yield [58]. The use of crop rotation in the experiment also contributes to the accumulation of organic matter.

Changes in soil N dynamics were not statistically significant among treatments and years due to microbial immobilization, ammonia volatilization, and N loss with harvesting,

soil particle size, or surface area [59,60]. One available form of N is the  $\text{NO}_3\text{-NO}_2\text{-N}$ , which was the only measured parameter with a relatively high variation in the control treatment in the two studied years (5.25 and 1.57  $\text{mg kg}^{-1}$ , respectively) (Table 2). Leaching of  $\text{NO}_3^-$  is mainly determined by the clay and organic matter content of soil [61]. Despite the variation in N content of soil, it plays a key role in soil fertility. The plant available N had the strongest impact on crop yield (0.80) in 2024. Increasing the SOM content of SSC-treated plots could decrease the  $\text{NO}_3^-$  leaching from the subsoil [62]. The variable role of N in yield over the two years suggested a more gradual, slower release of N content from SSC. This highlights the need for additional treatments like using cover crops or  $\text{N}_2$ -fixing plants which can coordinate N release and plants' N-demand in time.

Regarding the effect of SSC on soil nutrient dynamics, the greatest change was found in the plant available P content, which can be attributed to the high P content of sewage sludge. This high concentration of P can be a risk factor, especially in the case of an improperly chosen compost dose [63]. The main difference between SSC and animal manure compost is that SSC only increased the P content, while animal manure increased both the N and P content [64]. Potassium (K) plays an important role in enzymatic processes and osmoregulation, enhancing stress tolerance, nutrient, and metabolite transport [65]. Although most of the K is eliminated during the wastewater treatment procedure [66], the soil K content also increased with the treatments, although not significantly, with 48.7% in 2024 by the highest compost dose. The soil potassium content is determined by factors like the soil buffering capacity of clay minerals, plant uptake,  $\text{K}^+$  fixation and release, or leaching, while soil plant available K depends on several other factors [67].

Microbes have a central role in nutrient cycling, mainly with the production of exoenzymes for SOM degradation [68]. As our earlier results revealed, the microbes take part in the degradation of the organic matter of the applied SSC, indicated by increased  $\beta$ -glucosidase and alkaline phosphatase activity, parallel with decreasing acidic phosphatase activity. These results indicated the role of pH in enzyme activity and the increasing role of microbes in P mobilization from SSC with its increasing doses [28].

Copper (Cu) and zinc (Zn) are essential microelements for living organisms [69]. Their concentrations are generally low in acidic sandy soils, which are represented by the control plots (Table 2). The higher increase in Zn content of treated soil reflected the 3–10 times higher Zn content than Cu content of the applied SSC, depending on the quality of the applied compost. The concentrations of these elements in soil were stable in the studied years and their increasing concentrations in the treated plots did not exceed the toxicity threshold. Their correlation with each other suggests similar mobilization mechanisms with organic ligands or redox reactions [70].

The high standard deviations of grain yield were attributed to the natural heterogeneity of the soil in the 1.4-hectare experimental area, despite having five replications for each treatment. The year 2022 was a dry and hot year (yearly precipitation was 466 mm, yearly mean temperature 11.6 °C), which decreased the yield of rye in control plots where the SOM was the lowest one with the lower water holding capacity of soil [32]. This was the next year after the SSC treatment in 2021 that resulted in doubled yield mainly in 18 and 27  $\text{t ha}^{-1}$  treatments indicating the role of organic matter in dry periods [71,72]. The germination of winter rye in 2023 was supported by relatively high precipitation, followed by regular precipitation in the plant development phase in 2024. This weather condition resulted in higher plant yield in the control treatment, compared to 2022, but the yields of treated plots were a bit lower than in 2022, caused by the longer time after SSC treatment. However, rye is a cereal of soils with low nutrient content, but the good nutrient supply resulted in a 0.5–2 times higher yield than the control treatment [73]. The long-term application of SSC resulted in a significant improvement in crop yield, which was greatly increased

in all treatments. However, the optimal result achieved by the dose of  $18 \text{ t ha}^{-1}$  was not significantly higher than in the  $27 \text{ t ha}^{-1}$  treatment (Table 4). The optimal dosage effects on crop yield remain understudied in current agronomic research. The decrease in yield in the highest SSC dosage may underscore the importance of optimizing compost dosage rather than maximizing it, as several factors influence the effect of the treatment [74,75]. The findings by Zhang et al. [76] indicated that the agricultural impact of the sludge with various chemical treatments was most influenced by the amount used. Our study does not examine the agricultural effect of the pre-treatment process. Long-term experiments also have an important role in determining the optimum rates of SSC or other organic manures. Previous main crop, temperature, and a reliable water supply determine crop production. When winter rye is sown after corn, corn silage reduces the soil water supply [77]. The lower yield in 2022 compared to 2024 is also due to less water supply and lower temperature during the winter and spring period in the control plot. The influence of precipitation during plant development and yield formation is more important in winter cereals than in spring cereals. Since we do not apply any N supplementation in the experiment, the available N content of the soil is also an important factor in determining the grain yield. In 2024, the available N content was also lower in the  $18$  and  $27 \text{ t ha}^{-1}$  plots than in 2022. The lower yield in 2024 is supported by the available N content and crop yield  $r$  value (0.80). Comparing the soil chemical parameters of the two years (Table 3) showed that there were no significant changes in the values therefore, the results proved that application of SSC in every third year is a good way to keep the basic soil chemical parameters—except N—on a higher level than in the control treatment.

The Nyírkompeszt sewage sludge compost contains trace toxic elements, all below regulatory limits. Our previous soil and plant analyses [78] confirmed that these elements remained well under safe thresholds with minimal accumulation over time.

## 5. Conclusions

Wastewater treatment is the first stage of waste management. Its effectiveness depends on influent quality, technology, plant capacity, and available funding. The high quantity of sewage sludge that remains at the end of water treatment could be a valuable material for further treatment to produce products for agricultural purposes. The utilization of a waste-based product is in line with the theory of the European Green Deal. A good quality compost based on waste contains a high quantity of organic matter, which is a key component for soil health and fertility. To utilize sewage sludge compost as soil improving material could be a useful method against the main threat of soils: the decrease in the soil organic matter content. Our study proved that the long-term sewage sludge compost experiment on acidic sandy soil maintains the soil organic matter content and improves the soil chemical properties. It is very important because acidic sandy soil is a very sensitive soil type against degradation processes. Otherwise, strong threats are identified against the agricultural utilization of sewage sludge compost, which could be excluded by well-designed production and quality control processes. Based on the results of the more than 20 year-old Hungarian long-term sewage sludge compost experiment we concluded that regular utilization of a good-quality sewage sludge compost can maintain the level of organic matter in a ploughed acidic sandy soil and increase its pH and macro- and micronutrient content. The agricultural use of sewage sludge compost can decrease landfilling, promote agricultural sustainability, and reduce the need for mineral fertilizers, which are often costly or environmentally harmful. It is especially important in the case of phosphorus, whose natural sources are limited, but the sewage sludge compost contains it in high quantities.

Future research can focus on several points, including an economic analysis of phosphorus supply based on good-quality sewage sludge composts. Moreover, with the development of more specific analytical methods, different micropollutants (e.g., PFAs, pharmaceuticals, microplastics, PCBs, etc.) are in focus. Our long-term sewage sludge compost experiment is a perfect site to study the environmental fate of these micropollutants (if the applied SSC contains them). Most of these micropollutants can be destroyed by microbes, so studying the microbial community and their activity could give information about microbial adaptation to the micropollutants. In line with the One Health perspective, the more complex analysis of sewage water treatment, composting and the effect of agricultural utilization of compost product has to be performed, for which our long-term experiment will be a good reference site presenting the possible accumulation and leaching processes and adaptation of the microbial community to the possible pollutants.

**Supplementary Materials:** The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/w17132026/s1>, Table S1: Pearson’s numerical correlation (*r* values) matrix between soil chemical parameters and grain yield of rye.

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## Abbreviations

The following abbreviations are used in this manuscript:

|        |                                                           |
|--------|-----------------------------------------------------------|
| BOD5   | 5 days Biological oxygen demand                           |
| COD    | Chemical oxygen demand                                    |
| d.m.   | Dry matter                                                |
| IAREF  | Institutes for Agricultural Research and Educational Farm |
| LCS    | Laboratory control sample                                 |
| PAH    | Polycyclic aromatic hydrocarbons                          |
| PCB    | Polychlorinated biphenyls                                 |
| PCDD/F | Polychlorodibenzo-p-dioxins and polychlorodibenzofurans   |
| PE     | Population equivalent                                     |
| RSD    | Relative standard deviation                               |
| SD     | Standard deviation                                        |
| TSS    | Total suspended solid                                     |
| SSC    | Sewage sludge compost                                     |
| T.E.Q. | Toxic equivalency                                         |
| TN     | Total nitrogen                                            |

|     |                                              |
|-----|----------------------------------------------|
| TP  | Total phosphorus                             |
| TPH | Aliphatic and aromatic petroleum hydrocarbon |
| SOM | Soil organic matter                          |
| UD  | University of Debrecen                       |

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