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Developing soil conditioner composites for enhancing nitrogen mineralization to mitigate the negative effects of climate change in a sandy soil

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Abstract

Self-developed soil conditioner composites containing fermented chicken manure as a raw material alongside bentonite and super-absorbent polymer in different doses and combinations were tested in a 112 day long soil incubation experiment. This study aimed to determine their effects on soil N mineralization, and the changes in the amount of soil mineralized nitrogen forms, cumulative mineralized nitrogen (N_{min}), and C/N ratio in a sandy soil (Lamellic Arenosol) at two different soil water holding capacity (SWHC) levels and soil layers. Potentially mineralized nitrogen (PMN), net mineralization rates (NMR), and nitrification rates (NNR) were also calculated to study the effectiveness of treatments. Soil NH_4-N decreased by 50–70% while NO_3-N increased by 150–200% in the treated soil, so the NO_3-N and NH_4-N ratio changed from 1/3 to 2/1 during the incubation. N_{min} gradually increased and was described by a linear tendency ($R \geq 0.99$) for both soil layers and SWHC levels. Composite treatments increased significantly the PMN, and NMR values by 2–4 times and NNR values by 40–240% compared to the control. Applied composites enhanced the mineralized proportion of total nitrogen content by 2–6%. It was found that the composites were more effective at lower SWHC level and in their application layer than chicken manure alone. Overall, the developed organic-based composites are able to cope with changing soil conditions, which can help mitigate the negative effects of climatic anomalies, especially in arid areas with limited water resources by improving soil nutrient supply, thus contributing to sustainable nutrient management.

1. Introduction

One of the most important environmental cycles that affects the sustainability in agriculture is the conversation and mineralization of carbon (C) and nitrogen (N) in soils. Soil organic matter (SOM) greatly affects the C/N equilibrium, and soil fertility, biodiversity, structure, water retention capacity, erosion and compaction of soils. However, the unsustainable use and management of land, climatic anomalies and urbanization have an increasing effect on soil degradation and the loss of SOM. Approximately 45% of soils in Europe have lower than 2% organic carbon content that is continuously decreasing (Jones et al., 2012). Therefore, nowadays there is a growing concern about the decrease of SOM content in EU countries (Panagos et al., 2013; Yigini and Panagos, 2016). Many authors pointed out that major effort should be taken to maintain or enhance soil organic matter stocks in the EU (Günal et al., 2015; Virto et al., 2015). Usage of organic materials, and co-products (crop residues, animal and green manures) to improve SOM is frequented in sustainable agricultural practices (Escobar and Hue, 2008; Roy and Kashem, 2014; King et al., 2020) and it also has a priority for waste management, and in the Circular Economy Concept (Diacono et al., 2019).

Among animal manures, chicken manure is considered as an excellent fertilizer due to its high nutrient content with increasing amounts all over the world due to the demand for low-cholesterol meat products, and rapid production turnover. Nevertheless, it is potentially hazardous waste, generated in huge amounts annually contributing to environmental problems unless properly treated (Sharpley et al., 2007; Manogaran et al., 2022).

Excessive use of manure has serious environmental impacts, and leads to environmental pollutions in different spheres:

deterioration of air quality (odour effects, ammonia gas emission), water quality (accumulation of harmful pathogens, nitrate leaching into the groundwater, eutrophication), and soil quality (ammonia volatilization, nutrient runoff, and erosion) (Zhang et al., 2018). Therefore, the establishment and application of correct dosages is essential for sustainable and environmental nutrient management in agricultural practice.

However, chicken manure alone does not provide sufficient nutrient supply and favourable circumstances (Amanullah et al., 2010) especially for soils that can be characterized by poor nutrient management, and insufficient water regime (Gaikwad et al., 2017).

Therefore, it is important to supplement manures with additive materials that may improve its properties, mainly water management properties. To improve properties of chicken manure, superabsorbent polymers (SAPs) and bentonite were used in our study. These amendments enhance water and nutrient use efficiency, soil permeability, density, structure, and evaporation of soil (Abobatta, 2018; Mi et al., 2020; Fayek et al., 2020; Grabowska-Polanowska et al., 2021; Fernández et al., 2022; Patra et al., 2022; Malik et al., 2023). Bentonite significantly increases the concentration of soil organic C, total N, and the retention of applied nutrient cations in the soil (Czaban et al., 2013; Czaban and Siebielec, 2013) thereby enhancing mineralization.

However, to recommend the use of such products it is necessary to know their transformation and nutrient supply properties. To determine the appropriate dosage of organic fertiliser, the transformation of organic matter in the soil needs to be investigated to maximize agricultural N use efficiency and to minimize environmental losses. Testing for soil mineral N and potentially mineralizable nitrogen during the growing season is important for forecasting how much additional fertiliser N may be required to meet crop demand.

Therefore, the main aims of our study are to develop and test organic (chicken manure) based composites (containing SAPs and bentonite) to study their effects on soil C and N form, C/N ratio, and potential rates of N mineralization, and to evaluate the usage of these composites as organic N sources in farming systems.

The novelty of our approach is that it provides a solution for the depletion of soil organic matter, while improving soil water management, and enhancing soil N mineralization at the same time. Such a multifactorial approach is highly recommended in all areas where the availability of nutrients, especially nitrogen, is severely limited due to field conditions (poor soil organic matter and nutrient content, eroded soil structure and low water holding capacity).

2. Materials and methods

2.1. Characteristics of the developed composites

To study the effects of developed composites on soil N mineralization, an aerobic laboratory incubation experiment was set up. For incubation, fermented chicken manure was used as a raw material, (Bio-Fer Natur Extra (NEX)), produced by Baromfi Coop Ltd. The main components of manure are shown in Table 1.

In the incubation experiment, two different additives were used to enhance the properties of manure. A synthetic (inorganic) (S) and an organic SAP (Z) were used to compare those effects. The S was a cross-linked acrylamide and potassium polyacrylate copolymer, Stockosorb (EVONIK Nutrition &Care GmbH). The Z was Zeba (starch-g-poly (2-propenamide-co-propenoic acid) potassium salt) which is an ionic starch graft copolymer (UPL LTD). Furthermore, bentonite as another soil additive was used as a clay mineral, consisting predominantly of smectite minerals, usually montmorillonite (Axis Bentonit Ltd.).

2.2. Soil characteristics

Before the incubation experiment, the basic parameters of soil were determined to establish the initial nutrient status of soil. During the experiment, collected soil samples were analysed to study the effectiveness of treatments.

Table 1
Main chemical characteristics of fermented chicken manure

Component	Value	Component	Value
N (w/w%)	5.50	Fe (mg kg^{-1})	545.00
P (P_2O_5) (w/w%)	3.00	Mn (mg kg^{-1})	374.00
K (K_2O) (w/w%)	2.50	Mo (mg kg^{-1})	3.66
Ca (w/w%)	6.00	Zn (mg kg^{-1})	367.00
Mg (w/w%)	0.50	Cu (mg kg^{-1})	53.30
S (w/w %)	1.00	Moisture content (w/w%)	12.00
B (mg kg^{-1})	31.40	pH	7.20
C (w/w%)	41.64	C/N ratio	7.57

Source: https://bio-fer.hu/bio-fer-natur-extra/

Nutrient contents are expressed in total element content. pH was determined in 10:1 extract solution.

Soil organic carbon (SOC) was determined by Walkley-Black method (Perkin-Elmer Analyst 300; MSZ-08-0210:1977). Soil total Carbon (TC) and total Nitrogen (TN) content was measured with the dry combustion method using a CNS analyzer (Nagy 2000; VarioMax Cube Elemental Analysensysteme GmbH, Hanau, Germany).

Soil organic nitrogen (SON) was determined by the Kjeldahl method (VELP DKL 20, MSZ-08-0458:1980). Soil nitrate and ammonium content was extracted by 1M KCl solution and assessed by spectrophotometric method (FOSS FIASTAR 5000; MSZ 20135:1999) Mineral nitrogen (MN) was calculated as the sum of nitrate-N and ammonium-N. Soil C/N ratios were calculated from the TC and TN results. From measured parameters the cumulative mineralized N, potentially mineralizable N, net mineralization rate and nitrification rate were computed.

The soil type is a brown forest soil with a mainly sandy texture (Pallag, Lamellic Arenosol) (Table 2). Based on the soil analysis, this soil had an average SOC content of 8.90 g kg^{-1}, and did not contain inorganic C forms, so TC was 8.94 g kg^{-1}. The TN content was 1.154 g kg^{-1}, a SON content was 1.14 g kg^{-1}, mineralized N contents (NO_3-N and NH_4-N) were 11.6 mg kg^{-1} and 12.4 mg kg^{-1}. The C/N ratio was low (7.75), indicating unfavourable mineralization conditions. Soil did not contain measurable water soluble salts and its pH was 6.07 (slightly acidic) at the start of the experiment. The unfavourable soil parameters measured confirmed the necessity of using composites.

2.3. Experimental conditions

Composites were tested with a typical Hungarian soil type, brown forest soil with a sandy texture (Pallag, Lamellic Arenosol). Samples were incubated at 25°C representing the mean soil temperature of the growing season in Hungary. Moreover, higher temperature promotes the decomposition of SOM by different microbial communities that are not normally active at lower temperatures, providing a spurious estimate of potentially mineralized nitrogen (Sharifi et al. 2007). In the four-month-long (112 days) aerobic incubation, controlled moisture conditions (at two soil water holding capacity levels (40% and 60%)) were maintained. Sieved (<2mm) soil samples (500 g) were packed into plastic incubation pots, then samples were collected monthly, and analysed. Soil moisture content was adjusted by daily irrigation using distilled water to avoid further nutrient addition and maintain the adequate water holding capacity levels.

Table 2
The chemical parameters of soils of Pallag

Basic soil parameters	**Pallag soil**
pH (KCl)	6.07
Water soluble salts (w/w%)	<0.02
Carbonate (w/w%)	< 0.10
TC (g kg^{-1})	8.94
SOC (g kg^{-1})	8.90
Nitrate (g kg^{-1}) (KCl)	0.0116
Ammonium (g kg^{-1}) (KCl)	0.0124
SON (g kg^{-1})	1.14
TN (g kg^{-1})	1.154
C/N	7.75
Soil texture (%)	
sand	52.54
silt	46.64
clay	0.82

KCl is a soil extractant according to the Hungarian standard (MSZ 20135:1999).

2.4. Treatments and doses

Fermented chicken manure, bentonite, and SAPs were mixed and filled in a cellulose capsule (capsule size: “0”; Capsule Connection LLC) manually with a capsule machine. Every capsule contained 0.5 g of the mixture and placed at a depth of 2 cm in the soil in every pots. Each treatment had three replicates, four sampling time (monthly), and two moisture levels resulting in 24 pots per treatment, representing 144 experimental pots overall.

For incubation, 450 mg of fermented chicken manure, 40–45 mg of bentonite, and 5–10 mg of SAPs were mixed with 500 g of soil samples, and put in a plastic incubation pot. To establish the application rates and doses manufacturer’s recommendations and earlier experiences were used (Tóth et al. 2023). In the incubation experiment, six treatments were applied. In addition to the absolute control (C), five treatments were set up and applied in the experiment, which can be divided into three groups:

- CM (contained solely of fermented chicken manure),
- Group S (containing fermented chicken manure and S in two different doses – S1 and S2),
- Group Z (containing fermented chicken manure and Z in two different doses – Z1 and Z2).

In the treatments, the NEX:SAPs:Bentonite ratios were 90:1:9 and 90:2:8 respectively, where the amount of chicken manure was constant, in all treatments. The constituents of the treatments are shown in Table 3.

Table 3
The constituents of the treatments used in the experiment

Treatments	Doses (mg/pot)			
	CM	Bentonite	S	Z
C	–	–	–	–
CM	450	–	–	–
S1	450	45	5	–
S2	450	40	10	–
Z1	450	45	–	5
Z2	450	40	–	10

Source: https://axisbentonitkft.hu/bentonit/.

2.5. Calculation of PMN, NMR and NNR constants

The cumulative N mineralization was calculated over the sum of 112 days of incubation. The advantage of the concept of potentially mineralized nitrogen and k is for use in characterizing soil-available N (Stanford and Smith, 1972). According to Nagy (2010) and Maitlo et al. (2022) the potentially mineralized nitrogen values were calculated by first-order kinetics.

The amount of N mineralized is defined as the difference between the amount of mineralizable N at time 0 and at time t. According to this concept, mineralized N and its cumulative values can be calculated by summing the nitrate and ammonium content throughout the entire experiment (Tóth et al., 2023). In the experiment the net mineralization rate values were calculated as well (Eq. 1.):

$$NMR = [(\text{Mineral N})_t - (\text{Mineral N})_{t0}]t \qquad \text{(Eq. 1.)}$$

where $(\text{Mineral N})_t$ is the mineralized N (NO_3-N and NH_4-N) measured in the soil at month t and $(\text{Mineral N})_{t0}$ is the mineralized N from the incubation measured in the soil in the initial time.

To establish the efficiency of the oxidation process the nitrification rates were also calculated using the following relationship (Eq. 2.). In this approach, the $N_{nitrified}$ as the nitrification rate is calculated from the nitrate concentrations at the beginning and at the end of incubation.

$$NNR = N_{nitrified} = (\text{NitrateT}_{112} - \text{NitrateT}_0)/112 \text{ days} \qquad \text{(Eq. 2.)}$$

Where: NitrateT_{112} = nitrate concentration at the end of the 112-day incubation,
NitrateT_0 = nitrate concentration at the beginning of the incubation.

2.6. Statistical analysis

Statistical analyses were performed using R studio agricolae package of R software (Mendiburu, 2019). The Shapiro-Wilk normality test was employed to assess the data distribution. Based on the results of the normality test, the appropriate type of statistical test was selected for further analysis. To determine the significant differences between the treatments, a one-way analysis of variance (ANOVA) with Duncan's post hoc test was conducted at a significance level of $p<0.05$. For correlation analysis, Pearson Product-Moment correlation matrix was generated by Statgraphics 18 software.

3. Results and discussion

3.1. Soil mineral nitrogen forms

The mineralisation of the organic-N fraction was revealed by the evolution of the inorganic forms in the soil. Soil NH_4-N and NO_3-N contents during the experiment are presented in Fig. 1–4. The obtained results pointed out that the soil NH_4-N content was decreased, while NO_3-N content increased in all treatments during the incubation period at lower moisture content in the upper soil layer due to the mineralization processes. The initial predominance of NH_4-N over NO_3-N mainly in the upper soil layer turned to nitrate dominance during the incubation (Fig. 1 and Fig. 3). In general, the NO_3-N and NH_4-N ratio changed from ≈1/3 to 2/1 by the end of the incubation. It means that the NO_3-N content became dominant by the end of incubation. For instance, NO_3-N content increased from 5 mg kg^{-1} to 25 mg kg^{-1} on average, while the amount of NH_4-N decreased by 50–70% depending on the treatments in the upper soil layer at both moisture levels,

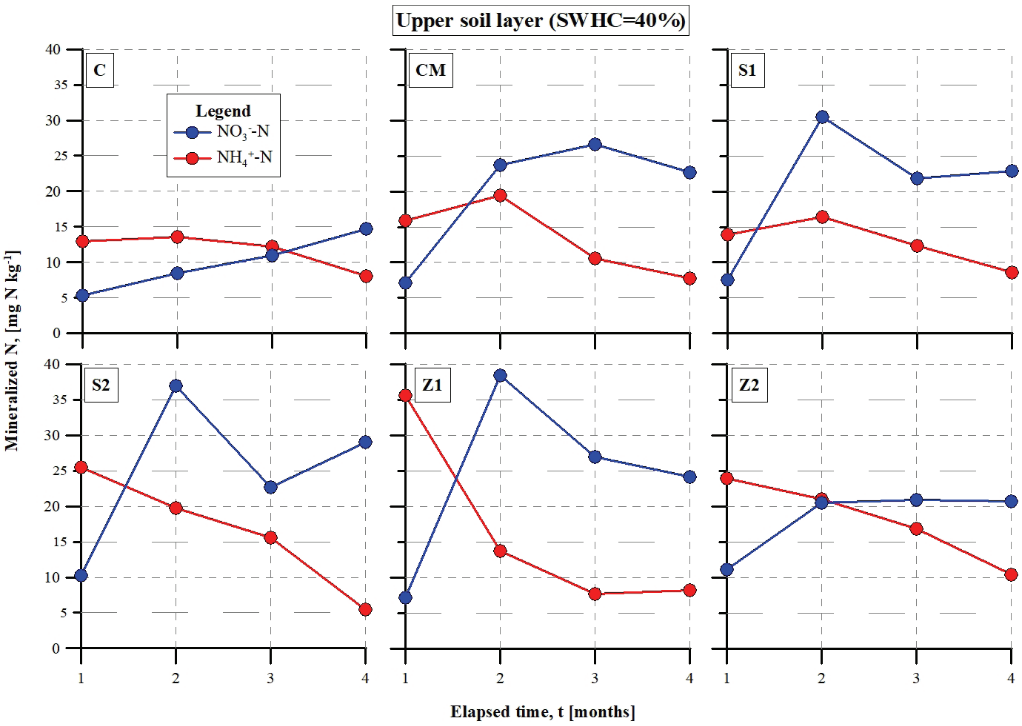


Fig. 1. Effects of treatments on the mineralized N forms of soil (mg N kg^{-1}) in the upper soil layer at SWHC=40%

respectively (Fig. 1. and Fig. 3). Li and Li (2014) found a similar tendency while studying nitrogen mineralization in animal manures.

Soil NH_4-N content did not change (≈15 mg N kg^{-1}) in the control treatment in the incubation period at lower water holding capacity level in the lower soil layer. The other treatments slightly decreased soil NH_4-N content during the incubation. In contrast, NO_3-N content increased in most of the treatments during the incubation period (except S1, and Z1 treatments). Significantly, about twice as much increment was observed at CM and S2 treatments compared to the control. In this layer, soil NO_3-N content was higher than NH_4-N content in all treatments during the whole incubation period. It can be explained by the difference in the moving ability of these forms. Moreover, the changing pattern of these two mineralized forms showed a similar tendency. Similarly to that obtained in the upper layer, the NO_3-N content became the dominant N form, its amount was 2-4.5 times higher than the NH_4-N content (Fig. 2).

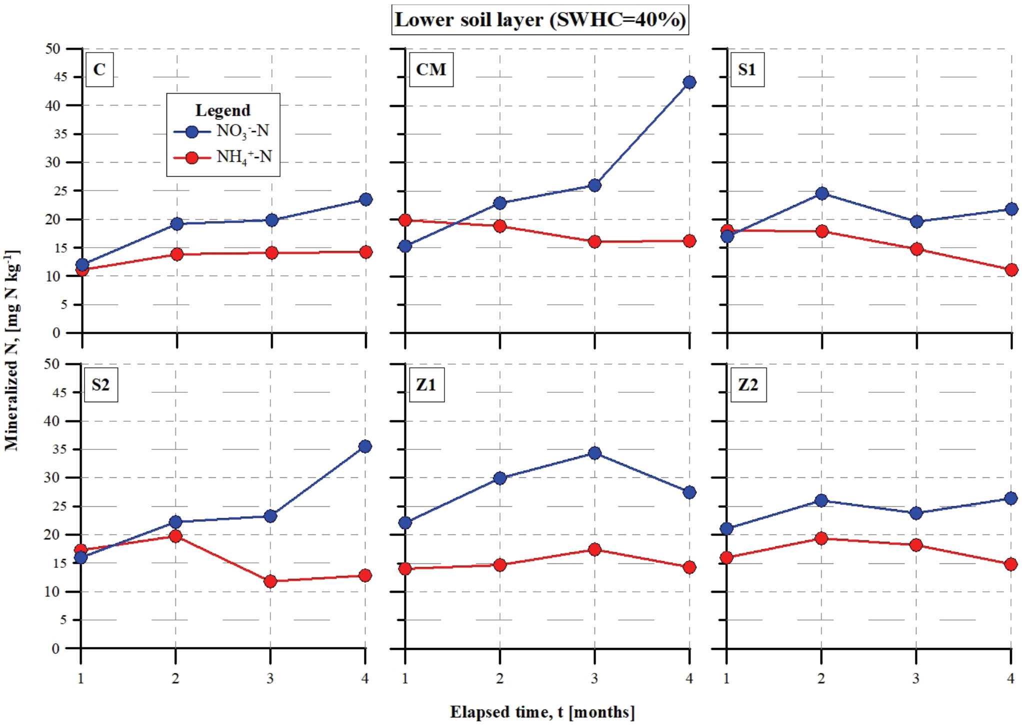


Fig. 2. Effects of treatments on the mineralized N forms of soil (mg N kg^{-1}) in the lower soil layer at SWHC=40%

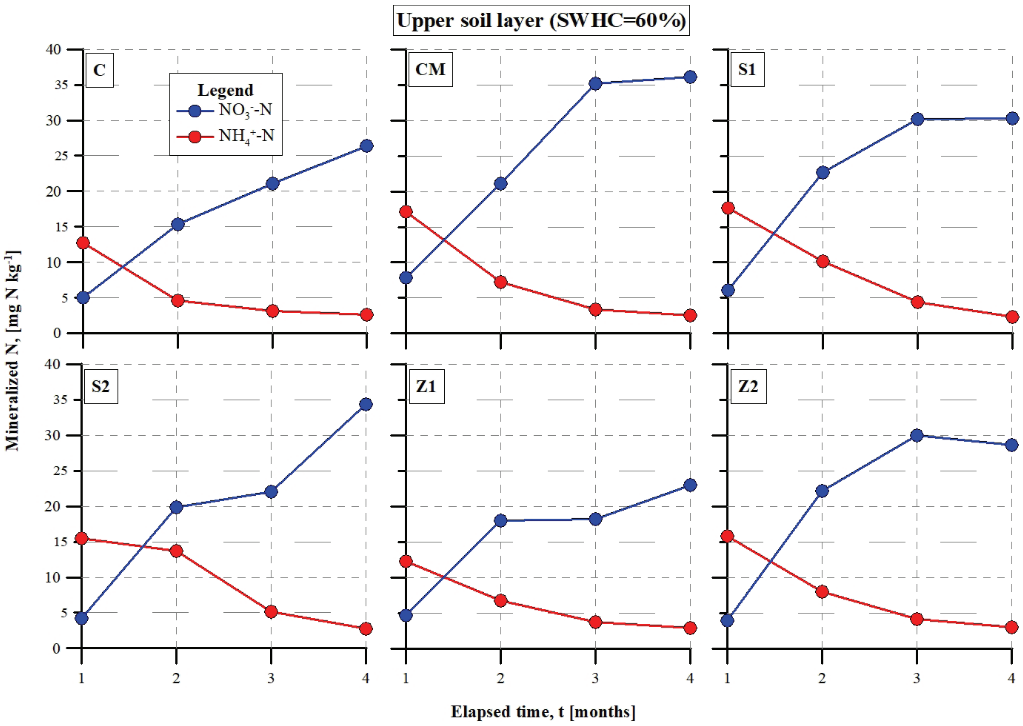


Fig. 3. Effects of treatments on the mineralized N forms of soil (mg N kg^{-1}) in the upper soil layer at SWHC=60%

Similarly to those observed at lower moisture level, soil NH_4-N content continuously decreased, while NO_3-N content increased in all treatments in the incubation period at higher moisture level in the upper soil layer. Similarly to those obtained by Calderón et al. (2004), in the treated soil, ammonium was the dominant form at the beginning of the incubation, whereas nitrate dominated at the end of the incubation. Its amount was six times higher on average than the NH_4-N content (Fig. 3).

Similar tendency was obtained at higher water content in the lower soil layer. The concentration of nitrate and ammonium ions were nearly equal (10–20 mg N kg^{-1}) at the beginning of incubation, but by the end of the experiment the NO_3-N content was two to five times higher than the NH_4-N content, depending on the treatments. These results also confirm a shift in the amounts, and ratio of the two studied mineral nitrogen forms, and the higher oxidation status (nitrate form) became dominant by the end of the incubation (Fig. 4). Our results are in agreement with many past studies that have shown similar tendency and curve profiles of mineralized N forms during incubation (Sistani et al. 2008; Tóth et al. 2023). Similarly, Álvarez-Alonso et al. (2022) also reported that in the low-rate incubation process the concentration of NH_4^+-N slightly decreased during the incubation, reaching low values and remained virtually stable during the rest of the incubation time. Sistani et al. (2008) also published that the decrease in the NH_4^+-N concentration was concomitant with increases in the NO_3^--N concentration, which, increased continuously and reached its highest value.

In general, the decreasing trend in NH_4-N concentration was correlated by an increase in NO_3-N concentration during the incubation period. This indicates that the two main inorganic forms of soil N, changed coherently during the incubation, possibly due to an increasing mineralization potential. Furthermore, our results pointed out that the changing of NH_4-N content between the two layers remained below the nitrate due to the soil clay particles attracted and temporarily retained ammonium ions in cation-exchange complexes. Some authors published a similar trend in a laboratory evaluation of the effect of broiler litter (Sistani et al. 2008) and organic composites (Tóth et al., 2023) on nitrogen mineralization. Honeycutt et al. (2005) and Griffin et al. (2002) also reported that surprisingly, soil moisture content (constant or fluctuating) did not have an impact on N mineralization, while soil type had the greatest impact. Their results similar to our findings where NH_4–N decreased and NO_3–N increased non-linearly during the incubation period, and NH_4^+ was rapidly nitrified to NO_3^-.

3.2. Nitrogen mineralization potentials of soil

The Fig. 5 presents the effects of the treatments on the cumulative mineralized N values during the entire incubation period. The cumulative amount of mineralized N continuously increased during the incubation in all treatments. The amount of mineralized N produced can be described by a linear relationship for both soil layers and moisture levels in the whole examined incubation period (Fig. 5 and Table 4). The slopes of equations and R values for these relationships are shown in Table 4, with R values exceeding 0.99 in all cases. These indicated that a linear regression model, regardless of moisture, and layers can correctly describe the forming amounts of mineralized N during the whole incubation period. Appel (1998), Griffin et al. (2002), and Honeycutt et al. (2005), have reported similar findings, when investigating the effect of soil moisture content on N mineralization. They established that the soil moisture regimes did not significantly influence the N mineralization of soil.

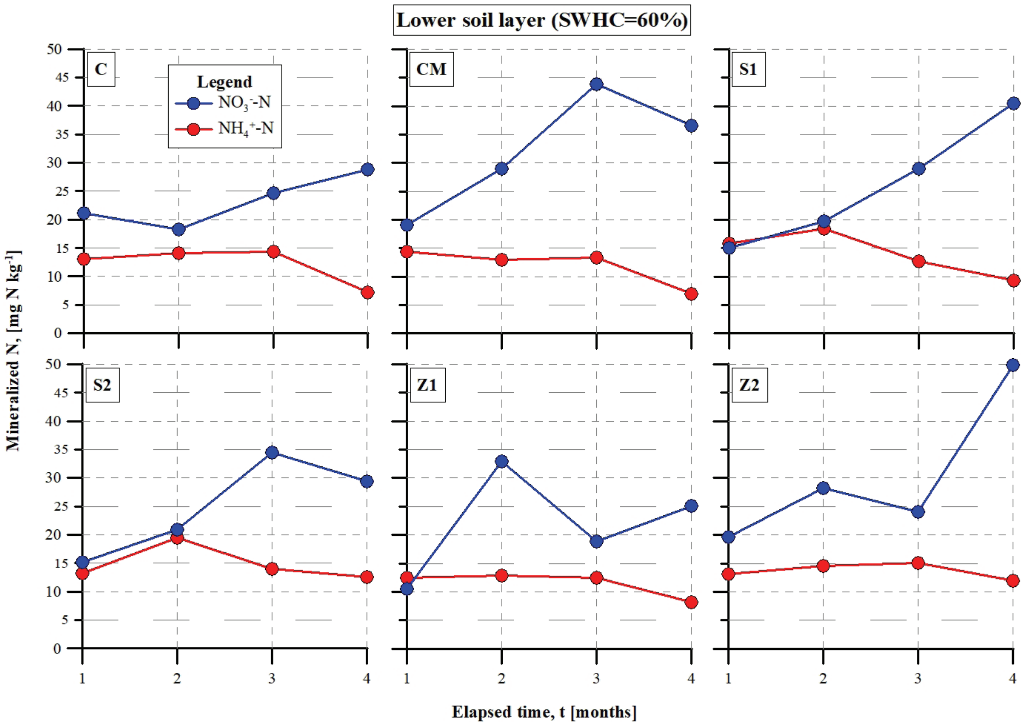


Fig. 4. Effects of treatments on the N_{min} forms of soil (mg N kg^{-1}) in the lower soil layer at SWHC=60%

However, Maitlo et al. (2023) obtained a logarithmic relationship between cumulative N mineralization and time in a longer (32 weeks) incubation experiment. The linear correlation obtained in our experiment is associated with the capsulated application of composites resulting in a prolonged prevalence of the included components during the incubation.

Fig. 5. shows that the amount of mineralized N increased significantly during the incubation time, and a higher mineralization rate was observed in all treatments than in the control treatment (except Z1 treatment Fig. 5. c,d) indicating the higher mineralization potential.

It can also be concluded that a more significant treatment effect was observed at a lower moisture level, which points to the more positive effect of SAPs at lower soil moisture contents (Adjuik et al., 2022). It can be explained that, the hydrogels store and supply water to microorganisms more efficiently at lower moisture contents than at higher moisture contents, when the circumstances are better for N mineralization. For instance, at the lower water content, in the upper layer, 1.5 to 2 times the amount of mineralized N was obtained compared to the control (see slope (m) values in Table 4.). Cumulative mineralized N values reached 140–180 mg kg^{-1} in all treatments compared to the control (90–130 mg kg^{-1}) at a lower moisture level (Fig. 5 a,b). At higher water holding capacity level, less difference between the treatments and the control was observed. However, composite treatments and chicken manure also increased the cumulative mineralized N value compared to the control at higher moisture level (except Z treatments) (Fig. 5 c and d). The lowest mineralized N values were found in the upper soil layer at higher water capacity level which is explained by the more pronounced nitrate leaching (Fig. 3, 4 and 5c).

Equations of mineralization were established according to the changes in the cumulative mineralized N values during the entire incubation period. The Table 4 presents the m and R values of the equations. The m of these equations described both the direction and the steepness of these curves. It can be established that all treatments significantly increased the value of m compared to the control at both layers and moisture levels. It suggests that the rate of mineralization in these treatments is greater than in the control, independently of moisture content and layer. The most significant differences were found between the treatments in the upper layer at lower water content, where the S2 and Z1 treatments have twice the m value of the control and 20% more than the CM treatment. Similarly, significant treatment effects were also observed in other layers and moisture levels (Table 4). It pointed out that the composites were more effective at lower moisture content and in the topsoil layer in the application zone. It can be explained by the water retention ability of SAPs. In drier conditions, where the microorganisms involved in mineralization cannot work as efficiently,

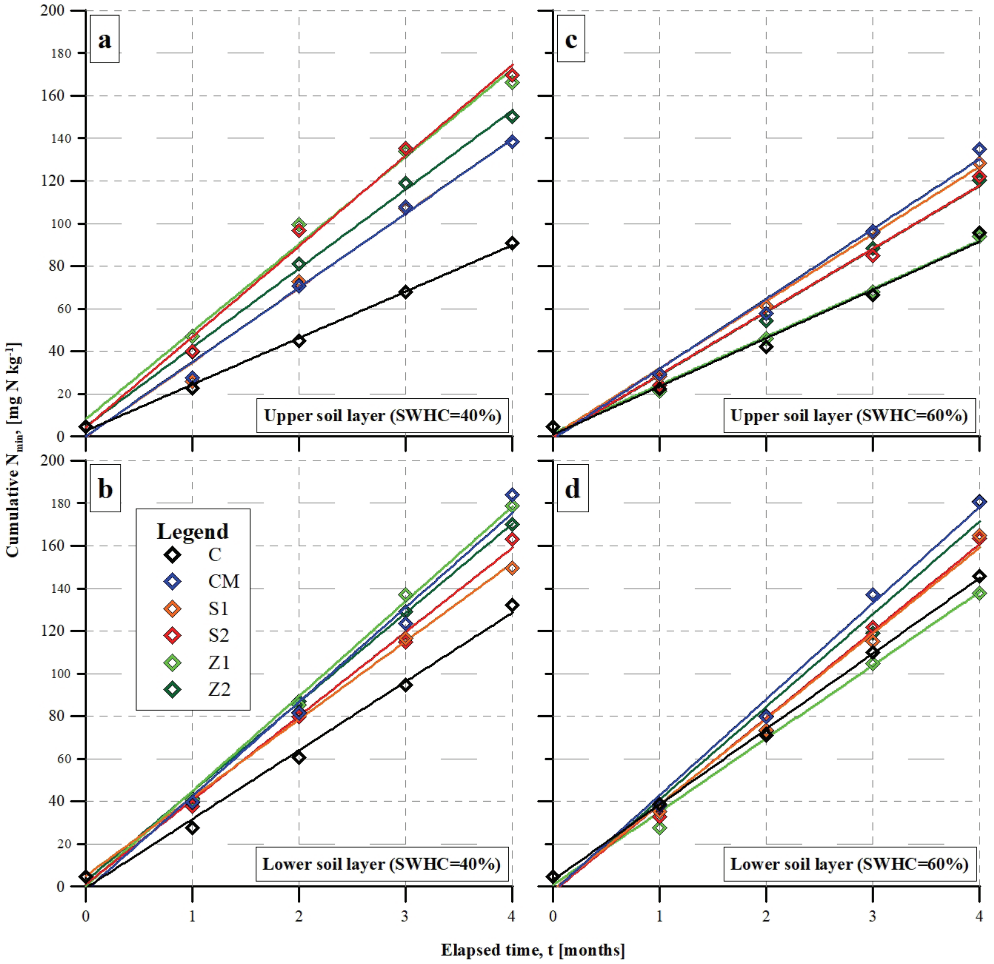


Fig. 5. The effects of the treatments on the cumulative N$_{min}$ values during the entire incubation period

they ensure (due to their swelling and shrinking ability) the right amount of moisture in the soil, which creates more favourable living conditions for microbes. These findings are in good agreement with those described earlier in the interpretation of Fig. 1–4. Obtained correlation (R) values were greater than 0.99 for all treatments, suggesting that the amount of mineralized N over the period can be well described by linear relationships.

Findings have enabled the estimation of the mineralized proportion of total N of the soil in different treatments. Over the course of the 112-day-long incubation experiment, the proportion of total N that was mineralized ranged from 8.14% to 15.63% (average 11.92%). The presence of chicken manure and additives in compost treatments significantly increased the mineralization proportion of total N (from 7.87% to 14.4–14.7%) at both moisture levels in all investigated layers compared to the control (except Z1 treatment). Composites were more effective at lower water content in the application layer. S2, Z1, and Z2 treatments significantly increased the mineralization proportion of total N compared to the CM treatment by 2.7, 2.4 and 1%, respectively, while S1 resulted the same value. In the lower layer, the effectiveness of CM and S2, Z1, and Z2 treatments were no different from each other. The CM treatment proved to be as effective as the composite treatments at higher moisture content. This may be explained by the fact that higher soil moisture content provides equal conditions for mineralisation processes (activity of microorganisms). Thus, organic matter in chicken manure is mineralised more efficiently and faster than in lower moisture conditions. Moreover, there was no significant difference between the treatments, except for the Z1, which caused the lowest values 8.14 and 11.94 respectively (Table 5).

Table 4
The m and R values of the mineralization curves of treatments in the upper and lower layer

Upper layer					
SWHC=40%			SWHC=60%		
Treatment	m	R	Treatment	m	R
C	21.784	0.999	C	22.622	0.995
CM	34.825	0.996	CM	32.802	0.995
S1	34.918	0.995	S1	31.515	0.998
S2	42.518	0.996	S2	29.586	0.995
Z1	41.029	0.996	Z1	22.547	0.998
Z2	37.060	0.999	Z2	29.579	0.996
Lower layer					
SWHC=40%			SWHC=60%		
Treatment	m	R	Treatment	m	R
C	32.268	0.997	C	35.414	0.999
CM	44.268	0.995	CM	45.069	0.996
S1	36.674	0.999	S1	40.094	0.996
S2	39.442	0.998	S2	40.717	0.996
Z1	44.484	0.998	Z1	34.355	0.996
Z2	41.868	1.000	Z2	43.451	0.993

Table 5
Effects of treatments on the calculated mineralized proportion of TN (%)

Mineralized proportion of TN (%)				
	SWHC=40%		SWHC=60%	
Treatments	Upper layer	Lower layer	Upper layer	Lower layer
C	7.87^{c}	9.46^{b}	8.27^{c}	12.64^{b}
CM	11.99^{b}	12.88^{a}	11.70^{a}	15.63^{a}
S1	12.00^{b}	9.91^{b}	11.12^{a}	14.30^{a}
S2	14.70^{a}	11.26^{a}	10.57^{a}	14.18^{a}
Z1	14.41^{a}	12.36^{a}	8.14^{c}	11.94^{b}
Z2	13.01^{a}	11.53^{a}	10.42^{a}	15.67^{a}

Numbers followed by different letters in columns are statistically different p≤0.05.

Our findings have enabled the estimation of potentially mineralized nitrogen and net mineralization rate of the soil in different treatments. The calculated values are shown in Table 6. Potentially mineralized nitrogen values range was 54 and 232 mg N kg^{-1} according to the applied treatments, moisture level, and depth, which are similar to those reported for soils in the USA (18 to 358 mg kg^{-1}) in Canada (155 to 246 mg kg^{-1}) and in Italy (21 to 405 mg kg^{-1}) (Maitlo et al. 2022). Similarly, Li and Li (2014) obtained the same results when they studied the effect of different manure types on soil N mineralization. The lowest values were obtained in the control samples (54–70 mg N kg^{-1}). More significant treatment effect was observed in the application layer at lower water holding capacity level than in lower layer, and at higher water holding capacity level in both layers. Higher dose SAP supplements in composites (S2 and Z2 treatments) increased the value of potentially mineralized nitrogen by 3–4 times compared to the control and CM treatment (Table 6.). Z1 treatment resulted in twice as much potentially mineralized nitrogen as the control while S1 and Z2 treatments increased its value by three-fold compared to the control at higher moisture level in the lower layer. Furthermore, these treatments increased potentially mineralized nitrogen by 50 mg kg^{-1} compared to the CM treatment. However, at higher moisture level in the upper layer, the CM treatment resulted in the highest potentially mineralized nitrogen value (227 mg N kg^{-1}).

These results suggested that a significant correlation can be established between composite treatments and mineralization and that the at lower water holding capacity level composite treatments are more effective than the other treatments to reach the maximum mineralization potential.

Net mineralization rate varied between 2.4 and 4.7 mg kg^{-1} according to the applied treatments, moisture level, and depth. The lowest values were calculated in the control (2.41–3.85 mg kg^{-1}) respectively. Applied treatments significantly increased the net mineralization rate compared to the control. In the lower layer, CM, Z1, and Z2 treatments had the highest increasing effect on the net mineralization rate at lower moisture and CM and Z2 treatments at higher moisture level. In the upper layer the most effective treatments were S2, Z1 at lower, and CM, S1 at higher water holding capacity level respectively.

The nitrification rate varied between 0.38 and 1.17 mg kg^{-1} according to the applied treatments, water holding capacity level, and depth. The lowest values were calculated in the control (0.38–0.85 mg kg^{-1}) respectively. Treatments caused significantly higher nitrification rates at lower moisture level compared to the control, in both soil layers (except for S1). S2 and Z1 treatments resulted in an almost two and a half-fold increase in nitrification rate compared to the control, and increased by 20% compared to the CM treatment in the application layer at a lower moisture level. Treatments caused significantly higher nitrification rates at higher moisture level compared to the control, in both soil

Table 6
Effects of treatments on calculated PMN, NMR and NNR values (N mg kg^{-1})

Upper layer							
SWHC=40%				SWHC=60%			
Treatment	PMN	NMR	NNR	Treatment	PMN	NMR	NNR
	mg N kg^{-1}				mg N kg^{-1}		
C	54^{c}	2.41^{c}	0.38^{c}	C	70^{c}	2.41^{c}	0.63^{b}
CM	64^{c}	3.64^{b}	0.74^{b}	CM	227^{a}	3.37^{a}	0.92^{a}
S1	68^{c}	3.63^{b}	0.76^{b}	S1	139^{b}	3.31^{a}	0.82^{a}
S2	192^{a}	4.65^{a}	0.91^{a}	S2	71^{c}	3.05^{b}	0.74^{b}
Z1	103^{b}	4.70^{a}	0.87^{a}	Z1	147^{b}	2.44c	0.59^{b}
Z2	232^{a}	4.11^{b}	0.68^{b}	Z2	76^{c}	3.04^{b}	0.78^{a}
Lower layer							
SWHC=40%				SWHC=60%			
Treatment	PMN	NMR	NNR	Treatment	PMN	NMR	NNR
	mg N kg^{-1}				mg N kg^{-1}		
C	55^{c}	3.33^{c}	0.69^{b}	C	61^{d}	3.85^{c}	0.85^{b}
CM	89^{b}	4.51^{a}	0.99^{a}	CM	147^{b}	4.58^{a}	1.17^{a}
S1	54^{c}	4.08^{b}	0.76^{b}	S1	208^{a}	4.10^{b}	0.95^{a}
S2	81^{b}	4.16^{b}	0.89^{a}	S2	101^{c}	4.12^{b}	0.92^{a}
Z1	109^{a}	4.65^{a}	1.04^{a}	Z1	66^{d}	3.62^{c}	0.80^{b}
Z2	73^{b}	4.50^{a}	0.89^{a}	Z2	192^{a}	4.39^{a}	1.11^{a}

Numbers followed by different letters in columns are statistically different $p \leq 0.05$.

layers (except S2, Z1 in upper layer and Z1 in lower layer). However, the composites did not result in a higher nitrification rate at this moisture level compared to the CM treatment. This finding also pointed out that composites are more effective in the mineralization process at lower water holding capacity level.

These findings confirmed that earlier incubation studies pointed out that some manures act as net suppliers of N, while others may result in net N immobilization (Hadas, 1994; Sorensen, 1998; Calderón et al., 2004; Calderón et al., 2005; Álvarez-Alonso et al., 2022).

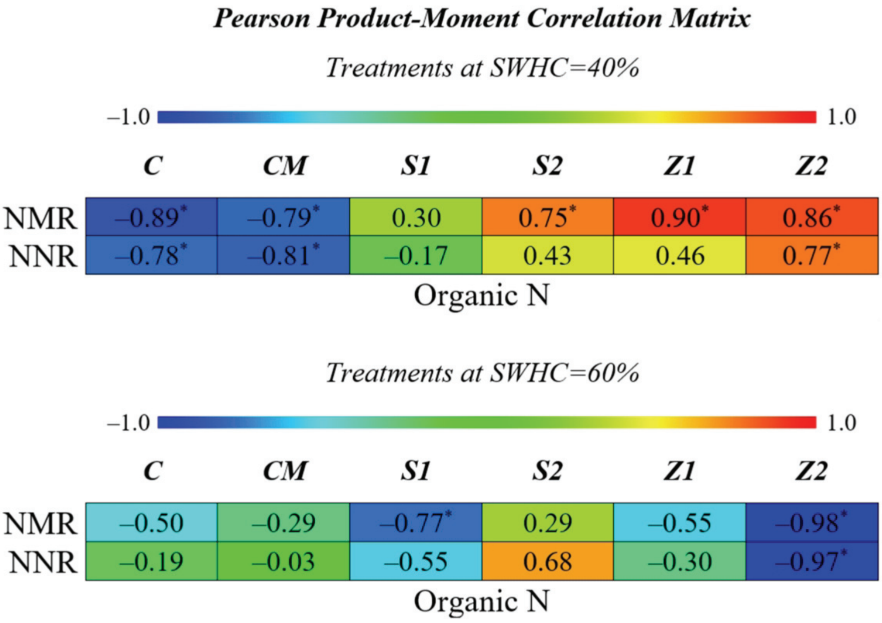
To explore the correlations among measured and calculated parameters described, the mineralization correlation analysis was made. The Fig. 6 shows Pearson Product-Moment correlations among net mineralization rate, nitrification rate and organic N at 40% and 60% of soil water holding capacity levels in the treatments. Colour is used to denote the magnitude of the correlations coefficients that range between –1 and +1, measuring the strength of the linear relationship between the above-mentioned parameters.

Significant correlations were found between net mineralization rate and organic N parameters at the 95.0% confidence level ($p < 0.05$) in C, CM, S2, Z1 and Z2 treatments where 40% of the soil water holding capacity level was set up and maintained during the experiment. Negative correlations were revealed between net mineralization rate and organic N parameters in C and CM treatments, while positive correlations were observed in those treatments where SAPs were applied in the composites (except for S1). These findings indicate that the SAPs had a statistically significant positive effect on the net mineralization rate of the organic N. A similar tendency can be seen between nitrification rate and organic N parameters. Based on the results of the correlation matrix, it can be concluded that the application of SAPs significantly enhanced the net mineralization rate alongside the nitrification rate in the investigated soils at 40% of soil water holding capacity level. This can be explained by the fact that the SAPs, with their water absorption, created a more favourable microenvironment for the microbes involved in mineralization.

In general, at 60% of soil water holding capacity level, weak negative correlations were obtained in all treatments among net mineralization rate, nitrification rate and organic N, except S2 treatment where weak positive correlations were computed. Significant correlations can be seen between net mineralization rate and organic N parameters at the 95.0% confidence level ($p < 0.05$) in S1 and Z2 treatments. Moreover, a statistically significant correlation was found between nitrification rate and organic N with a value of –0.97 in Z2 treatment. It seems that in the experimental arrangement used, at 60% water capacity level, the microbial transformations are not as pronounced as at lower moisture content. Because, manure N conversation is greatly affected by soil moisture content; for example formation of N_2O can take place under high soil water conditions (Linn and Doran, 1984).

Overall, these results confirm that the efficiency of applied SAPs are optimal at 40% of soil water holding capacity level, since negative correlations were found among net mineralization rate, nitrification rate and organic N at 60% of soil water holding capacity level. Even the application of SAPs in the composites were not able to compensate these negative correlations. Indicating, that this water capacity level is not optimal for mineralization processes under used arrangement.

Soil C/N ratios during the experiment are presented in Fig. 7. Soil C/N ratio varied between 6.8 and 8.8, and between 6.6 and 8.2 at lower moisture, and between 6.5 and 9.0, and between 6.2 and 8.1 at higher moisture level, respectively. The treatments slightly increased the C/N ratio during incubation. Maitlo et al. (2022) reported a similar time pattern for the C/N ratio. This effect became more significant mainly in the second half of the experiment. The rate of change was much less pronounced in the lower soil layer than in the upper layer at both moisture levels. This also suggests that the composites were mainly effective in the layer of application. Composite treatments slightly



Treatments at SWHC=40%

	C	CM	S1	S2	Z1	Z2
NMR	–0.89*	–0.79*	0.30	0.75*	0.90*	0.86*
NNR	–0.78*	–0.81*	–0.17	0.43	0.46	0.77*

Treatments at SWHC=60%

	C	CM	S1	S2	Z1	Z2
NMR	–0.50	–0.29	–0.77*	0.29	–0.55	–0.98*
NNR	–0.19	–0.03	–0.55	0.68	–0.30	–0.97*

Fig. 6. Pearson Product-Moment correlations among net mineralization rate, nitrification rate and organic N at 40% and 60% of soil water holding capacity levels in the treatments

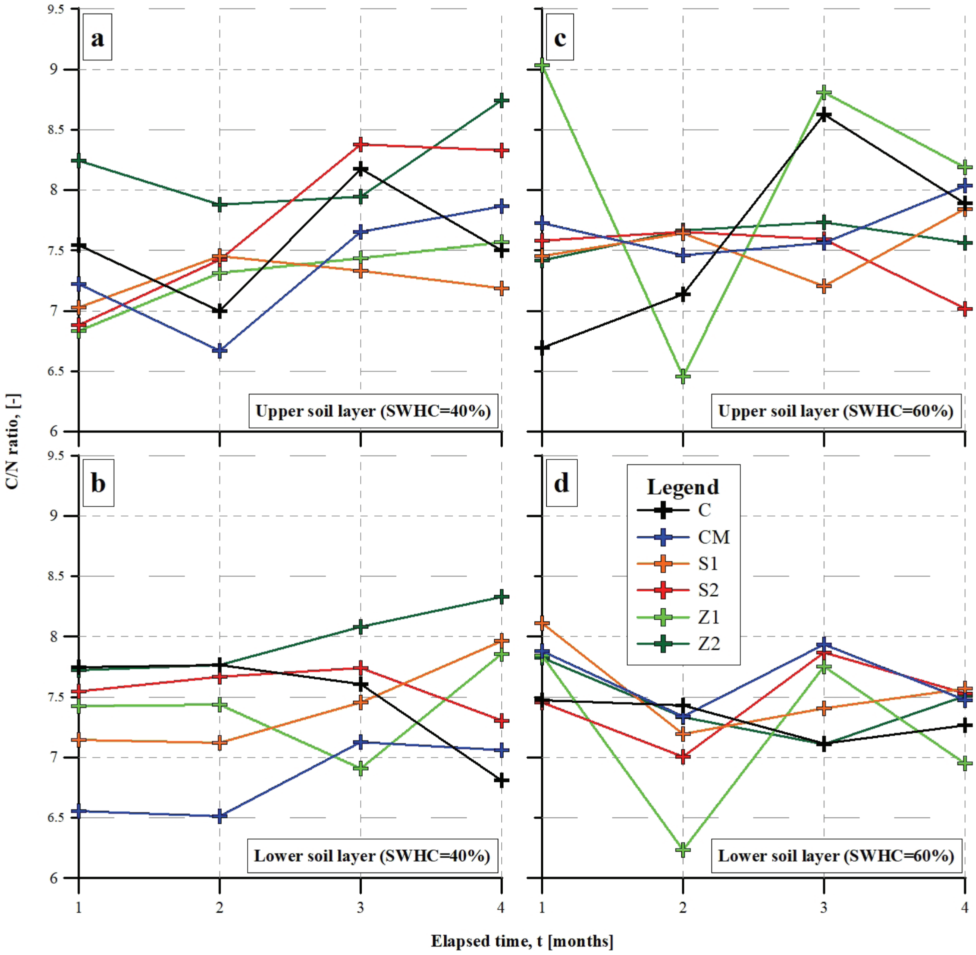


Fig. 7. The effects of the treatments on the C/N ratio during the entire incubation period

increased the C/N ratio towards a more favourable value compared to control and CM treatment, at lower water capacity level. No such correlation was found at higher water capacity level among treatments. Obtained results confirmed that the evidence for a correlation between the soil C/N ratio and N mobilization and mineralization is equivocal. Results were in correlation with those, that the variations of the C/N ratios of different pools of organic matter may also confound the usefulness of the soil C/N ratio to predict gross nitrogen transformation rates (Bengtsson et al. 2003). Similar tendencies were published by Ostrowska and Porębska (2015), who studied the evaluation of the C/N ratio as an indicator of the degradability of organic matter.

4. Conclusions

Results indicated that the applied composites were effective in increasing the NO_3-N and cumulative mineralized N form in the soil during the incubation, which confirmed their positive effect on the mineralization process in the soil.

A linear regression model was found to describe the amounts of mineralized N during the whole incubation period, regardless of moisture levels, and layers.

Applied composite treatments significantly increased the amount of potentially mineralized nitrogen, net mineralization rate and nitrification rate compared to the control. Moreover, applied composites caused higher mineralization values compared to the CM treatment, which contained only chicken manure. Composites had an effect on C/N ratio but the obtained results were not tendentious due to the short incubation time.

Treatments significantly increased the mineralization proportion of total N (from 7.87% to 14.4–14.7%) at both moisture levels in both investigated layers compared to the control.

In summary, the applied composites supported the N mineralization process effectively, mainly in the application layer, and at a lower moisture content of soil. Therefore, usage of this kind of composites is highly recommended where nitrogen use efficiency is a limiting factor in agriculture sustainability.

Furthermore, the developed organic-based composites, which included raw material originated from recycling technology, can cope with changing soil circumstances that could help to mitigate the negative effects of climatic anomalies, especially in arid areas where improving soil nutrient supply, and retaining the limited water resources in the soil, essential for sustainable nutrient management.

Finally, the application of the studied composites can be a useful tool to enhance the interactions of nutrient cycling with water availability to plants, that is becoming more important with climate change and associated implications for the resistance of agroecosystems, mostly in the arid regions.

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