JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2026, 27(1), 29–39
https://doi.org/10.12911/22998993/208824
ISSN 2299–8993, License CC-BY 4.0

Received: 2025.07.17
Accepted: 2025.09.05
Published: 2025.11.25

The content of mineral forms of nitrogen in light soil fertilized with various doses of sewage sludge

Grażyna Żukowska[1], Magdalena Myszura-Dymek[1*], Marta Bik-Małodzińska[1]

[1] Institute of Soil Science, Environment Engineering and Management, University of Life Sciences, Leszczyńskiego 7, 20-069 Lublin, Poland

* Corresponding author's e-mail: magdalena.myszura-dymek@up.lublin.pl

ABSTRACT

The article analyzed the effect of sewage sludge application on the content of total nitrogen and its mineral forms (NH_4^+, NO_3^-) in light cultivated soil, indicating the potential of sewage sludge as a source of nitrogen and the environmental risk associated with its excess. The study was conducted in a 3-year pot experiment. The light soil was fertilized with sewage sludge at fertilizer (10 Mg·ha^{-1}) and reclamation (100 Mg·ha^{-1}) rates applied alone and with the addition of mineral wool. The study showed that fertilizing light soils with sewage sludge, especially at a high doses combined with mineral wool, effectively increased organic matter and total nitrogen. The high total nitrogen content persisted throughout the study period. The dose of applied sludge had an impact on the content of mineral forms of nitrogen in light soil. The highest values of NH_4^+ and NO_3^- were observed in the soil fertilized with sludge reclamation dose. No significant increase in the proportion of mineral forms of nitrogen in its total content was observed. The addition of mineral wool in combination with sewage sludge further enhances the fertilizing effect, which can be practically used for the reclamation and enrichment of soils with low humus content.

Keywords: light soil, mineral forms of nitrogen, sewage sludge, fertilization doses.

INTRODUCTION

Among the environmental factors influencing the potential of agricultural production areas, soil and its properties are considered the most important. The quantity and quality of crops depend on the mutual arrangement of chemical, physical and biological properties of the soil. The properties of cultivated soils not only limit the profitability of agricultural production, but also affect the burden on the environment, especially surface water in the vicinity of agricultural crops (Hillel, 2012; Mocek, 2015). In Poland, the soils used for agriculture are predominantly acid-prone light and very light soils, which formed from carbonate-free post-glacial sediments. The lack of carbonates in the bedrock translates into soil pH. Soil chemistry assessments conducted as part of the Environmental Monitoring Program indicate that over two-thirds of Polish soils are acidic or strongly acidic. Another significant problem in Polish soils is the content of soil humus, which plays a key role in shaping the soil's ability to provide ecosystem services.

According to the division used in Poland, the soils with low humus content (below 2.0%) occupy approximately 33% of the country's agricultural land area. According to the European Soil Database (ESB), low and very low organic carbon content is found in approximately 45% of European soils, while only 5% have a high organic carbon content (Panagos et al., 2013). These soils are characterized by low fertility, unfavorable aeration and water retention properties, and require substantial inputs for fertilization and liming. According to the criteria established in international conventions, a soil organic matter content below 2% is considered an indicator of desertification (Grilli et al., 2021). The minimum organic matter content in light and medium soils, which predominate in Poland, should be at least 2–3%. This content ensures that the physicochemical properties of the soil are maintained at an optimal level and indicates effective soil management in agricultural systems (Zimnoch et al., 2024). A commonly employed remedial measure for soil fertility issues is mineral fertilization, primarily due to the rapid release of nutrients (IFPRI, 2002). However, mineral fertilizers do not possess the ability to enhance soil physical properties, which results in an imbalanced approach to fertility improvement when relying solely on mineral fertilization. Excessive use of mineral fertilizers without due care regarding organic matter can lead to the degradation of key environmental components, including soil, water, and air pollution, and consequently threaten food security (Tilman et al., 2015). (Tilman et al., 2015). Furthermore, the production of mineral fertilizers is highly material- and energy-intensive, which affects the high prices of mineral fertilizers (Kacprzak, 2023). Due to the significant ecological and financial costs, increasing attention is being paid to sustainable soil fertilization, including increasing the share of organic fertilization. Numerous studies confirm the beneficial effects of traditional and unconventional organic fertilizers on the properties as well as production potential of soils (Suge et al., 2011; Mavis and Abigail, 2022).

Traditional organic fertilizers (manure, slurry) can be replaced by organic waste and thus effectively recycled in agriculture, in line with the assumptions of the circular economy (Chojnacka et al., 2020). Organic wastes are used in agriculture to increase the CO_2 sequestration potential of soil, improve nutrient availability, and optimize air-water properties. Levasseur et al., (2022), depending on the purpose and dose in which they are used, divide them into additives and fertilizers. Within the group of organic solid waste, sewage sludge (SS) is recognized as an excellent fertilizer, as the organic matter content of sludge can range from 25% to 90% depending on the stabilization technology and its use in agriculture is a low-cost technology. The benefits of using SS include increasing the humus content of soil as well as the abundance and activity of soil microorganisms (Singh et al., 2012; Larney and Angers, 2012). Studies by Zafar et al. (2020) and Bik-Małodzińska et al. (2021) confirmed improved water-air properties of soils fertilized with SS. They noted an optimization of density, porosity, water capacity, and plant-available water content.

Fertilization with sewage sludge, apart from numerous proven beneficial effects on soil properties and crops, may pose a potential threat to terrestrial and aquatic ecosystems. Particular attention has been paid to the risks associated with heavy metals and pathogens (Delibacak et al., 2020; Hasan et al., 2024). Research findings on the content of undesirable components in sewage sludge have formed the basis for the development of legal regulations ensuring the safe management of sewage sludge. Depending on the legislation, individual countries specify requirements for sludge stabilization and hygienization, permissible levels of chemical and biological contamination, as well as application rates and frequencies.

A direct and quickly noticeable effect of using SS as a fertilizer is increased plant biomass production. This is due to the richness of SS in macro- and micronutrients. (Riaz et al., 2025). Nitrogen is the nutrient that most limits plant biomass production (Li et al., 2022). In synthetic mineral fertilizers, fertilizer components are easily available to plants, while N introduced into the soil with sewage sludge is present in both inorganic (mainly NH_4^+ and partly NO_3^-), and organic forms. The availability of N to plants in sludge-enriched soil depends on the inorganic N content and the forms and availability of organic N present. Estimation of mineral forms of nitrogen in sludge-fertilized soil is crucial both to reduce N deficiency for crops and its excessive concentration, which can pose environmental risks associated with the movement of accumulated N compounds through leaching, runoff and erosion (Rigby et al., 2016).

The article presents the results of research aimed at assessing the effect of different doses of sewage sludge on the content of mineral forms of nitrogen in light soil.

MATERIAL AND METHODS

The impact of different doses of sewage sludge on the content of total and mineral nitrogen forms was assessed in a closed-pot experiment. The soil with a granulometric composition of slightly loamy sand was introduced into 12-dm^3 pots. Basic soil characteristics are presented in Table 1.

The sewage sludge from a municipal wastewater treatment plant and mineral wool waste from greenhouse crops were used to fertilize the light soil. Basic fertilization parameters of the materials used to establish the experiment are presented in Table 1. The sewage sludge was applied in two doses: fertilizer (100 M·ha^{-1}) and reclamation (100 Mg·ha^{-1}), and mineral wool was applied at 400 m^3·kg^{-1}. Waste doses are expressed in dry matter. Controls included soil without additives

Table 1. Characteristics of the materials used to set up the experiment. Average values (Wójcikowska-Kapusta et al., 2012)

Propertes	Unit	Soil	Mineral wool	Sewage sludge
Granulometric composition	sand 2.0-0,05mm (%) dust 0.05-0.002mm (%) clay <0.002 (%)	90 4 6	- - -	- - -
pH	H_2O	5.6	6.9	6.8
	KCl	5.0	6.6	6.4
H_h	$cmol(+)\cdot kg^{-1}$	3.20	3.82	4.50
BC		2.22	57.04	50.04
CEC		5.52	60.86	54.54
V	%	40.2	93.7	91.7
Total nitrogen (TN)	$g\cdot kg^{-1}$	0.50	4.0	28.0
Total organic carbon (TOC)		5.80	28.5	193.8
C/N	-	11.6	7.1	6.9
P available to plants	$mg\cdot kg^{-1}$	1.15	22.99	60.40
K available to plants		2.98	33.00	17.02
Total copper content		2.33	42.75	139.0
Total zink content		9.14	133.50	935.0
Total lead content		6.28	35.50	29.2
Total cadmium content		0.17	0.02	3.45
Total chromium content		10.89	18.50	26.7
Total nickel content		6.30	9.30	55.1
Total mercury content		0.02	0.02	0.45

(S_{C1}) and soil + NPK (S_{C2}). A detailed design of the pot experiment is presented in Table 2. For each variant, pots were prepared with three replicates. Test plants with the species composition presented in Table 2 were sown in the pots and grown for three growing seasons. The study included soil samples collected on four dates: date I – before sowing the plants; dates II, III, and IV – after harvesting the plants in subsequent years of the study. A representative soil sample was prepared from each pots, which, after drying and averaging, was sent for laboratory testing.

Total organic carbon (TOC) content was determined using a VCSH SSM-5000A TOC analyzer (Shimadzu Corp., Kyoto, Japan) according to the procedure described in the Polish standard (PN-EN 15936:2013:02) by measuring the carbon content in the gases generated during the combustion of a soil sample at 900 °C. Total nitrogen (TN) content was determined using the modified Kjeldahl method (ISO 13878:1998). The analysis involved sample mineralization in concentrated sulfuric acid, liberation of ammonia from ammonium sulfate by distillation in an alkaline environment using a Kjeltech TM 8100 automatic distillation apparatus, quantitative binding of the distilled ammonia to ammonium sulfate in a sulfuric acid solution, and neutralization of the excess with an equivalent amount of standardized NaOH. The calculated C/N ratio is the ratio of TOC to TN. Mineral nitrogen forms were determined using the colorimetric method, according to ISO 14255. The ammonium nitrogen content ($N\text{-}NH_4^+$) was determined by reducing ammonium ions with Nessler's reagent and spectrophotometrically determining the color intensity at a wavelength of 695 nm. The nitrate nitrogen content ($N\text{-}NO_3^-$) was determined by measuring the absorbance of the solution following the reaction of nitrates with sodium salicylate in the presence of concentrated sulfuric acid at a wavelength of 480 nm. The measurements were carried out on a Hitachi U-02010 spectrophotometer. The share of ammonium nitrogen and nitrate nitrogen in the total nitrogen pool was calculated according to the formula:

$$\%\, N_{mineral} = N_{mineral} \times 100/TN \tag{1}$$

where: TN – total nitrogen, $N_{mineral}$ – $N\text{-}NH_4^+$, $N\text{-}NO_3^-$.

Analysis of variance (ANOVA) was used to analyze the data, allowing for the assessment of the significance of the influence of the studied

Table 2. Scheme of the experiment

Variant	Fertilization	Doses	Composition of grass mixture (test plants)
S_{C1}	without additives (control I)	-	Meadow fescue (*Festuca pratensis*) – 41,2%; Red fescue (*Festuca rubra*) – 19,2%; Perennial ryegrass (*Lolium perenne*) – 14,7%; Italian ryegrass (*Lolium multiflorum*) – 12,4%; Common cocksfoot (*Dactylis glomerata*) – 6,5%; Red clover (*Trifolium pratense*) – 6%.
S_{C2}	NPK (control II)	N80, P40 i K60 kg·ha^{-1}	
S_{SS10}	sewage sludge	10 Mg·ha^{-1}	
S_{SS100}	sewage sludge	100 Mg·ha^{-1}	
S_{MW400}	mineral wool	400 m^3·ha^{-1}	
$S_{MW400+SS10}$	mineral wool + sewage sludge	400 m^3·ha^{-1} + 10 Mg·ha^{-1}	
$S_{MW400+SS100}$	mineral wool + sewage	400 m^3·ha^{-1} + 10 Mg·ha^{-1}	

factors. The significance of differences between means was assessed using the Tukey test at a significance level of $\alpha = 0.05$. Additionally, to assess the similarity of the analyzed variables, cluster analysis using Ward's method was performed using Statistica PL 13.3 and Microsoft Excel 2019.

RESULTS AND DISCUSSION

Sewage sludge is rich in organic matter, therefore, its positive impact on improving the organic carbon content in the soil is not questioned (Joniec et al., 2021; Rigby et al., 2016; Kacprzak, 2023). The sewage sludge used for soil fertilization was characterized by a high TOC content, i.e. 193.8 g·kg^{-1} (Table 2). In the first term of the study in the soil without additives (S_{C1}) and fertilized with NPK (S_{C2}), the TOC content was 6.03 and 6.93 g·kg^{-1}, respectively. In the soil without fertilization (S_{C1}), the fluctuation of TOC content, in successive test terms, was insignificant – in the third term, TOC content increased to 6.75 g·kg^{-1} and in the fourth term to 6.51 g·kg^{-1}. This is confirmed by literature reports, which show that the agricultural use of soils, without the use of organic fertilizer maintains the TOC content at similar levels or promotes its reduction (Pahalvi et al., 2021). In the soil of the NPK fertilization variant, the TOC content was similar in the evaluated test dates. The obtained results are consistent with those presented in the works by Körschens et al., (2012) and Maltas et al., (2018). In their studies on the effect of mineral fertilization on the humus balance in arable soils, they showed that fertilization of soils with measured doses of mineral fertilizers stabilizes the organic carbon content therein or may influence its increase.

Statistical analysis confirmed a significant effect of sewage sludge application on the increase of total organic carbon (TOC) content. In the first sampling period, TOC content increased to 7.81 g·kg^{-1} following the application of the fertilizing dose (10 Mg·ha^{-1}), and to 8.41 g·kg^{-1} after the application of the reclamation dose (100 Mg·ha^{-1}). In the soil with the addition of sewage sludge at a rate of 10 Mg·ha^{-1}, insignificant content fluctuations of TOC were found in subsequent test dates compared to the first test date. The TOC content in the soil of this object (average of the test dates) was 7.55 g·kg^{-1} and remained higher compared to the soil without fertilization and the soil fertilized with NPK. In the soil of variant S_{SS100} (fertilized with reclamation dose of sludge), further increases of TOC content were recorded on subsequent test dates. The recorded increase in TOC content was indirectly influenced by the higher amount of plant residues at the site (Rakshit et al., 2018;

Table 3. The effect of different doses of sewage sludge on TOC content

Date of sampling	TOC g·kg^{-1}							Average for the term
	S_{C1}	S_{C2}	S_{SS10}	S_{SS100}	S_{MW400}	$S_{MW400+SS10}$	$S_{MW400+SS100}$	
I	6.03	6.93	7.81	8.41	7.76	7.54	8.98	7.64A
II	6.20	7.07	7.50	8.79	7.73	7.89	10.50	7.95B
III	6.75	6.85	7.65	11.42	8.41	8.40	10.67	8.59C
IV	6.51	6.97	7.24	11.40	9.30	8.56	10.84	8.69D
Average for the variant	6.37a	6.96b	7.55c	10.00f	8.30e	8.10d	10.25g	

Siedt et al., 2021). The TOC content of the mineral wool used for soil fertilization was 28.5 g·kg^{-1}. Adding mineral wool (S_{MW400}) to the soil increased TOC to 7.76 g·kg^{-1}, which is significantly higher than the soil in the control treatments) (S_{C1} and S_{C2}). Compared to the control treatments, the TOC content in the soil fertilized with sludge and wool was significantly higher (Table 3). In the soil of the $S_{MW400+SS10}$ variant, compared to S_{SS10}, a systematic increase in the organic matter content was observed in the subsequent test dates. The application of a high dose (100 Mg·ha^{-1}) of sewage sludge with mineral wool significantly increased TOC. In the fourth test period, TOC content was 10.84 g·kg^{-1}, i.e. 66% higher compared to SC1. The significantly higher TOC content in the soil of the $S_{MW400+SS10}$ and $S_{MW400+SS100}$ fertilizer variants is largely due to the beneficial effect of mineral wool on the properties of water and air, which has a significant impact on the transformation of organic compounds in the soil (Żukowska et al., 2023a, b).

Nitrogen (N) is a key macronutrient, the availability of which in the soil environment significantly determines the intensity of plant growth processes and the size of the yield obtained (Ye et al., 2022). In light soils, poor in organic matter and characterized by low sorption capacity, its content is often deficient (Dhaliwal et al., 2019). The TN content in sewage sludge is significant and similar to the content in natural fertilizer (manure), and sometimes higher (Chojnacka et al., 2023). The sewage sludge intended for soil improvement recycles nitrogen and may eliminate the need for mineral fertilizers (Markowicz et al., 2021; Myszura-Dymek, 2024). Numerous studies indicate that sludge application stimulates the accumulation of total nitrogen in arable soils (Buta et al., 2021; Żukowska et al., 2024).

In the soil of the control objects, in the first date of the study, the average TN content was approximately 0.50 g·kg^{-1} (Table 4). The analysis shows that sewage sludge had the most positive impact on TN content in the soil. This effect was significantly dependent on its dose. In the 1st term, in the soil fertilized with sewage sludge at a rate of 10 Mg·ha^{-1}, the TN content was 0.61 g·kg^{-1}.

An increase in the TN concentration in the soil was statistically confirmed after adding sewage sludge at the reclamation dose. In the soil of this object, in the 1st term of the study, the TN content was 1.21 g·kg^{-1} (Table 4), and in the subsequent dates slight fluctuations were noted, with a tendency to reduce the TN content. The average TN content in the S_{SS100} variant soil during the studied period was 1.07 g·kg^{-1} and reached a statistically higher level compared to the content in the soil of the control objects and the variant with a lower dose of sewage sludge. High N content of municipal sludge makes it a potential source of N to support plant growth (Zhang et al., 2023). The results obtained are confirmed by studies by other authors (Valchev et al., 2024; Giannopoulos et al., 2025). The extent of the increase in the TN content in the soils fertilized with sewage sludge depends on the N content of the sludge and the properties of the soil on which it is applied (Ding et al., 2021; Żukowska et al., 2024). However, Raheem et al., 2018 show that the application of municipal sludge can replace mineral nitrogen fertilizers.

The indicator used to assess the state of nitrogen management in soil is the C/N ratio (Tamagno et al., 2024). Under the conditions of this experiment, this ratio changed relatively little. In the soil of the control objects (S_{C1} and S_{C2}), the C/N ratio was approximately 10.6 (Table 5). Fertilization of the soil with various doses of sewage sludge applied alone and with the addition of mineral wool modified the C/N ratio only slightly, the values of which ranged from 9.50 to 10.55 and were typical for the top layers of mineral soils (Dhanker et al., 2021).

Table 4. The effect of different doses of sewage sludge on TN content

Date of sampling	TN g·kg^{-1}							Average for the term
	S_{C1}	S_{C2}	S_{SS10}	S_{SS100}	S_{MW400}	$S_{MW400+SS10}$	$S_{MW400+SS100}$	
I	0.50	0.52	0.61	1.21	0.61	061	0.93	0.71A
II	0.61	0.71	1.01	1.14	0.92	0.90	0.93	0.89D
III	0.64	0.75	0.81	0.95	0.85	0.88	0.97	0.83B
IV	0.63	0.75	0.83	0.98	0.98	0.93	1.06	0.88C
Average for the variant	0.59c	0.67d	0.82a	1.07f	0.84b	0.83ab	0.97e	

Table 5. The effect of different doses of sewage sludge on C/N ratio

Date of sampling	C/N						
	S_{C1}	S_{C2}	S_{SS10}	S_{SS100}	S_{MW400}	$S_{MW400+SS10}$	$S_{MW400+SS100}$
I	12.06	13.33	12.80	6.95	12.72	12.36	9.66
II	10.16	9.96	7.43	7.71	8.40	8.77	11.29
III	10.55	9.13	9.44	12.02	9.89	9.55	11.00
IV	10.33	9.29	8.72	11.63	9.49	9.20	10.23

The majority of nitrogen (approximately 99%) occurs in soils in organic compounds, most often in humic fractions. Only 1–5% of TN is accounted for by nitrogen compounds belonging to the mineral fraction (Odlare et al., 2008). Organic forms of soil nitrogen undergo complex and dynamic transformations, the direction and dynamics of which largely depend on the amount of inorganic nitrogen that can be formed during the decomposition of exogenous organic matter (EOM) (Odlare et al., 2008; Gil et al., 2011). The main transformation processes are mineralization and immobilization, the intensity of which is determined by the carbon to nitrogen (C/N) ratio, especially in EOM (Wang et al., 2006; Gil et al., 2011). Among the mineral forms of N in soil, the most important are $N\text{-}NH_4^+$ and $N\text{-}NO_3^-$. Nitrogen found in these combinations is most easily absorbed by plants (Chang et al., 2014; Chen et al., 2018). Ammonium nitrogen in soil is found in non-exchangeable and exchangeable forms and in soil solution, while nitrate (V) is found entirely in water-soluble form. These two forms of nitrogen (ammonium and nitrate (V)) are the primary source of nitrogen compounds in the arable layer of soils (Bednarek and Tkaczyk, 2002), and if not utilized by plants, they can be a source of chemical nitrogen pollution of soils (mainly nitrates).

The results showed that the content of mineral forms of nitrogen in the soil was closely related to the dose of sewage sludge (Table 6). In the soil of S_{C1} the content of ammonium nitrogen ($N\text{-}NH_4^+$) was 26.20 mg·kg^{-1} (Table 6). The introduction of a fertilizing dose of sludge (variant S_{SS10}) and NPK (variant S_{C2}) into the soil did not show any significant effect on the content of ammonium nitrogen. After introducing sewage sludge into the light soil at the reclamation dose, a statistically significant improvement in the $N\text{-}NH_4^+$ content was observed, which increased to 85.01 mg·kg^{-1}. In the soil amended with sewage sludge and mineral wool, a further improvement in the content of this form of nitrogen was observed.

A significant effect of the test date on the $N\text{-}NH_4^+$ content was found, which was reflected in a decrease in the content of this form of nitrogen. The greatest effect on the content of $N\text{-}NH_4^+$ in the soil was exerted by sewage sludge, which, applied at a reclamation rate, increased, compared to the fertilizer rate, its content by 22.83 mg·kg^{-1} – 77.52%. This increase for the sewage sludge-mineral wool mixture was 27.44 mg·kg^{-1} – 91%.

The studied fertilization/reclamation methods changed the amount of ammonia nitrogen in total nitrogen, which ranges from 2.3–11.4% (Table 7). In general, the highest proportion of ammonium nitrogen in total nitrogen was recorded in the soil with the highest addition of organic matter. Under the conditions of lower organic matter and the addition of mineral wool, the content of ammonium nitrogen in total nitrogen decreased. This was

Table 6. The effect of different doses of sewage sludge on $N\text{-}NH_4^+$ content

Date of sampling	$N\text{-}NH_4^+$ mg kg^{-1}							Average for the term
	S_{C1}	S_{C2}	S_{SS10}	S_{SS100}	S_{MW400}	$S_{MW400+SS10}$	$S_{MW400+SS100}$	
I	26.20	32.96	40.57	85.01	31.52	34.82	106.39	51.07C
II	26.08	23.75	23.22	38.27	26.83	34.50	38.70	30.19AB
III	24.31	25.76	30.29	42.88	23.25	24.94	51.63	31.87B
IV	20.35	24.94	23.73	42.96	29.57	26.12	33.44	28.73A
Average for the variant	24.23b	26.85ab	29.45a	52.28c	27.79ab	30.10a	57.54d	

Table 7. The effect of different doses of sewage sludge on % $N\text{-}NH_4^+$

Date of sampling	% $N\text{-}NH_4^+$						
	S_{C1}	S_{C2}	S_{SS10}	S_{SS100}	S_{MW400}	$S_{MW400+SS10}$	$S_{MW400+SS100}$
I	5.2	6.3	6.7	7.0	5.2	5.6	11.4
II	4.3	3.3	2.3	3.4	2.9	3.8	4.2
III	3.8	4.0	3.7	4.5	2.7	2.8	5.3
IV	3.2	3.3	2.9	4.4	3.0	2.9	3.2

Table 8. The effect of different doses of sewage sludge on the $N\text{-}NO_3^-$ content

Date of sampling	$N\text{-}NO_3^-$ mg kg^{-1}							Average for the term
	S_{C1}	S_{C2}	S_{SS10}	S_{SS100}	S_{MW400}	$S_{MW400+SS10}$	$S_{MW400+SS100}$	
I	37.49	81.70	74.31	156.40	48.10	69.49	165.75	90.46A
II	23.15	45.55	95.20	276.29	30.70	50.40	294.07	116.48D
III	41.20	42.02	78.13	260.13	38.52	59.12	293.87	116.15C
IV	68.29	46.55	53.10	290.84	39.93	38.71	235.57	110.43B
Average for the variant	42.53b	53.97c	75.18e	245.91f	39.31a	54.43d	247.32g	

associated with more intensive mineralization processes of organic matter.

The fertilizer/reclamation variants studied had a significant effect on the nitrate nitrogen (V) content of the soil (Table 8). These changes varied, especially between successive test dates, and thus the average values of the four test dates were relied on when discussing changes in the content of this form of nitrogen.

In the soil without fertilization (S_{C1}), the content of nitrates (V) was 42.53 mg·kg^{-1}. The applied NPK fertilization and the addition of sewage sludge at doses of 10 and 100 Mg·ha^{-1} significantly increased the content of this nitrogen form. The highest and high $N\text{-}NO_3^-$ content was noted in the soil with the addition of reclamation dose of SS, which was 245.91 mg·kg^{-1}.

In the soil of the fertilizer variants, in which mineral wool only, the content of $N\text{-}NO_3^-$during the study period ranged from 48.1 to 39.93 mg·kg^{-1} (average 39.31 mg·kg^{-1}) and was comparable to the content of this form of nitrogen in soil without fertilizer (S_{C1}).

The average nitrate nitrogen content in the soil with sewage sludge addition in fertilizer dose and mineral wool, compared to the soil without fertilization (S_{C1}) was 54.43 mg·kg^{-1} and it was the content that showed a statistically significant increase. A very high (average 247.32 mg·kg^{-1}) nitrate (V) content was characterized by soil to which a land reclamation application (100 Mg·ha^{-1}) of sewage sludge with the addition of mineral wool. This contributed to increasing the soil's nitrogen content available to plants.

The influence of the studied fertilization/reclamation methods is also observed in the different proportion of nitrate nitrogen in total nitrogen, with an average of 3.3–31.6% (Table 9). In general, the highest amount of nitrate nitrogen in total nitrogen was noted in the soil with the highest (100 Mg·ha^{-1}) addition of sewage sludge. Under conditions of fertilizer application of sewage sludge (10 Mg·ha^{-1}) and addition of mineral wool, the amount of nitrate nitrogen in total nitrogen was lower.

The results obtained are confirmed by the study of Kleber et al. (2015), who showed that the content of mineral forms of nitrogen increases along with sludge application rates, but the level of their content did not pose a threat caused by nitrogen leaching and environmental pollution. Also, Achkir et al., (2023), showed in their study a significant increase in mineral form ($N\text{-}NO_3^-$) with increasing sewage sludge dose. At the same time, they did not notice a significant increase in the amount of these forms in the total nitrogen content. The content and proportion of mineral forms of nitrogen observed can be explained by the optimal C/N ratio, which ensured balanced decomposition of organic matter, leading to a gradual release of nitrogen compounds, thereby increasing their availability to plants (Wołejko et al., 2014). In this study, the C/N ratio ranged

Table 9. The effect of different doses of sewage sludge on % N-NO_3^-

Date of sampling	% N-NO_3^-						
	S_{C1}	S_{C2}	S_{SS10}	S_{SS100}	S_{MW400}	$S_{MW400+SS10}$	$S_{MW400+SS100}$
I	7.5	15.7	12.18	12.93	7.9	11.4	17.8
II	3.8	6.4	9.4	24.24	3.3	5.6	31.6
III	6.4	5.6	9.6	27.38	4.5	6.7	30.3
IV	10.8	6.2	6.4	29.26	4.1	4.16	22.2

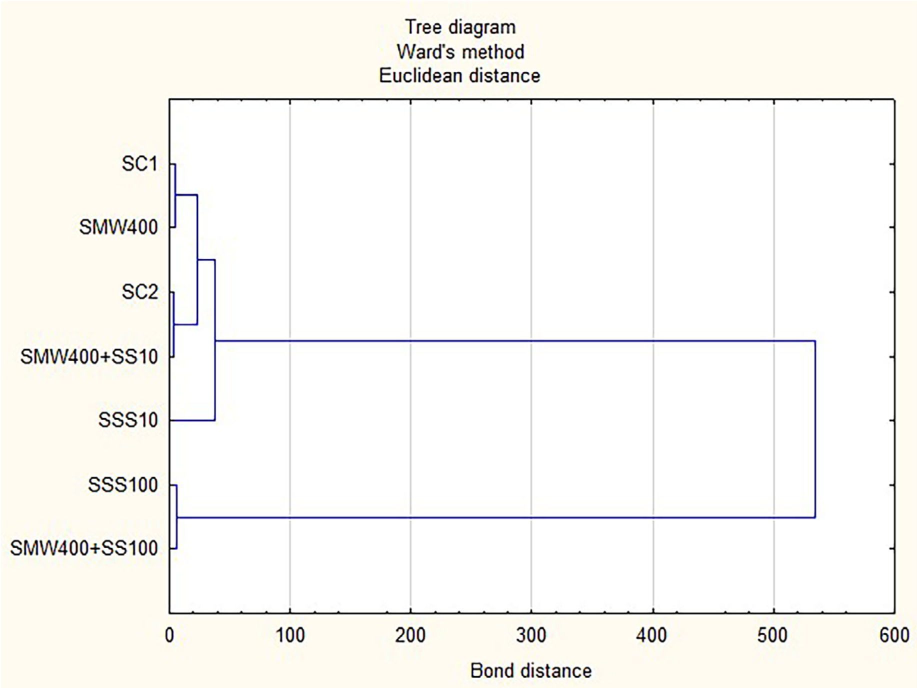

Figure 1. Comparison of similarities of the evaluated fertilizer variants based on the results of Ward's cluster analysis

from 9.5 to 10.55, which provided optimal conditions for the mineralization of organic matter introduced into the soil and the transformation of nitrogen and the release of its mineral forms (Wang et al., 2013).

The results obtained were summarized by conducting Ward analysis (Figure 1). The cluster analysis confirmed that the content of total nitrogen and its mineral forms was closely correlated with sludge application dose. The highest content of TN and its mineral forms was characterized by the soil of variants S_{SS100} and $S_{MW400+SS100}$.

CONCLUSIONS

Fertilizing light soils with sewage sludge, especially at a high dose in combination with mineral wool, effectively increases organic matter content, which can help improve soil fertility. Fertilization with sewage sludge, especially at a high dose (100 Mg·ha^{-1}), significantly increased the total nitrogen content of the soil compared to control sites, confirming the effectiveness of this method in improving the nitrogen richness of light soils. High TN values were maintained throughout the study period, despite little changes. The dose of applied sewage sludge had an impact on the content of mineral forms of nitrogen in light soil. The highest values of N-NH_4^+ and N-NO_3^- were observed in the soil fertilized with sludge at a dose of 100 Mg·ha^{-1}. No significant increase in the share of mineral forms of nitrogen in the total nitrogen content was observed. The addition of mineral wool combined with sewage sludge further enhances the fertilizing effect, which can be practically used in the reclamation and improvement of soils with low humus content. The use of high doses of sewage sludge, especially in combination with mineral wool, can be practically used to improve the fertility of nitrogen-poor soils and increase the efficiency of fertilization in agriculture.

REFERENCES

1. Achkir, A., Aouragh, A., El Mahi, M., Lotfi, L.M., Labjar, N., EL Bouch, M., Ouahidi, M.,L., Badza, T., Farhane, H., EL Moussaoui, T. (2023). Implication of sewage sludge increased application rates on soil fertility and heavy metals contamination risk. *Emerging Contaminants, 9*(1), 100200. https://doi.org/10.1016/j.emcon.2022.100200
2. Bik-Małodzińska, M., Żukowska, G., Myszura, M., Wójcikowska-Kapusta, A., Mazur, J. (2021). The Changes in Physicochemical Properties in Soils Subjected to Many Years of Reclamation. *Journal of Ecological Engineering. 22*(2): 47–53. https://doi.org/10.12911/22998993/130877
3. Buta, M., Hubeny, J., Zieliński, W., Harnisz, M., Korzeniewska, E. (2021). Sewage sludge in agriculture – the effects of selected chemical pollutants and emerging genetic resistance determinants on the quality of soil and crops – a review. *Ecotoxicology and Environmental Safety, 214*, 112070, https://doi.org/10.1016/j.ecoenv.2021.112070
4. Chang, E. H., Wang, C. H., Chen, C. L., Chung, R. S. (2014). Effects of long-term treatments of different organic fertilizers complemented with chemical N fertilizer on the chemical and biological properties of soils. *Soil Science and Plant Nutrition, 60*(4): 499–511. https://doi.org/10.1080/00380768.2014.917333
5. Chen, Y., Camps-Arbestain, M., Shen, Q. (2018). The long-term role of organic amendments in building soil nutrient fertility: a meta-analysis and review. *Nutr Cycl Agroecosyst, 111*: 103–125. https://doi.org/10.1007/s10705-017-9903-5
6. Chojnacka, K., Moustakas, K., Witek-Krowiak, A. (2020). Bio-based fertilizers: a practical approach towards circular economy. *Bioresour. Technol., 295*, 122223. https://doi.org/10.1016/j.biortech.2019.122223
7. Chojnacka, K., Skrzypczak, D., Szopa, D., Izydorczyk, G., Moustakas, K., Witek-Krowiak, A. (2023). Management of biological sewage sludge: Fertilizer nitrogen recovery as the solution to fertilizer crisis. *Journal of Environmental Management, 326*, 116602. https://doi.org/10.1016/j.jenvman.2022.116602
8. Delibacak, S., Voronina, L., Morachevskaya, E. (2020). Use of sewage sludge in agricultural soils: Useful or harmful. *Eurasian Journal of Soil Science, 9*(2): 126–139. https://doi.org/10.18393/ejss.687052
9. Dhaliwal, S.S., Naresh, R.K., Mandal, A., Singh, R., Dhaliwal, M.K. (2019). Dynamics and transformations of micronutrients in agricultural soils as influenced by organic matter build-up: A review. *Environmental and Sustainability Indicators, 1–2*, 100007. https://doi.org/10.1016/j.indic.2019.100007
10. Dhanker, R., Chaudhary, S., Goyal, S., Garg, V.K. (2021). Influence of urban sewage sludge amendment on agricultural soil parameters. *Environmental Technology & Innovation, 23*, 101642. https://doi.org/10.1016/j.eti.2021.101642
11. Ding, S.J., Zhang, X.F., Yang, W.L. (2021). Soil Nutrients and Aggregate Composition of Four Soils with Contrasting Textures in a Long-Term Experiment. *Eurasian Soil Sc. 54*: 1746–1755. https://doi.org/10.1134/S1064229321110041
12. Giannopoulos, G., Tzanakakis, V.A., Duelli, G., Anastopoulos, I., Aschonitis, V.G., Arampatzis, G., Barouchas, P.E. (2025). Municipal sewage sludge treatment and soil pH conclusively affect the nitrogen dynamics of amended soils. *Environmental Advances, 19*, 100618. https://doi.org/10.1016/j.envadv.2025.100618
13. Gil, M.V., Carballo, M.T., Calvo, L.F. (2011). Modelling N mineralization from bovine manure and sewage sludge composts. *Bioresource Technology, 102*(2): 863–871. https://doi.org/10.1016/j.biortech.2010.09.010
14. Grilli, E., Carvalho, S.C.P., Chiti, T., Coppola, E., D'Ascoli, R., La Mantia, T., Marzaioli, R., Mastrocicco, M., Pulido, F., Rutigliano, F.A., Quatrini, P., Castaldi, S. (2021). Critical range of soil organic carbon in southern Europe lands under desertification risk. *Journal of Environmental Management, 287*, 12285. https://doi.org/10.1016/j.jenvman.2021.112285
15. Hasan, M., Hasan, M.R., Khan, R.A., Rashid, T.U. (2024). *Sewage Sludge: Is It a Sustainable Fertilizer or a Source of Contaminants?* In: V. Kumar, S.A. Bhat, S. Kumar, P. Verma (Eds), Environmental Engineering and Waste Management. Springer, Cham. https://doi.org/10.1007/978-3-031-58441-1_4
16. Hillel, D. (2012). *Soil in the environment*. Warszawa: PWN.
17. International Food Policy Research Institute (IFPRI). (2002). *Sustainable Options for Ending Hunger and Poverty*. Green Revolution: Blessing or Curse. Washington DC, USA.
18. ISO 13878:1998; Soil Quality. *Determination of Total Nitrogen Content by Dry Combustion.* International Organization for Standardization: Geneva, Switzerland, 1998.
19. ISO 14255, 1998. *International Standard Organization. Soil quality – Determination of nitrate nitrogen, ammonia nitrogen and total soluble nitrogen in air-dry soils.*

20. Joniec, J., Żukowska, G., Bik-Małodzińska, M., Kwiatkowska, E., Rojek, K. (2021). Reaction of microorganisms to long-term waste reclamation of soil degraded by the sulfur mining industry. *Minerals, 11*, 1226. https://doi.org/10.3390/min11111226
21. Kacprzak, M. (2023). *Sewage sludge as a source of organic to be used as soil improvement.* In: G. Miltiadis, G. Zamparas, L. Grigorios, L. Kyriakopoulos (Eds), Water Management and Circular Economy, Elsevier. https://doi.org/10.1016/B978-0-323-95280-4.00013-8
22. Kleber, M., Eusterhues, M., Keiluweit, M., Mikutta, C., Mikutta, R., Nico, P.S. (2015). *Mineral–Organic Associations: Formation, Properties, and Relevance in Soil Environments*. In: L. Donald, L. Sparks (Eds), Advances in Agronomy, Academic Press, 130: 1–140. https://doi.org/10.1016/bs.agron.2014.10.005
23. Körschens, M., Albert, E., Armbruster, M., Barkusky, D., Baumecker, M., Behle-Schalk, L., Zorn, W. (2012). Effect of mineral and organic fertilization on crop yield, nitrogen uptake, carbon and nitrogen balances, as well as soil organic carbon content and dynamics: results from 20 European long-term field experiments of the twenty-first century. *Archives of Agronomy and Soil Science, 59*(8): 1017–1040. https://doi.org/10.1080/03650340.2012.704548
24. Larney, F.J., Angers, D.A. (2012). The role of organic amendments in soil reclamation: A review. *Can. J. Soil Sci, 92*: 19–38. https://doi.org/10.4141/cjss2010-064
25. Levavasseur, F., Lashermes, G., Mary, B., Morvan, T., Nicolardot, B., Parnaudeau, V., Thuriès, L., Houot, S. (2022). Quantifying and simulating carbon and nitrogen mineralization from diverse exogenous organic matters. *Soil Use Manag., 38*: 411–425, https://doi.org/10.1111/sum.12745
26. Maltas, A., Kebli, H., Oberholzer, H.R., Weisskopf, P., Sinaj, S. (2018). The effects of organic and mineral fertilizers on carbon sequestration, soil properties, and crop yields from a long-term field experiment under a Swiss conventional farming system. *Land Degrad Dev. 29:* 926–938. https:// doi.org/10.1002/ldr.291
27. Markowicz, A., Bondarczuk, K., Wiekiera, A. (2021). Is sewage sludge a valuable fertilizer? A soil microbiome and resistome study under field conditions. *J Soils Sediments 21*: 2882–2895. https://doi.org/10.1007/s11368-021-02984-1
28. Mavis, B.B., Abigail, A. (2022) Improving Soil Fertility with Organic Fertilizers. 2022. In: New Generation of Organic Fertilizers, (Ed.), Metin Turan and Ertan Yildirim.
29. Mocek, A. (2015). Soil science. Warszawa: PWN.
30. Myszura-Dymek, M. (2024). Properties of organic matter in composts based on sewage sludge. *Journal of Ecological Engineering. 25*(7): 70–81. https://doi.org/10.12911/22998993/187964
31. Odlare, M., Pell, M., Svensson, K. (2008). Changes in soil chemical and microbiological properties during 4 years of application of various organic residues, *Waste Management, 28*(7): 1246–1253. https://doi.org/10.1016/j.wasman.2007.06.005
32. Pahalvi, H.N., Rafiya, L., Rashid, S., Nisar, B., Kamili, A.N. (2021). *Chemical Fertilizers and Their Impact on Soil Health*. In: Dar, G.H., Bhat, R.A., Mehmood, M.A., Hakeem, K.R. (eds) Microbiota and Biofertilizers, Vol 2. Springer, Cham. https://doi.org/10.1007/978-3-030-61010-4_1.
33. Panagos, P., Hiederer, R., Van Liedekerke, M., Bampa, F. (2013). Estimating soil organic carbon in Europe based on data collected through an European network. *Ecological Indicators*, *24*: 439–450. https://doi.org/10.1016/j.ecolind.2012.07.020
34. PN-EN 15936:2013:02. Available online: https://sklep.pkn.pl/pn-en-15936-2013-02p.html (accessed on 10 July 2025).
35. Raheem, A., Singh Sikarwar, V., He, J., Dastyar, W., Dionysiou, D., Wang, W., Zhao, M. (2018). Opportunities and challenges in sustainable treatment and resource reuse of sewage sludge: A review. *Chemical Engineering Journal, 337*: 616–641, https://doi.org/10.1016/j.cej.2017.12.149
36. Rakshit, A., Sarkar, B., Abhilash, P. (2018). Soil amendments for sustainability: Challenges and perspectives. CRC Press.
37. Riaz, M., Liu, P., Khan, M.J. (2025). Exploitation of sewage sludge as a nutrient-dense edaphic enhancer for sustainable agronomy: Assessing ecological consequences and repercussions. *Water Air Soil Pollut, 236*, 433. https://doi.org/10.1007/s11270-025-08073-0
38. Rigby, H., Clarke, B.O., Pritchard, D.L., Meehan, B., Beshah, F., Smith, S.R., Porter, N.A. (2016). A critical review of nitrogen mineralization in biosolids-amended soil, the associated fertilizer value for crop production and potential for emissions to the environment, *Science of The Total Environment, 541*: 1310–1338, https://doi.org/10.1016/j.scitotenv.2015.08.089
39. Siedt, M., Schäffer, A., Smith, K. E., Nabel, M., Roß-Nickoll, M., van Dongen, J. T. (2021). Comparing straw, compost, and biochar regarding their suitability as agricultural soil amendments to affect soil structure, nutrient leaching, microbial communities, and the fate of pesticides. *Science of The Total Environment, 751*, 141607. https://doi.org/10.1016/j.scitotenv.2020.141607
40. Singh, S., Parihar, P., Singh, R., Singh, V.P., Prasad, S.M., Antonio, C. (2016). Heavy metal tolerance in plants: Role of transcriptomics, proteomics,

metabolomics, and ionomics. *Front. Plant Sci., 6*: 1–36. https://doi.org/10.3389/fpls.2015.01143

41. Suge, J.K., Omunyin, M.E., Omami, E.N. (2011). Effect of organic and inorganic sources of fertilizer on growth, yield and fruit quality of eggplant (*Solanum melongena* L). *Archives of Applied Science Research, 3*: 70–479.
42. Tamagno, S., McClellan Maaz, T., van Kessel, C., Linquist, B.A., Ladha, J.K., Lundy, M.E., Maureira, F., Pittelkow, K.M. (2024). Critical assessment of nitrogen use efficiency indicators: Bridging new and old paradigms to improve sustainable nitrogen management. *European Journal of Agronomy, 159*, 127231. https://doi.org/10.1016/j.eja.2024.127231
43. Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S. (2002). Agricultural sustainability and intensive production practices. *Nature, 418*: 671–677. https://doi.org/10.1038/nature01014
44. Valchev, D., Ribarova, I., Borisov, B. (2024). Valuable elements in sludge from eight municipal wastewater treatment plants in relation to their recovery potential. *Environ Sci Eur 36,* 11. https://doi.org/10.1186/s12302-023-00837-x
45. Wang, C., Wan, S., Xing, X., Zhang, L., Han, X. (2006). Temperature and soil moisture interactively affected soil net N mineralization in temperate grassland in Northern China. *Soil Biology and Biochemistry, 38(5)*: 1101–1110. https://doi.org/10.1016/j.soilbio.2005.09.009
46. Wang, X., Selvam, A., Chan, M., Wong, J.W.C. (2013). Nitrogen conservation and acidity control during food wastes composting through struvite formation. *Bioresour Technol. 147*: 17–22. https://doi.org/10.1080/19443994.2014.884714
47. Li, W., Gan, X., Jiang, Y., Cao, F., Lü, X., Ceulemans, T., Zhao, C. (2022). Nitrogen effects on grassland biomass production and biodiversity are stronger than those of phosphorus. *Environmental Pollution, 309*, 119720, https://doi.org/10.1016/j.envpol.2022.119720
48. Wołejko, E., Butarewicz, A., Wydro, U., Łoboda, T. (2014). Advantages and potential risks of municipal sewage sludge application to urban soil. *Desalination and Water Treatment, 52*(19–21): 3732–3742. https://doi.org/10.1080/19443994.2014.884714
49. Wójcikowska-Kapusta, A., Baran, S., Żukowska, G., Sugier, D., Sompor, M. (2012). The influence of sewage sludge on the content of zinc and lead in reclaimed land. *Przem. Chem., 2*(6): 1263–1266.
50. Ye, J.Y., Tian, W.H. Jin, C.W. (2022). Nitrogen in plants: from nutrition to the modulation of abiotic stress adaptation. *Stress Biology 2*, 4. https://doi.org/10.1007/s44154-021-00030-1
51. Zafar, S., Farooq, S., Qazi, H.A., Jaweed, T.H., Kadam, A.K., Lone, F.A. (2020). Evaluation of nutrient status of kale and spinach as affected by sewage sludge and mineral fertilizers. *J. Plant Nutr., 43*: 2633–2644. https://doi.org/10.1080/01904167.2020.1783306
52. Zhang, B., Zhou, X., Ren, X. (2023). Recent research on municipal sludge as soil fertilizer in China: a Review. *Water Air Soil Pollut 234*, 119. https://doi.org/10.1007/s11270-023-06142-w
53. Zimnoch, U., Bogusz, P., Brodowska, M.S., Michalak, J. (2024). The trend of changes in soil organic carbon content in Poland over recent years. 2024. *Archives of Environmental Protection. 50*(1): 35–44. https://doi.org/10.24425/aep.2024.149430
54. Żukowska, G., Futa, B., Myszura-Dymek, M. (2024a). Biochemical parameters of fallow light soil enriched with sewage sludge. *Agriculture, 14*, 1810. https://doi.org/10.3390/agriculture14101810
55. Żukowska, G., Myszura-Dymek, M., Durczyńska, Z. (2024b). The impact of exogenous organic matter on the properties of humus compounds of soils developing on a reclaimed fly ash landfill. *Sustainability. 16*(23): 10579. https://doi.org/10.3390/su162310579
56. Żukowska, G., Myszura-Dymek, M., Roszkowski, S., Bik-Małodzińska, M. (2023b). Effect of coal mining waste and its mixtures with sewage sludge and mineral wool on selected properties of degraded anthropogenic soil. *Journal of Ecological Engineering. 24*: 340–350. https://doi.org/10.12911/22998993/170949
57. Żukowska, G., Myszura-Dymek, M., Roszkowski, S., Olkiewicz, M. (2023a). Selected properties of soil-like substrates made from mine coal waste and their effect on plant yields. *Sustainability, 15,* 13341. https://doi.org/10.3390/su151813341