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Dynamics of nitrate, phosphorus and carbon in soil after sewage sludge application

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ABSTRACT

The use of sewage sludge in agriculture is becoming an increasingly important component of sustainable waste management strategies. However, its effective implementation requires a detailed understanding of the processes occurring in soil following application. The aim of this study was to evaluate the dynamics of transformations of organic nitrogen, nitrate nitrogen (NO_3^-), available phosphorus, and organic carbon in response to varying doses of sewage sludge. The experiments were conducted under field conditions, with temporal monitoring of changes using standard elemental analysis as well as spectrophotometric and colorimetric techniques. The analyses revealed a clear increase in organic carbon and phosphorus content, indicating the activation of processes that enhance soil fertility. At the same time, an intensification of short-term nitrate leaching was observed, particularly in the initial stages following application, highlighting the sensitivity of the soil system to both the rate and timing of sludge incorporation. The results clearly demonstrate that the optimization of application parameters, both in terms of dosage and timing, is crucial for improving process efficiency while minimizing environmental risk in environmental engineering practice.

Keywords: soil, sewage sludge, fertilization, mobility of nutrients.

INTRODUCTION

The growth of urbanization, the intensification of wastewater management, and increasingly stringent environmental regulations are leading to a systematic rise in the volume of sewage sludge generated worldwide. Global sludge production is estimated to reach tens of millions of tonnes of dry matter annually, and further increases are inevitable as wastewater treatment infrastructure continues to expand (Trzaska et al., 2025). This trend poses significant challenges for contemporary environmental engineering, particularly in developing safe, efficient, and sustainable strategies for sludge management aligned with the principles of the circular economy. Traditional methods of sludge disposal, such as landfilling or incineration, are associated with substantial environmental costs, including greenhouse gas emissions, odour problems, and the irreversible loss of valuable biogenic components (Kacprzak et al., 2025). Moreover, reliance on these methods represents a lost opportunity to recycle nutrients and organic matter that could otherwise support soil fertility. In response to these limitations, the agricultural use of sewage sludge as a source of organic matter and macro- and micronutrients particularly nitrogen (N), phosphorus (P), and carbon (C) has gained increasing importance. Sewage sludge typically contains 30–50% organic matter and substantial amounts of nitrogen (3–5%) and phosphorus (2–3%), making it a potentially valuable organic-mineral fertilizer (FAO, 1992; Nkoa, 2014; Muter et al., 2022; Britannica, 2024). Long-term field trials have demonstrated that these amendments can significantly alter soil nutrient stocks and improve soil fertility indicators. For example, in a 20year long-term sewage sludge compost experiment where treatments ranged from 9 to 27 Mg·ha^{-1}, soil organic matter (OM) content increased by up to 37.1% relative to control plots, and plant-available phosphorus

(ALP_2O_5) rose from around 106 mg·kg^{-1} in untreated soil to more than 696 mg·kg^{-1} under the highest sludge application rate (27 Mg·ha^{-1}) (Almási et al., 2025). In the same experiment, total soil carbon increased by 10.5–43.8%, total nitrogen by 5.3–32.5%, and total phosphorus by 50.5–146.2% with increasing sludge doses, clearly indicating substantial nutrient accumulation over time (Almási et al., 2025). From the perspective of soil ecosystem functioning, the dynamics of biogeochemical transformations especially within the C–N–P system are of fundamental importance (Paganini et al., 2024). Incorporating sewage sludge into soil enhances mineralization and immobilization processes, which determine both nutrient availability to plants and nutrient mobility in the environment (Arrobas et al., 2024; Petryk, 2023). For example, studies on light soils fertilized with sewage sludge have reported significant increases in total organic carbon (TOC), with low application doses (equivalent to 30 Mg·ha^{-1}) resulting in TOC increases of around 24%, and higher doses (up to 300 Mg·ha^{-1}) yielding increases of up to 192% compared to unfertilized controls (Biochemical Parameters study, 2024). Nitrogen content in sludge-amended soils has also been shown to shift markedly, with total N and its mineral forms increasing in response to sludge additions, although the relative proportions of different N fractions depend on application history and sludge composition (Wierzbowska et al., 2021). A particularly important issue is nitrogen transformation. During the mineralization of organic matter, nitrogen is converted into mineral forms, primarily nitrates (NO_3^-). This form is highly mobile within the soil profile, creating a risk of leaching into groundwater and surface waters and ultimately contributing to eutrophication. The intensity of these processes depends, among other factors, on the C:N ratio, soil moisture conditions, and microbial activity (Almasi et al., 2025). Long-term field experiments indicate that higher organic input rates can lead to elevated soil nitrate pools, but the degree of increase is variable and influenced by soil texture, climate, and management practices. Phosphorus, in contrast to nitrogen, exhibits lower mobility in soil; however, its accumulation may lead to long-term environmental concerns. In long-term maize monoculture systems, applications of sewage sludge corresponding to 120–240 kg P·ha^{-1} increased phosphorus availability and soil P saturation, leading to larger legacy P pools that could exceed environmental thresholds over decades of continuous application. Inorganic P fractions tend to accumulate in more stable soil pools over time, and the introduction of sludge-derived organic P has also been linked to shifts in enzymatic activity and microbial-mediated P cycling processes (Asrade et al., 2024). Organic carbon contained in sewage sludge plays a crucial role in shaping the physicochemical and biological properties of soil. Its incorporation improves soil structure, increases water-holding capacity, and stimulates microbial activity. While a portion of the carbon undergoes rapid decomposition, another fraction may be stabilized in the soil over the long term, contributing to carbon sequestration and climate change mitigation. Studies (Żukowska et al., 2024; Klatka et al., 2019) have shown that sewage sludge can serve as a significant source of soil organic carbon, with sustained applications enhancing TOC stocks by factors exceeding 1.5–2 times over initial baseline levels modern approaches, such as sludge pyrolysis and biochar production, further enhance the potential for long-term carbon stabilization in soil environments by converting labile organic fractions into more recalcitrant forms that resist microbial breakdown (Serwecińska et al., 2024). Recent research also highlights the role of the soil microbiome in regulating nutrient cycling following sludge application. The introduction of sewage sludge has been shown to alter microbial community structure and functional potential, with implications for nutrient turnover, organic matter decomposition, and even the dissemination of antibiotic resistance genes (Serwecińska et al., 2024; Markowicz et al., 2021). These shifts can lead to both beneficial effects, such as enhanced biological activity and nutrient mineralization, and potential risks, including changes in microbial resistance gene pools that warrant careful management. Despite extensive research, significant knowledge gaps remain regarding the kinetics of biogenic element transformations under different soil conditions, the longterm stability of organic carbon, interactions within the C–N–P cycles, and the influence of climatic variability on nutrient mobility. Therefore, further studies integrating experimental and modelling approaches are necessary to improve our understanding of soil processes following sewage sludge application and to develop optimal strategies for its use in environmental engineering practice. The aim of the present study is to analyze the dynamics of nitrates, phosphorus, and organic carbon in soil following the application of sewage sludge, with particular emphasis on their interactions and implications for soil and water environmental protection.

METHODOLOGY AND CHARACTERISTICS OF THE AREA UNDER STUDY

For the field experiment, native soil was collected from Klecza Dolna (Figure 1) near Wadowice (Małopolskie Province, Poland), classified as silty loam. The experiment was conducted on a loess-derived silty loam soil (wheat complex, good upland and foothill type, soil quality class RIIIa), selected due to its high sensitivity to changes in physicochemical properties following the addition of organic amendments. Loess soils are characterised by high waterholding capacity, considerable sorptive surface area, and good permeability, which makes them particularly suitable for studying mineralization, immobilization, and nutrient transport processes. Their moderate natural fertility allows the effects of sewage sludge application to be clearly distinguished. Furthermore, the site had been left fallow for approximately twenty years, eliminating the influence of previous fertilization and enabling the assessment of changes resulting solely from the applied sludge doses.

The experiment utilized dewatered and limestabilised sewage sludge obtained from a municipal wastewater treatment plant located in southern Poland. Preliminary analyses confirmed that the material did not exceed permissible concentrations of heavy metals and met the sanitary requirements for sludge intended for environmental use [Journal of Laws, 2015]. Microbiological assessment showed no presence of pathogenic Salmonella bacteria or eggs of soiltransmitted helminths (Ascaris, Trichuris, Toxocara), whose occurrence restricts the agricultural application of sewage sludge.

In the field experiments, three application rates of sewage sludge were used for each soil type: 50 Mg·ha^{-1} (single dose), 100 Mg·ha^{-1} (double dose), and 200 Mg·ha^{-1} (quadruple dose). Chemical analyses were conducted to determine key soil parameters affected by the application of sewage sludge. The procedures employed a combination of instrumental and colorimetric techniques commonly used in environmental studies, ensuring high analytical precision and reproducibility.

Determination of total carbon and total nitrogen

Total carbon (TC) and total nitrogen (TN) were determined using a Vario Max Cube elemental analyzer (Elementar), operating on the principle of hightemperature combustion at up to 1200 °C. The measurements followed the Dumas method, involving complete oxidation of the sample in an oxygen-rich atmosphere. Approximately 2.5 g of airdry soil was placed in reusable ceramic crucibles and analyzed using an automated sample changer. The resulting nitrogen oxides

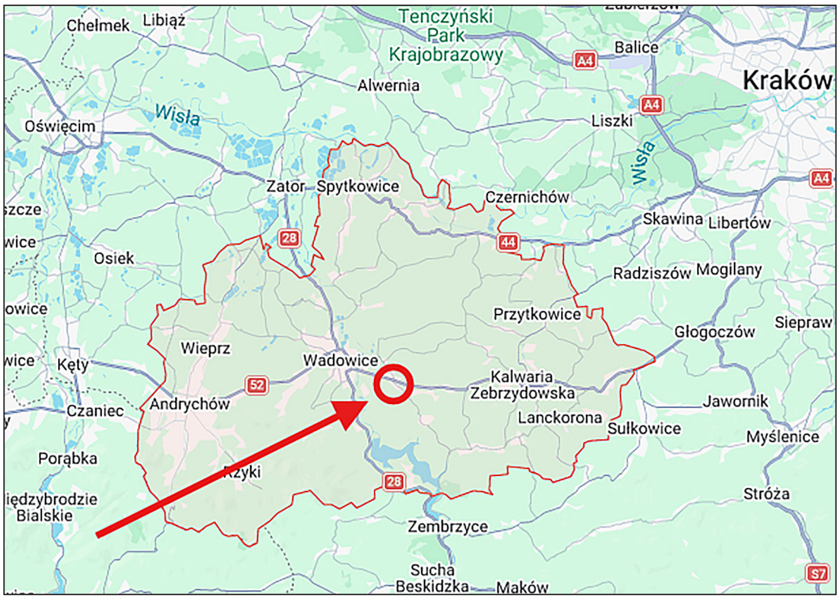

Figure 1. Localization of experimental pool – Klecza Dolna, Małopolskie Province (source: Google Maps)

were catalytically oxidized, purified, dried, and subsequently reduced to molecular nitrogen, which was quantified using a thermal conductivity detector. The instrument software calculated TC and TN contents based on sample mass and detector response.

Determination of plantavailable phosphorus

Plantavailable phosphorus was determined using the Egner–Riehm method following extraction with calcium lactate solution (pH 3.55). Analyses were performed using ICPOES with an Optima 7300 DV spectrometer (PerkinElmer). The buffered extractant ensured adequate solubility of phosphorus compounds. After extracting 5 g of soil in 250 cm³ of calcium lactate for 1.5 hours, the filtrate was collected for further analysis. Phosphorus concentration was quantified colorimetrically using a calibration curve, with absorbance measured at 575 nm.

Determination of nitrate nitrogen (NO_3^-N)

Nitrate nitrogen was determined colorimetrically (Panak, 1997) after extraction with 1% potassium sulfate, using a Beckman DU 640 spectrophotometer. In the presence of concentrated sulfuric acid(VI), nitrate ions reacted with phenolsulfonic acid to form a yellow nitrophenoldisulfonic compound, whose color intensity increased upon alkalization. After evaporating 5–10 cm³ of extract to dryness and performing the color reaction, absorbance was measured at 420 nm against a reagent blank. Nitrate concentration was calculated from a standard calibration curve.

RESULTS

To rigorously assess the significance of the observed differences between treatments, an analysis of variance (ANOVA) was performed. Posthoc Tukey tests were subsequently applied to identify which specific sewage sludge application rates differed from one another. Such tests are essential because ANOVA only indicates whether a significant overall effect exists, while posthoc comparisons determine precisely between which treatments these differences occur, ensuring a reliable interpretation of dosedependent responses.

The total nitrogen content in the soil increased systematically with the application of sewage sludge, showing a clear dose-dependent pattern. In the control soil, the mean nitrogen concentration was 0.092%, whereas even the lowest sludge dose (50 Mg·ha^{-1}) resulted in a substantial increase to 0.167%. A similar value was observed at 100 Mg·ha^{-1} (0.168%), indicating a temporary stabilisation of nitrogen levels at moderate application rates (Table 1). The highest dose (200 Mg·ha^{-1}) produced a marked increase to 0.209%, reflecting strong nitrogen enrichment. The relatively low variability observed at higher doses suggests high consistency of the treatment effect. In comparison, the sewage sludge itself contained 5.40% total nitrogen, confirming its role as a concentrated source of organic nitrogen.

A one-way analysis of variance (ANOVA) revealed a significant effect of dose on total nitrogen content ($F = 180.29$; $p < 0.001$), indicating statistically significant differences among treatments (Table 2). Tukey's HSD test ($\alpha = 0.05$) showed that the control (0 Mg·ha^{-1}) and the highest dose

Table 1. Total nitrogen content (%) in soil with sewage sludge application

Soil type	Sludge dose [Mg·ha^{-1}]	n	Range [%]	Mean [%]	SD [%]	SE [%]
Silty loam	0	12	0.056–0.128	0.092	0.018	0.005
Silty loam	50	12	0.161–0.172	0.167	0.003	0.001
Silty loam	100	12	0.162–0.173	0.168	0.003	0.001
Silty loam	200	12	0.204–0.214	0.209	0.003	0.001
Sewage sludge	–	12	5.39–5.41	5.40	0.005	0.001

Table 2. Total nitrogen content in soil with sewage sludge application – analysis of variance

Source of variation	SS	df	MS	F
Between groups	0.08541	3	0.02847	180.29
Within groups	0.00695	44	0.000158	-
Total	0.09236	47	-	-

(200 Mg·ha^{-1}) differed significantly from all other treatments. No significant differences were found between the 50 and 100 Mg·ha^{-1} doses, suggesting that increasing the application rate within this range does not lead to further significant changes in nitrogen content. In contrast, the highest dose (200 Mg·ha^{-1}) resulted in a distinct and statistically significant increase.

The total carbon content increased systematically with rising sewage sludge doses, showing a clear dosedependent response. In the control soil, the mean Ctotal value was 0.941%, whereas the application of 50 Mg·ha^{-1} nearly doubled the carbon content to 1.489%. A further increase was observed at 100 Mg·ha^{-1} (1.522%), while the highest dose (200 Mg·ha^{-1}) resulted in a substantial enrichment, reaching 1.781% (Table 3). The low standard deviation at higher doses indicates high consistency and uniformity of the treatment effect. The sewage sludge itself contained 6.234% total carbon, confirming its role as a concentrated source of organic matter and explaining the strong accumulation observed in amended soils. The application of sewage sludge had a significant effect on the analyzed soil parameter in the silty loam. A oneway analysis of variance (ANOVA) demonstrated a very strong influence of sludge dose on the measured variable ($F \approx 10,500$; $p < 0.0001$). A systematic and highly significant increase in the parameter value was observed with increasing sludge doses from 0 to 200 Mg·ha^{-1} (Table 4). The Tukey posthoc test confirmed that all compared dose levels differed significantly from one another ($p < 0.001$), indicating a clear and progressive dosedependent response of the soil to sludge application. The effect size ($\eta^2 = 0.998$) showed that nearly all variability in the dataset was explained by the sludge dose. These results clearly demonstrate that the amount of sewage sludge applied is a key factor determining the level of the studied parameter, and that the soil response exhibits a strongly dosedependent pattern.

Available phosphorus increased sharply with rising sewage sludge doses, showing a strong and clearly dosedependent response. In the control soil, the mean Pavail value was 27.72 g·10^{-3}·kg^{-1}, whereas the application of 50 Mg·ha^{-1} resulted in a nearly fivefold increase to 135.85 g·10^{-3}·kg^{-1}. A further rise was observed at 100 Mg·ha^{-1} (155.07 g·10^{-3}·kg^{-1}), while the highest dose (200 Mg·ha^{-1}) produced a pronounced enrichment, reaching 265.07 g·10^{-3}·kg^{-1} (Table 5). The relatively low standard deviation at higher doses indicates high consistency of the treatment effect. The sewage sludge itself contained 473.25 g·10^{-3}·kg^{-1} of phosphorus, confirming that sludge is a concentrated source of P and explaining the strong accumulation observed in amended soils. Application of sewage sludge had a highly significant effect on available phosphorus content in soil. Oneway ANOVA showed an extremely strong influence of sludge dose on P availability ($F = 19,000$; $p < 0.0001$). Mean phosphorus levels increased sharply and consistently with increasing doses from 0 to 200 Mg·ha^{-1}. Tukey's posthoc test confirmed that all dose levels differed significantly from one another ($p < 0.001$). The effect size was very high ($\eta^2 = 0.999$), indicating that nearly all variability in the dataset was

Table 3. Total carbon content (%) in soil with sewage sludge application

Soil type	Sludge dose [Mg·ha^{-1}]	n	Range [%]	Mean [%]	SD [%]	SE [%]
Silty loam	0	12	0.532–1.349	0.941	0.204	0.144
Silty loam	50	12	1.452–1.503	1.489	0.013	0.004
Silty loam	100	12	1.456–1.580	1.522	0.031	0.009
Silty loam	200	12	1.780–1.853	1.781	0.018	0.005
Sewage sludge	–	12	6.23–6.24	6.234	0.003	0.001

Table 4. Total carbon content in soil with sewage sludge application – analysis of variance

Source of variation	SS	df	MS	F
Between groups	8.676	3	2.892	10.500
Within groups	0.013	44	0.00030	-
Total	8.689	47	-	-

Table 5. Available phosphorus content ($g\cdot10^{-3}\cdot kg^{-1}$) in soil and sewage sludge

Soil type	Sludge dose [$Mg\cdot ha^{-1}$]	n	Range [$g\cdot10^{-3}\cdot kg^{-1}$]	Mean [$g\cdot10^{-3}\cdot kg^{-1}$]	SD	SE
Silty loam	0	12	18.62–36.82	27.72	4.55	3.22
Silty loam	50	12	124.7–147.0	135.85	5.58	1.61
Silty loam	100	12	146.0–164.1	155.07	4.53	1.31
Silty loam	200	12	257.3–273.0	265.07	3.93	1.13
Sewage sludge	–	12	473.2–473.3	473.25	0.03	0.02

Table 6. Available phosphorus content ($g\cdot10^{-3}\cdot kg^{-1}$) in soil and sewage sludge– analysis of variance

Source of variation	SS	df	MS	F
Between groups	147 978	3	49 326.2	19 000
Within groups	114.7	44	2.61	-
Total	148 093.3	47	-	-

explained by the applied sludge dose (Table 6). These results demonstrate a clear, strongly dosedependent increase in available phosphorus following sludge application.

Nitrate nitrogen increased markedly with rising sewage sludge doses, showing a strong and clearly dosedependent response. In the control soil, the mean NO_3^-–N concentration was 12.50 $g\cdot10^{-3}\cdot kg^{-1}$, whereas the application of 50 $Mg\cdot ha^{-1}$ resulted in a nearly fourfold increase to 47.25 $g\cdot10^{-3}\cdot kg^{-1}$. A further rise was observed at 100 $Mg\cdot ha^{-1}$ (54.74 $g\cdot10^{-3}\cdot kg^{-1}$), indicating continued intensification of nitrogen mineralization. The highest dose (200 $Mg\cdot ha^{-1}$) produced a pronounced enrichment, reaching 117.86 $g\cdot10^{-3}\cdot kg^{-1}$, which represents the strongest relative increase among all treatments (Table 7). The high standard deviation at this dose suggests substantial spatial variability, likely reflecting heterogeneous nitrification dynamics. The sewage sludge itself contained 297.30 $g\cdot10^{-3}\cdot kg^{-1}$ of nitrate nitrogen, confirming that sludge is a concentrated source of mineral N and explaining the strong accumulation observed in amended soils. Application of sewage sludge significantly affected the nitrate nitrogen content in the silty loam. Oneway ANOVA revealed a strong effect of sludge dose on P availability ($F=420$; $p < 0.0001$). Mean phosphorus concentrations increased markedly and consistently with increasing doses from 0 to 200 $Mg\cdot ha^{-1}$. Tukey's posthoc test confirmed that all dose levels differed significantly from one another ($p < 0.001$). The effect size was very high ($\eta^2 = 0.97$), indicating that the sludge dose explained nearly all variability in the dataset (Table 8). These results demonstrate a clear and strongly dosedependent increase in available phosphorus following sludge application (Figure 2).

Table 7. Nitrate nitrogen content ($g\cdot10^{-3}\cdot kg^{-1}$) in soil and sewage sludge

Soil type	Sludge dose [$Mg\cdot ha^{-1}$]	n	Range [$g\cdot10^{-3}\cdot kg^{-1}$]	Mean [$g\cdot10^{-3}\cdot kg^{-1}$]	SD	SE
Silty loam	0	12	9.14–15.86	12.50	1.68	1.19
Silty loam	50	12	35.7–59.00	47.25	5.83	1.68
Silty loam	100	12	52.7–57.20	54.74	1.13	0.33
Silty loam	200	12	95.7–139.50	117.86	10.95	3.16
Sewage sludge	–	12	297.2–297.40	297.30	0.05	0.04

Table 8. Nitrate nitrogen content ($g\cdot10^{-3}\cdot kg^{-1}$) in soil and sewage sludge – analysis of variance

Source of variation	SS	df	MS	F
Between groups	46 676.3	3	15 558.8	420
Within groups	1 631.7	44	37.1	-
Total	48 308	47	-	-

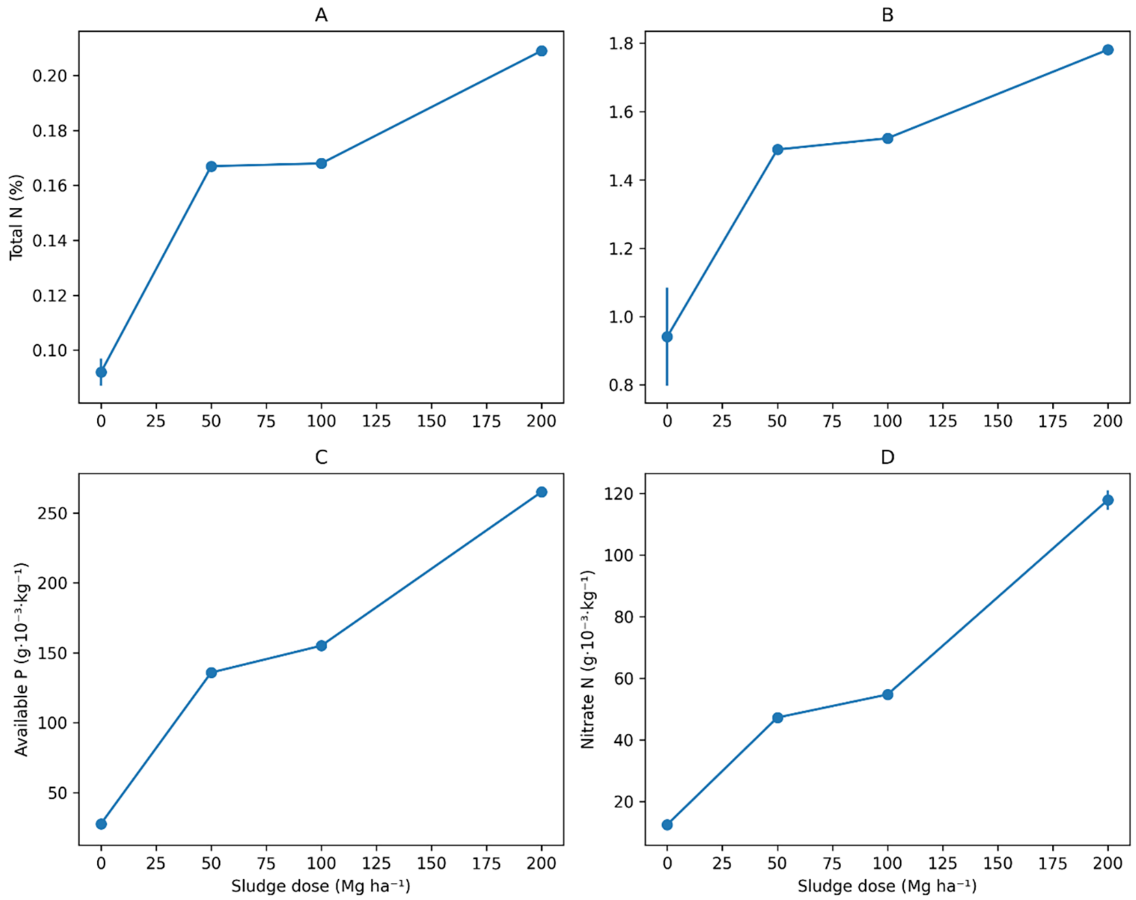

Figure 2. Effect of sewage sludge dose on selected soil properties (average: (A) total nitrogen content (%), (B) total carbon content (%), (C) available phosphorus (g·10⁻³·kg⁻¹), and (D) nitrate nitrogen (g·10⁻³·kg⁻¹)

When analyzing the mean values of all measured parameters, a clear and consistent increase in nutrient concentrations was observed with each successive sewage sludge dose. Total nitrogen, nitrate nitrogen, available phosphorus, and total carbon all showed a strong dosedependent response, with the highest values recorded at 200 Mg·ha⁻¹. Even the lowest application rate (50 Mg·ha⁻¹) resulted in substantial enrichment compared with the control, indicating that sewage sludge acted as an effective source of both organic matter and mineral nutrients. The low standard deviations at higher doses further confirm the uniformity and stability of the treatment effects across replicates.

Across all analysed soil properties, the observed increases followed a uniform and highly consistent dosedependent pattern, indicating that the soil responded to sewage sludge application in a predictable and systematic manner. This coherence across parameters highlights the stability of the treatment effect and reinforces the reliability of the observed trends.

DISCUSSION

The application of sewage sludge significantly influenced the chemical properties of the soil, particularly within the C–N–P system, with observed changes clearly dependent on the applied dose. Across all treatments, a consistent increase in total nitrogen, nitrate nitrogen, available phosphorus, and total carbon was observed, confirming the high fertilization potential of sewage sludge (Nkoa, 2014; Muter et al., 2022; Fytili and Zabaniotou, 2008).Total nitrogen (N-total) increased from 0.092% in the control soil to 0.209% at the highest dose of 200 Mg·ha⁻¹. Even the lowest dose of 50 Mg·ha⁻¹ nearly doubled nitrogen content, indicating the efficiency of sewage sludge as a source of organic nitrogen. The relatively small difference between 50 and 100 Mg·ha⁻¹ (0.167% vs. 0.168%) may reflect temporary stabilization of nitrogen in organic forms or partial immobilization by soil microorganisms. Similar patterns have been reported in long-term studies, where organic amendments increase total nitrogen while modifying its fractions and availability (Wierzbowska et al., 2021; Żukowska et al., 2024). The role of sludge-derived nitrogen in enhancing soil fertility and influencing nitrogen dynamics has also been highlighted (Rigby and Smith, 2011). The pronounced increase at 200 Mg·ha^{-1} suggests that the soil system exceeded its buffering capacity, resulting in nitrogen accumulation. Nitrate nitrogen (NO_3^-–N) exhibited a dramatic increase from 12.50 to 117.86 mg·kg^{-1}, with the most substantial rise occurring between 100 and 200 Mg·ha^{-1}, indicating intensified mineralization and nitrification processes. The availability of easily decomposable organic matter likely stimulated microbial activity, accelerating the conversion of organic nitrogen into mineral forms (Almási et al., 2025; Bastida et al., 2017). This also implies an increased risk of nitrate leaching under field conditions, as widely documented in sludge-amended soils (Nkoa, 2014; FAO, 1992; Singh and Agrawal, 2008). The high variability observed at the highest dose reflects the dynamic and spatially heterogeneous nature of nitrogen transformations in soil.

The interpretation of nitrate results should be considered within a broader environmental context, particularly with regard to potential nitrogen losses through leaching under varying soil–hydrological conditions. Nitrate is highly mobile in soil, and its accumulation following sewage sludge application may increase the risk of transport to groundwater and surface waters, especially in permeable soils or during periods of high precipitation (Di and Cameron, 2002; Cameron et al., 2013). Therefore, the observed increases in NO_3^-–N not only reflect enhanced nitrogen availability but also indicate a potential pathway for environmental losses, which should be taken into account when evaluating the sustainability of sludge application practices.

A similar dose-dependent trend was observed for available phosphorus, which increased from 27.72 to 265.07 mg·kg^{-1} at 200 Mg·ha^{-1}. This strong accumulation confirms that sewage sludge is a significant phosphorus source capable of rapidly enriching soil P pools (Muter et al., 2022; Fytili and Zabaniotou, 2008). Long-term studies indicate that repeated sludge application can lead to the formation of "legacy phosphorus" pools, potentially exceeding environmental thresholds (Asrade et al., 2024; Harrison and Oakes, 2002a,b). Although phosphorus is less mobile than nitrogen, its accumulation increases the risk of losses via surface runoff, contributing to eutrophication (Breitenmoser et al., 2026; Singh and Agrawal, 2008). Application of sewage sludge significantly increased plant-available phosphorus, reflecting both direct input and the accumulation of legacy P. Stabilized in the soil through binding to minerals and organic matter, this phosphorus can remain available to plants over time. Environmentally, legacy P may gradually leach into surface waters, raising eutrophication risks, which underscores the need for long-term monitoring of fertilization practices. Low variability at higher doses suggests progressive stabilization of phosphorus in mineral and organic fractions (Condron et al., 2013; Sharpley et al., 2013). The pronounced increase between 0 and 50 Mg·ha^{-1} can be attributed both to the direct input of readily available phosphorus in the sludge and to desorption and solubilization of soil-bound phosphorus induced by organic matter addition. Organic acids released during decomposition may further enhance phosphorus mobility by competing with phosphate ions for sorption sites.

Total carbon (C-total) increased from 0.941% to 1.781% (+89%), confirming that sewage sludge is a significant source of organic matter, improving soil structure, water retention, and biological activity (Żukowska et al., 2024; Serwecińska et al., 2024). Long-term sludge application can substantially increase soil organic carbon stocks and promote carbon sequestration, although a portion of this carbon remains labile and subject to mineralization (Serwecińska et al., 2024; Lal, 2004). Improvements in soil physical and microbiological properties following organic amendments have also been widely documented (Debosz et al., 2002).

Considering interactions within the C–N–P system, the simultaneous increase in carbon and nitrogen promotes microbial processes that regulate nutrient availability (Paganini et al., 2024; Bastida et al., 2017). At moderate doses (50–100 Mg·ha^{-1}), a balance between mineralization and immobilization appears to be maintained, ensuring efficient nutrient use without excessive accumulation. In contrast, the highest dose (200 Mg·ha^{-1}) results in nutrient surpluses, enhanced mineral nitrogen formation, and potential environmental risks.

In conclusion, sewage sludge represents a valuable source of organic matter and nutrients, but its application requires careful management (Figure 3). Moderate doses improve soil fertility while minimizing the risk of nitrate leaching and

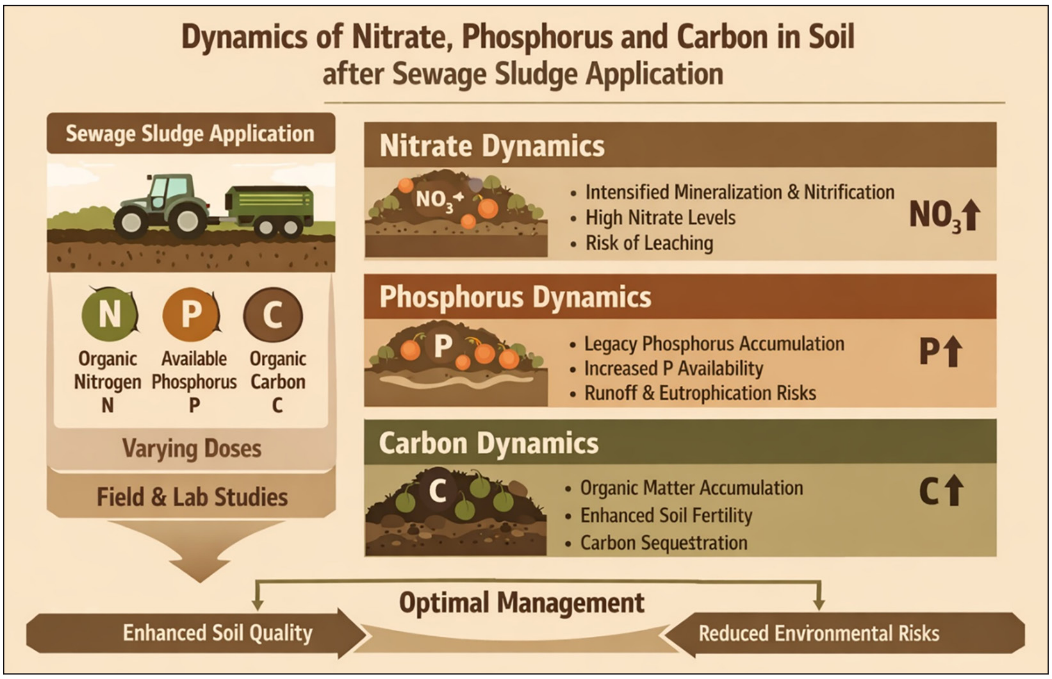

Figure 3. Dynamics of biogenic elements in the soil environment

phosphorus accumulation, whereas excessive doses can cause nutrient imbalances, increased environmental pressure, and reduced system sustainability (Nkoa, 2014; Muter et al., 2022; Singh and Agrawal, 2008). The results confirm that sewage sludge stimulates key soil biogeochemical processes, particularly mineralization and nitrification, increasing nutrient availability. The non-linear response of nitrate nitrogen indicates that high sludge doses may exceed the soil's buffering capacity, with associated environmental implications.

About changes in microbial activity and community structure should be interpreted with caution, as observed patterns may reflect complex interactions between nutrient availability, soil physicochemical properties, and temporal dynamics. Highlighting the interpretative nature of these findings is important, and supporting them with literature on microbial responses to organic amendments can strengthen the discussion (Fierer et al., 2007; Rousk et al., 2010). This approach helps contextualize shifts in microbial biomass, enzymatic activity, and community composition, distinguishing between direct effects of sewage sludge addition and broader soil-environment interactions.

For future research, it is recommended to include substantially higher sludge application rates, such as 400, 800, and 1200 Mg·ha^{-1}, in order to better capture the behavior of nutrient accumulation trends under intensified sludge fertilization. The observed accumulation of nitrogen and phosphorus in the soil may have significant environmental implications, particularly in the context of eutrophication of surface waters. An excess of these nutrients increases the risk of their transport into water bodies through surface runoff and leaching, which can lead to intensified algal blooms and a deterioration of water quality. This effect is especially pronounced at high sewage sludge application rates, where the greatest enrichment of soil with N and P was recorded.

CONCLUSIONS

In summary of the present study, the following conclusions were obtained regarding the dynamics of nitrate, phosphorus and carbon in soil after sewage sludge application:

1. Sewage sludge application significantly increased soil nutrient content in a dose-dependent manner, with total nitrogen rising from 0.092% to 0.209% and nitrate nitrogen from 12.50 to 117.86 mg·kg^{-1} at the highest dose. The relatively high nitrate accumulation at 200 Mg·ha^{-1} suggests that excessive sludge doses can increase the risk of groundwater contamination, highlighting the importance of integrating sludge management with local hydrological conditions.

2. Available phosphorus exhibited nearly tenfold enrichment, confirming sludge as an effective P source but highlighting the risk of long-term "legacy P" accumulation. The relatively low variability in phosphorus at higher doses suggests that sludge-derived P becomes increasingly stabilized in soil mineral and organic fractions, reducing immediate bioavailability but creating long-term nutrient reservoirs.
3. Total carbon increased by approximately 89%, demonstrating the role of sewage sludge in enhancing soil organic matter, structure, water retention, and microbial activity, with implications for carbon sequestration.
4. Moderate application rates (50–100 $Mg \cdot ha^{-1}$) optimized nutrient balance, whereas excessive doses (200 $Mg \cdot ha^{-1}$) led to nutrient surplus and potential environmental hazards.
5. Careful dose management and long-term monitoring are essential to maximize agronomic benefits while minimizing risks, with further research needed on nutrient transformation kinetics, C–N–P interactions, and climate-related variability.
6. Incremental increases in soil carbon with sludge application indicate that repeated amendments can enhance microbial activity and enzymatic processes, potentially improving nutrient cycling efficiency and soil resilience.
7. Sludge amendments may alter microbial community structure, indirectly influencing nutrient availability, soil enzymatic activity, and the balance between mineralization and immobilization processes; this emphasizes the need for integrated studies on soil microbiome dynamics following sludge application.

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REFERENCES

1. Almási, C., Orosz, V., Tóth, T., Mansour, M. M., Demeter, I., Henzsel, I., Bogdányi, Z., Szegi, T. A., Makádi, M. (2025). Effects of sewage sludge compost on carbon, nitrogen, phosphorus, and sulfur ratios and soil enzyme activities in a long-term experiment. *Agronomy, 15*(1), 143. https://doi.org/10.3390/agronomy15010143
2. Arrobas, M., Meneses, R., Gusmão, A. G., da Silva, J. M., Correia, C. M., Rodrigues, M. Â. (2024). Nitrogen-rich sewage sludge mineralized quickly, improving lettuce nutrition and yield, with reduced risk of heavy metal contamination of soil and plant tissues. *Agronomy, 14*(5), 924. https://doi.org/10.3390/agronomy14050924
3. Asrade, D. A., Kulhánek, M., Balík, J., Černý, J., Sedlář, O., Suran, P. (2024). Phosphorus availability and balance with long-term sewage sludge and nitrogen fertilization in chernozem soil under maize monoculture. *Plants, 13*(15), 2037. https://doi.org/10.3390/plants13152037
4. Bastida, F., Jehmlich, N., Hernández, T. (2017). The soil microbiome and its role in nutrient cycling. *Applied Soil Ecology, 120*, 1–12.
5. Bornø, M. L., Zervas, A., Bak, F., Merl, T., Koren, K., Nicolaisen, M. H., Jensen, L. S., Müller-Stöver, D. S. (2023). Differential impacts of sewage sludge and biochar on phosphorus-related processes: An imaging study of the rhizosphere. *Science of The Total Environment, 905*, 166888. https://doi.org/10.1016/j.scitotenv.2023.166888
6. Breitenmoser, L., Eggimann, S., Sharma, A., et al. (2026). Phosphorus recovery from Indian sewage sludge by acidification and precipitation. *Scientific Reports, 16*, 3804. https://doi.org/10.1038/s41598-025-34006-2
7. Cameron, K. C., Di, H. J., Moir, J. L. (2013). *Nitrogen losses from the soil/plant system: A review.* Annals of Applied Biology, 162(2), 145–173. https://doi.org/10.1111/aab.12014
8. Charlton, A., Sakrabani, R., Tyrrel, S., Rivas Casado, M., McGrath, S. P., Crooks, B., Cooper, P., Campbell, C. D. (2016). Long-term impact of sewage sludge application on soil microbial biomass: An evaluation using meta-analysis. *Environmental Pollution, 219*, 1021–1035. https://doi.org/10.1016/j.envpol.2016.07.050
9. Condron, L. M., Turner, B. L., CadeMenun, B. J. (2013). Evaluating the benefits of legacy phosphate. *Plant and Soil, 472*, 56–68. https://doi.org/10.1007/s11104022056013
10. Debosz, K., Petersen, S. O., Kure, L. K., Ambus, P. (2002). Evaluating effects of sewage sludge on soil properties. *Applied Soil Ecology, 19*(3), 237–248.
11. Di, H. J., Cameron, K. C. (2002). Nitrate leaching in temperate agroecosystems: Sources, factors and mitigating strategies. *Nutrient Cycling in Agroecosystems, 64*, 237–256. https://doi.org/10.1023/A:1021471531188
12. Encyclopaedia Britannica. (2024). Compost, peat, and sludge. https://www.britannica.com/technology/agricultural-technology/Compost-peat-and-sludge

13. FAO. (1992). Agricultural use of sewage sludge. Food and Agriculture Organization. https://www.fao.org/4/t0551e/t0551e08.htm
14. Fierer, N., Bradford, M. A., Jackson, R. B. (2007). Toward an ecological classification of soil bacteria. *Ecology, 88*(6), 1354–1364. https://doi.org/10.1890/05-183
15. Fytili, D., Zabaniotou, A. (2008). Utilization of sewage sludge in EU. *Renewable and Sustainable Energy Reviews, 12*(1), 116–140. https://doi.org/10.1016/j.rser.2006.05.014
16. Harrison, E. Z., Oakes, S. R. (2002a). Effects of biosolids application on soil phosphorus. *Journal of Environmental Quality, 31*(3), 989–995.
17. Harrison, E. Z., Oakes, S. R. (2002b). Land application of sewage sludge: An appraisal of the US regulations. *International Journal of Environment and Pollution, 18*(1), 1–23.
18. Kacprzak, M., Baran, J., Fijalkowski, K. (2025). Emerging sewage sludge treatment technologies for land carbon sequestration: A comprehensive review. *Journal of Material Cycles and Waste Management, 27*, 2866–2886. https://doi.org/10.1007/s10163-025-02369-3
19. Klatka T.S., Malec M., Ryczek M. (2019). Analysis of spatial variability of selected soil properties in the hard coal post-mining area. *Journal of Ecological Engeneering; 20*(3), 185–193. https://doi.org/10.12911/22998993/99781
20. Lal, R. (2004). Soil carbon sequestration impacts on climate change. *Science, 304*(5677), 1623–1627. https://doi.org/10.1126/science.1097396
21. Markowicz, A., Bondarczuk, K., Wiekiera, A., et al. (2021). Is sewage sludge a valuable fertilizer? A soil microbiome and resistome study under field conditions. *Journal of Soils and Sediments, 21*, 2882–2895. https://doi.org/10.1007/s11368-021-02984-1
22. Muter, O., Dubova, L., Kassien, O., Cakane, J., Alsina, I. (2022). Application of the sewage sludge in agriculture: Soil fertility, technoeconomic, and life-cycle assessment. *IntechOpen*. https://doi.org/10.5772/intechopen.104264
23. Nkoa, R. (2014). Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: A review. *Agronomy for Sustainable Development, 34*(2), 473–492. https://doi.org/10.1007/s13593-013-0196-z
24. Panak, H. (1997). *Colorimetric determination of nitrate nitrogen in soil.* Instructional materials, Institute of Soil Science and Plant Cultivation.
25. Paganini, E. A. L., Silva, R. B., Ribeiro Roder, L., Guerrini, I. A., Capra, G. F., Grilli, E., Ganga, A. (2024). A systematic review and meta-analysis of the sustainable impact of sewage sludge application on soil organic matter and nutrient content. *Sustainability, 16*(22), 9865. https://doi.org/10.3390/su16229865
26. Petryk A. (2023). Case study on the use of sewage sludge for the reclamation of mining sites contaminated with heavy metals. *Journal of Ecological Engineering, 24*(9), 171–182
27. https://doi.org/10.12911/22998993/169160
28. Rousk, J., Brookes, P. C., Bååth, E. (2010). Investigating the mechanisms for the opposing pH relationships of fungal and bacterial growth in soil. *Soil Biology and Biochemistry, 42*(6), 926–934. https://doi.org/10.1016/j.soilbio.2010.02.009
29. Serwecińska, L., Font-Nájera, A., Strapagiel, D., et al. (2024). Sewage sludge fertilization affects microbial community structure and its resistome in agricultural soils. *Scientific Reports, 14*, 21034. https://doi.org/10.1038/s41598-024-71656-0
30. Sharpley, A. N., Kleinman, P. J. A., McDowell, R. W., Gitau, M. (2013). Toward a transdisciplinary and unifying definition of legacy phosphorus. *Journal of Environmental Quality, 42*(2), 406416. https://doi.org/10.2134/jeq2012.0418
31. Singh, R. P., Agrawal, M. (2008). Benefits and risks of sewage sludge application. *Waste Management, 28*(2), 347–358.
32. Trzaska, K., Gil, F., Çalış, D., et al. (2025). Carbon-rich waste-derived fertilizers: Impacts on soil carbon dynamics and plant growth. *Waste and Biomass Valorization*. https://doi.org/10.1007/s12649-025-03304-1
33. Wierzbowska, J., Sienkiewicz, S., Załuski, D. (2021). Nitrogen fractions in soil fertilized with waste organic materials. *Agronomy, 11*(8), 1474. https://doi.org/10.3390/agronomy11081474
34. Żukowska, G., Futa, B., Myszura Dymek, M. (2024). Biochemical parameters of fallow light soil enriched with sewage sludge. *Agriculture, 14*(10), 1810. https://doi.org/10.3390/agriculture14101810
35. Poland. (2015). *Journal of Laws of the Republic of Poland, item 257*. https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20150000257