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Decomposition of Hemp Residues in Soil as Facilitated by Different Nitrogen Sources

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Abstract: Improving soil health across agroecosystems has continued to receive attention around the globe, with an emphasis on sustainable organic inputs from agricultural practice. It is well known that different organic materials, such as composts, manure and cereal straws, positively affect soil carbon. The changing agricultural practices have continuously led to new and improved plants in farming. One of these innovative plants is industrial hemp. With the increasing cultivation of industrial hemp globally, the problem of the disposal of hemp residues has been encountered. However, the rich carbon content found in hemp residues in soil is anticipated to enhance the soil quality and address the challenge of effectively utilizing hemp straw. In this study, we conducted a two-way experimental trial to evaluate the decomposition of hemp residues using placement methods (residues incorporated into the soil or left on the soil surface) and nitrogen sources as additives. Different nitrogen additives (nitrogen fertilizer pellets, liquid nitrogen, organic fertilizers, and the preparation "Bioversio") were selected to accelerate the decomposition of hemp residues. The results showed that the mineralization rates were faster in the residues incorporated in the soil, with a mass loss of over 54% compared to the treatments left on the soil. The influence of additives on the decomposition rates was statistically significant. Additionally, there was a significant increase in the N content in the soil, while the change in carbon content in the soil was not statistically significant. These research results reinforce nitrogen fertilizers' positive role in accelerating hemp residue decomposition in soil. Furthermore, our findings will help contribute to the effective and sustainable utilization of hemp residues as a bioresource material to improve soil health.

Keywords: hemp residues; soil; nitrogen; carbon; mineralization

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1. Introduction

Exploring green, sustainable, and alternative energy sources and production methods is vital. Biomass resources, especially those derived from plants, have gained increased attention as clean, sustainable, and affordable energy sources, chemicals, and materials [1]. Plant biomasses that are rich in organic compounds, such as cellulose, hemicellulose, and lignin, promise to address these challenges [2]. Intensive agricultural practices contribute to soil degradation and climate change by releasing CO_2, converting natural grasslands into agricultural soils, and increasing the decomposition of organic matter in soils affected by tillage [3,4]. On the other hand, sustainable soil management practices, such as reduced tillage, cover cropping, composting, and the use of composts or plant residues instead of synthetic fertilizers, can help to mitigate the effects of climate change and enhance the resilience of agroecosystems by increasing the amount of soil carbon [5–7].

The chemical composition of plant residues influences their mineralization, organic matter formation, and carbon and nutrient efficiencies in agricultural soils [7,8]. Generally, above-ground plant residues decompose more quickly if they contain a low C:N ratio and lignin content. Incorporating plant residues into soil is less favorable, as decomposition is slow and enhances the carbon loss [9]. Organic carbon has a significant influence on fertility and the microorganisms in soil [10]. Although the long-term decomposition of organic carbon in soil mitigates the emission of greenhouse gases into the environment, the physical properties of soil are also highly dependent on the amount of organic carbon present. Assessments of the dynamics of carbon (C) and nitrogen (N) mineralization in soils reveal this complex process [11,12]. As crop residues decompose, the accelerated mineralization of soil organic matter releases organic acids [13], which may further facilitate the release of nutrients, such as phosphorus (P) and sulfur (S), from soil perfusion and desorption reactions [14]. These reactions vary across soil types due to differences in clay content, clay mineralogy, and multivalent cations (e.g., Ca^{2+}, Mg^{2+}, Fe^{2+}, and Al^{3+}) [15]. Moreover, these reactions are more pronounced in microaggregates, which are characterized by a larger specific surface area and ion sorption–desorption capacity compared to those of macroaggregates [16].

Certain agricultural management practices, such as no-till farming and intercropping with legumes or perennial woody crops in stubble, are one way to address land degradation and climate change in arid climates [16]. However, leaving them on the soil surface as mulch or plowing them into the soil still raises the question of how to increase the mineralization of semi-arid or lignin-rich plants and the accumulation of carbon and nitrogen in the soil. Furthermore, incorporating or leaving plant waste on the soil increases the activity of microbial biomass and dominant fungi, thus improving the soil quality [17]. Positive effects of crop residues have also been observed on the soil properties, such as microporosity, infiltration, and water retention, related to the essential soil organic matter content and faunal activity [18]. Green manure increases the soil organic carbon stocks [19]. However, it is essential to note that a comprehensive greenhouse gas balance should consider potential adverse impacts, such as the potential for more direct N_2O emissions from crop residues [20].

While it is important to focus on the long-term increases in the soil organic carbon total, the amount of soil organic matter must also be increased to enhance carbon and nitrogen's physical and biochemical properties, thereby improving soil health [14]. There is still a research gap in investigating the effects of different above-ground and soil-incorporated crop residues on carbon and nitrogen dynamics and stabilization in agricultural soils to evaluate different crop residue utilization strategies and soil improvement targets. As the demand for non-food crops and other agricultural products increases, industrial hemp is increasingly cultivated [21]. Industrial hemp stands out as an atypical plant that is highly adaptable to various climatic conditions and is not very demanding in soil [22]. This crop and its processed products can be used in various industries, including agriculture, textiles, automotive, construction, biofuels, oil, cosmetics, and pharmaceuticals [23].

Additionally, hemp stands out as a remarkable carbon sink, with an ability to absorb CO_2. The substantial hemp biomass helps to sequester carbon effectively through photosynthesis and stores it within its plant body and roots through bio-sequestration. About 9000 hectares of hemp were declared in Lithuania in 2023. Meanwhile, in Europe, over 56,196 hectares of land were dedicated to hemp cultivation in 2019 [24], with more production planned for the coming years. Each hectare can capture up to 22 tons of CO_2 [25]. However, with the increasing cultivation of industrial hemp, the problem of the disposal of hemp residues is encountered. The problem of the disposal of hemp residues is one of the most common issues among hemp growers. Currently, there are few or no scientific studies on the mineralization of hemp residues and their impact on soil.

Therefore, this study aimed to evaluate how different nitrogen sources influence the mineralization rate of hemp residues, both when the residues are on the soil and when the residues are incorporated into the soil. Specifically, this study hypothesized that different nitrogen fertilizers will improve the mineralization rate of hemp residues.

2. Materials and Methods

2.1. Experimental Design and Treatments

This experiment was conducted in 2023 (from March to June) at the Agrobiology laboratory, Lithuanian Research Centre for Agriculture and Forestry. Soil was collected from the field (Akademija, Lithuania). This experiment was conducted in climate chambers with a controlled environment and uniform conditions. The chamber parameters were set appropriately for cereal growth for a daytime 16 h period and nighttime 8 h mode as follows: temperature 24 ± 0.5 °C during the day and 16 ± 0.5 °C during the night, RH 75 ± 2%, fan mode on 100%, light on during the day and light off during the night. Each experimental pot (1.5 L) was filled with 1 kg of loamy soil. Hemp (Felina 32) residues were collected from the field in Lithuania (Lithuanian Research Centre for Agriculture and Forestry). Chopped hemp residues were harvested in 2022 autumn. A total of 5 g each of dry hemp residues was weighed and placed in 5×5 cm^2 litter bags. The bags were put 5 cm deep in the experimental pot. Additional nitrogen rate 270 kg·ha^{-1}. After determining the amount of nitrogen in different soils, the rate was calculated for each experimental pot (Table 1).

Table 1. Different nitrogen sources.

Fertilizer	N Content, %	Application Dose, g
Nitrogen pellets	34	1.22
Liquid nitrogen	36	1.15
Organic fertilizer	84	49.46
Bioversio	-	0.2

The following five treatments were selected: control, nitrogen fertilizer pellets (N 34.4%, (N-NH_4) 17.2%, and (N-NO_3) 17.2%), liquid nitrogen fertilizer (N 32%, NH_2 16%, NH_4 8%, and NO_3 8%), organic fertilizer (pig digestate), and a preparation made from "Bioversio" (*Reesei* BVO5 > 1×10^7 CFU/mL, *Longibrachiantum* BVO7 > 1×10^7 CFU/mL, and *Asperellum* BVO6 > 1×10^7 CFU/mL). The five treatments were mixed/incorporated into the soil, while another five treatments were left on the soil. Each treatment had four replicates.

2.2. Carbon and Nitrogen Contents

Carbon and nitrogen contents were measured using CNS elemental combustion system equipment (The Netherlands). A total of 10 g of the samples was weighed in the alov capsule, and then the capsule was folded and put into the machine (Table 2).

Table 2. Chemical properties of soil and hemp residues before experiment.

	N Content, %	C Content, %
Soil	0.03	1.89
Hemp	0.06	33.53

2.3. Statistical and Numerical Analyses

The observed data were statistically processed using R Studio 4.3.2 software. ANOVA two-way and the Tukey HSD and Duncan tests were applied to determine the significant differences between the means at an alpha level 0.05. Lowercase letters that differ denote significant differences at $p < 0.05$ and $p < 0.1$. Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1, no significant 'ns'.

3. Results

3.1. Mass Weight of Mineralized Hemp Residues

The weight of the hemp residues after mineralization using two different application methods is described in Figure 1. Mineralization occurred faster in the treatments mixed with soil, as evidenced by the higher mass loss (over 54%) compared to the lower mass loss in the treatments left on the soil. The "Bioversio" preparation had the highest mineralization rate when the hemp residues were mixed with the soil, with the lowest mineralization rate observed in the nitrogen fertilizer pellet treatments. Furthermore, in the treatment where the hemp residues were mixed with soil, significant differences ($p < 0.05$) were found in the treatments of "Bioversio" and control, as well as between the nitrogen pellet and liquid nitrogen fertilizers. Similarly, no significant differences were observed between the organic fertilizer treatments and the preparation made from "Bioversio" when mixed with the soil. Comparing the treatments where hemp residues were left on the soil surface, the only significant difference was observed between the control and the organic fertilizer (Figure 1). In comparing the results obtained between all the treatments available using the two methods of hemp residue application, statistically significant results ($p < 0.05$) were obtained in the interaction between the additives and the mode of application (placement) (Figure 1).

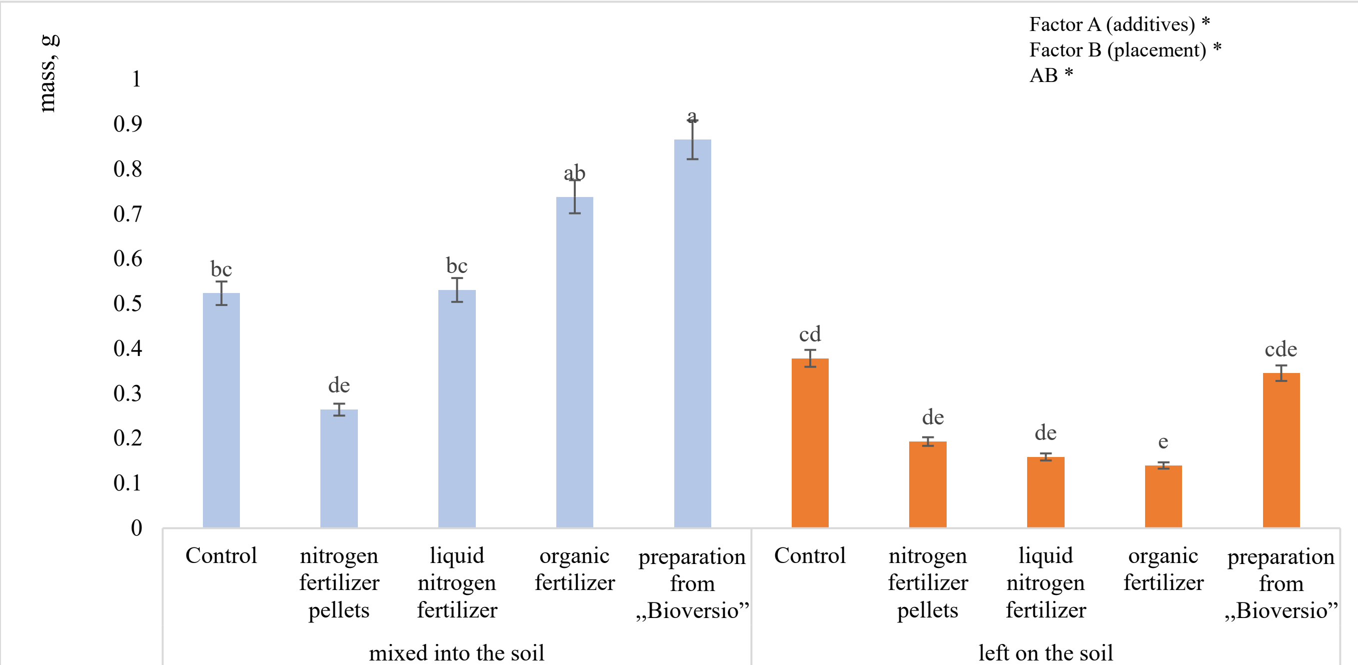

Figure 1. Change in weight of hemp residues after mineralization. Data are presented as means ± standard error; different letters correspond to significant differences ($p < 0.05$) between means according to Tukey HSD test. Signif. Codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '·' 1, no significant 'ns'.

Furthermore, the results showed that the mass of hemp residues decreased in all the variants after 90 days of the experiment. The nitrogen fertilizer significantly affected the decomposition of hemp residues and the increase in nitrogen content in the soil. However, it did not affect the amount of carbon in the residues and soil.

3.2. Carbon Content in Hemp Residues

These results show the differences between the carbon content in the hemp residues before and after the experiment (Figure 2). The carbon content in hemp residues before the experiment was 33.53%. At the same time, the carbon content of hemp residues increased in all the treatments after the experiment, with the highest change observed in liquid nitrogen fertilizer (12.11%), where the hemp residues were mixed into the soil. There was no significant difference observed in the interaction between the N additives and the treatment placement ($p < 0.1$). The carbon content increased when the hemp residues were left on and mixed into the soil. We can safely assume that hemp residues take up more nitrogen during mineralization, which promotes the rate of decomposition, while the carbon content has no effect on mineralization.

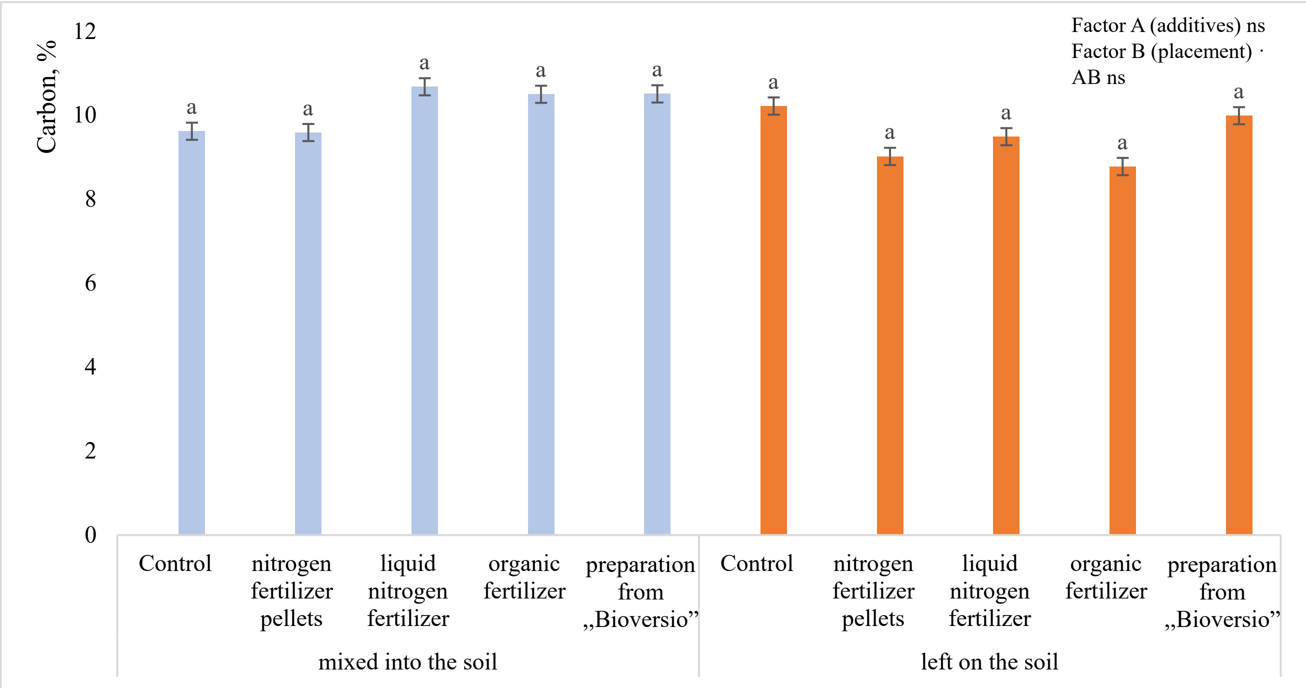

Figure 2. Carbon content in hemp residues. Data are presented as means ± standard error; different letters correspond to significant differences ($p < 0.1$) between means according to Tukey HSD test. Signif. Codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '·' 1, no significant 'ns'.

3.3. Nitrogen Content in Hemp Residues

Figure 3 shows the nitrogen content increased in hemp residues after the experiment. Before the experiment, the nitrogen content was 0.06%. The highest nitrogen content was determined in the treatment with organic fertilizer and nitrogen fertilizer pellets at 1.10% and 0.98%, respectively, when the hemp residues were left on the soil. However, these two treatments were not significantly different (Figure 3). Additionally, there was no significant difference observed in all the treatments that were mixed into the soil. The nitrogen content of hemp residues across the two placements increased due to the addition of the N source, which was used to accelerate the mineralization of the residues when they were incorporated into the soil or left on the soil surface (Figure 3). Mineralization often takes longer, and additional N sources are needed to accelerate it in tandem with the chemical properties of the hemp residues. Hence, using nitrogen preparations for the faster mineralization of the residues increased the amount of nitrogen in the residues.

3.4. Nitrogen and Carbon Contents in the Soil

The amount of nitrogen in the soil changes throughout the mineralization of plant residues. The results showed the amount of nitrogen in the soil before the experiment was 0.03%, which increased significantly in all the treatments after the experiment. The highest nitrogen content was observed in the "Bioversio" treatment at 0.20% when the hemp residues were mixed/incorporated into the soil. The lowest amount of nitrogen was found in the control treatment at 0.14% when the hemp residues were left on the soil surface (Figure 4).

However, between the treatments, there was no significant difference ($p < 0.05\%$) (Figure 4). Further analysis showed significant differences in the nitrogen total in the hemp residues before and at the end of the experiment. We observed no changes in nitrogen content after the investigation, affirming the mineralization of the hemp residues, which the different nitrogen sources enhanced.

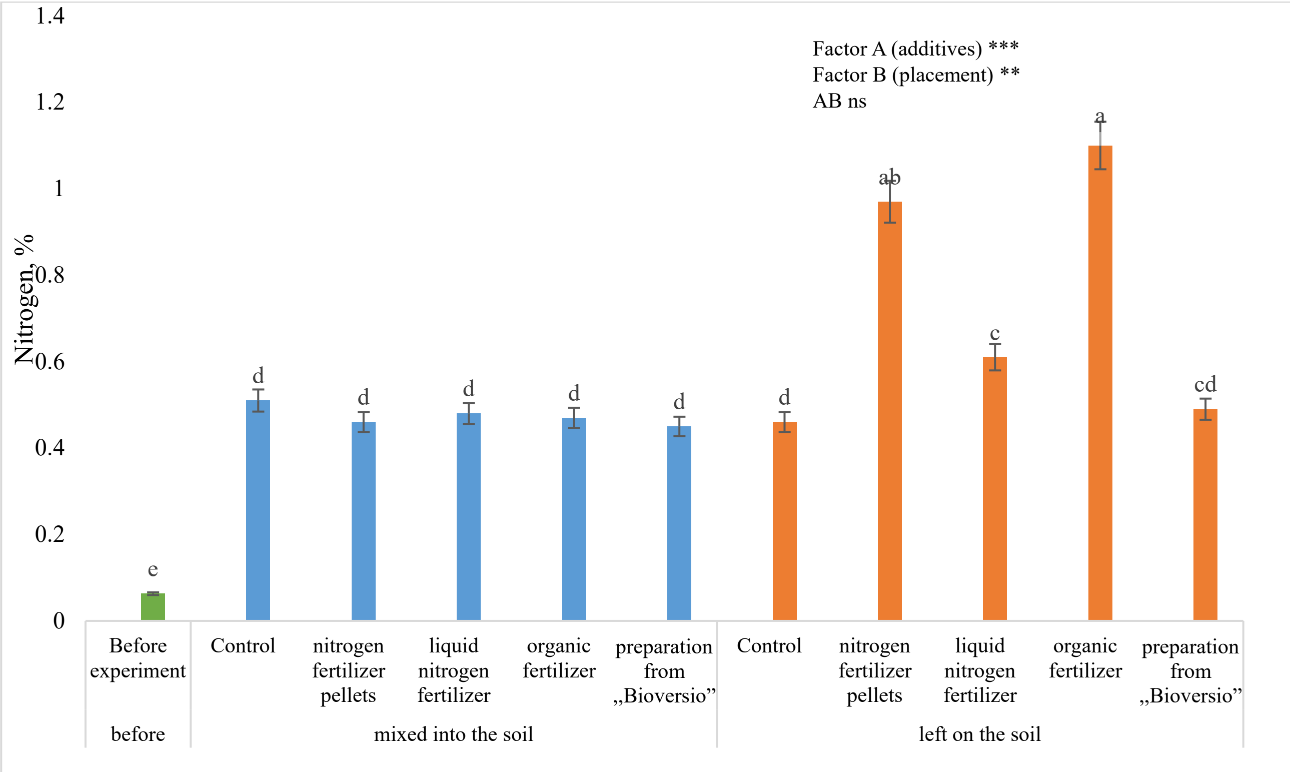

Figure 3. Nitrogen content in hemp residues. Data are presented as means ± standard error; different letters correspond to significant differences ($p < 0.05$) between means according to Tukey HSD test. Signif. Codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '·' 1, no significant 'ns'.

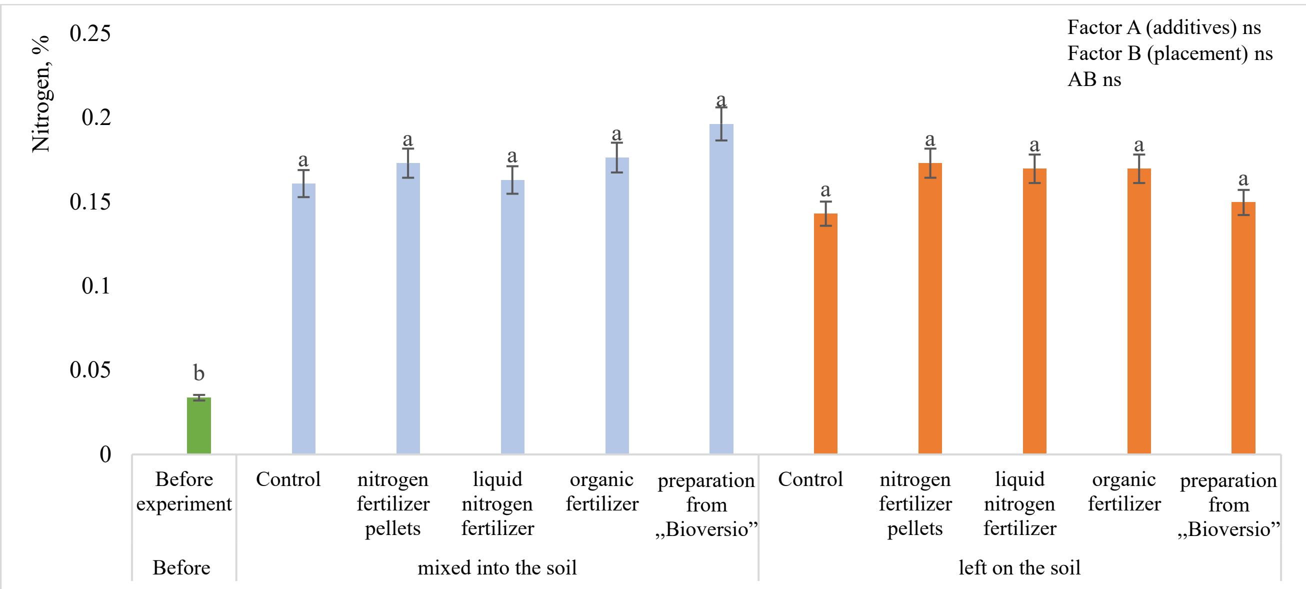

Figure 4. Nitrogen content in the soil. Data are presented as means ± standard error; different letters correspond to significant differences ($p < 0.05$) between means according to Tukey HSD test. Signif. Codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '·' 1, no significant 'ns'.

The amount of carbon in the soil increased very slightly after the experiment, going by the initial carbon content in the soil, which was 1.89% before the experiment. In the treatment where hemp residues were mixed with the soil and nitrogen fertilizer pellets were used, the amount of carbon decreased by 0.1% after the experiment (Figure 5). The same decreasing trend was observed in the control treatment, where the hemp residues were left on the soil surface. Although the carbon content increased slightly in all the other treatments, there were significant differences in the interaction between the placement and the N source. Conversely, the additional nitrogen used for the mineralization of hemp residues had no significant effect on the influence of carbon in the soil.

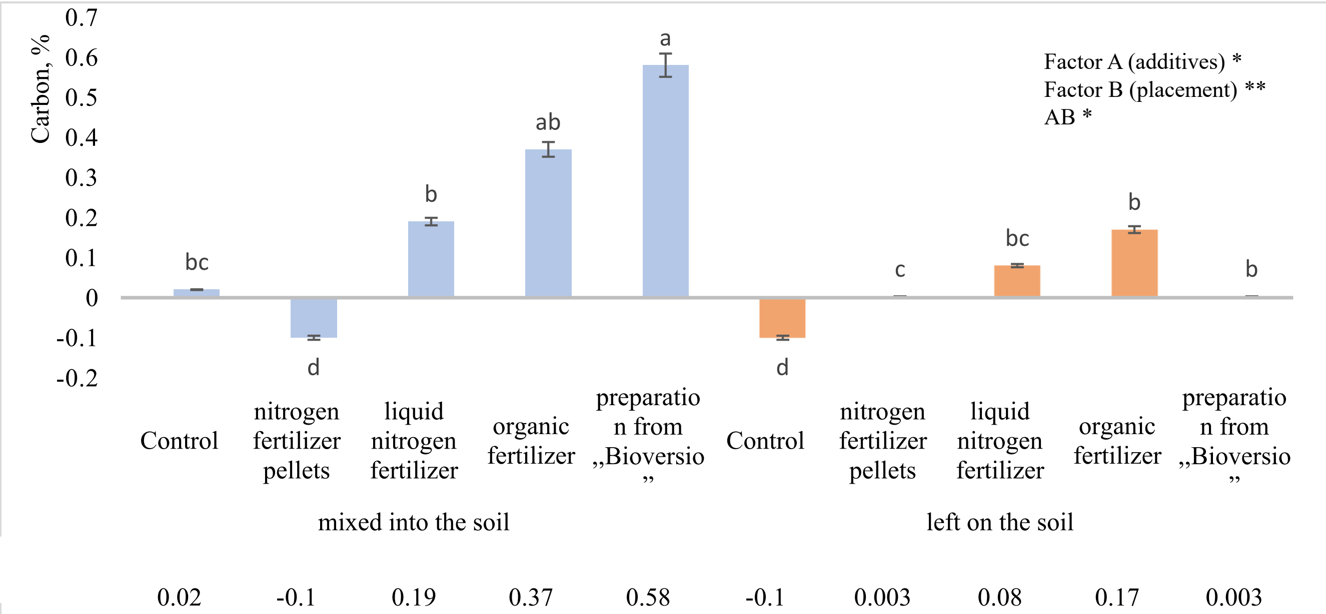

Figure 5. Carbon content in the soil. Data are presented as means ± standard error; different letters correspond to significant differences ($p < 0.05$ *; $p < 0.01$ **) between means according to Duncan test.

4. Discussion

Hemp is one of the most promising, high-yielding multifunctional plant that is rich in biochemicals, cellulose, and fiber [26]. Nevertheless, the influence of hemp agrotechniques and their potential on soil improvement is still unknown. Based on a detailed analysis of the literature and field research experiments on plant residue mineralization in soil, this study explains how different nitrogen rich additives affect the rate of decomposition of hemp residues.

4.1. Mass Loss in Hemp Residue Litter

The mass loss rate during the mineralization of hemp residue is aided by several factors, such as the climate, moisture content, C:N ratio, microbial community, particle size, and surface area. For instance, the more soil moisture that evaporates due to high daily temperatures, the lower the decomposition rates are. This aligns with similar studies, where increased rates of decomposition of hemp residues in mixed or belowground litter is associated with a higher moisture content and retention in litter bed field studies [27]. Additionally, the chemical makeup of plant residues (hemp residue) mainly consisting of cellulose, hemicellulose, and lignin which have been reported to play significant roles in decomposition and nutrient mineralization rates [28,29]. With the high lignocellulosic content in hemp residue, mineralization is typically slowed down, especially in treatments left on the soil due to there being less soil moisture, soil, and microbial interaction. Although there have been contrasting views on the influence of N addition on litter decomposition [30], this study reaffirmed the positive influence of N addition on hemp residue decomposition. The complementary roles played by the nitrogen sources which provided added nutrients and energy for the soil microbes to act on the residues mixed in the soil facilitated the degradation of the hemp residues. Our short-term study opined that the N addition did not inhibit microbial activity, hence enhancing the residue decomposition. Generally, the decay rates of the residues placed on the soil surface are slower than when the residues were incorporated into the soil [31]. An exception to surface-placed residues, slower rates of decay occur only when the moisture, nutrient status, and soil fauna activity are not limiting. Closer contact between the soil and residue facilitated the decomposition of the residues, as evidenced by high-level mineralization. Pronounced interaction with the microbial community in buried residues has been reported to be responsible for higher rates of mineralization in comparison to those of the residues left on the soil [32]. This argument and numerous others aligned with our study, where there was a lower mass loss of residues left on the surface due to a slower mineralization rate in relation to that of the residues mixed in the soil [33].

4.2. Carbon Content in the Hemp Residues

Plant residues like humus are a major component of organic matter. The amount and composition of which are important indicators of soil fertility and physicochemical properties [28]. Hemp plants are rich in carbon, as they accumulate carbon in their leaves, stems, and roots. The increased carbon content after this study explains the recent interest that has been shown in the cultivation of industrial hemp and its residue in soil carbon stock. When hemp residues, such as leaves, stems, and roots, are incorporated into the soil or left on a field after harvest, they contribute organic matter to the soil. This organic matter is a significant component of soil carbon, which helps improve the soil structure and fertility. Similar results were obtained when assessing the carbon content of hemp residues, as hemp residues are rich in lignin, which does not allow the residues to decompose faster [9]. The addition of N did not influence the changes in the carbon content of hemp residues in both the placements. This is demonstrated by the relatively low C: N ratio of the residue, indicating a sufficient amount of nitrogen for microbial activity; hence, additional nitrogen did not substantially impact the carbon content.

4.3. Nitrogen Content in the Hemp Residues

The amount of N in a residue can vary widely from one material to another, and this has a strong bearing not only on the amount of N released, but also on the rate at which it will be released from the residue. With the breakdown of hemp residue being dependent on the C:N ratio, there is the tendency for N addition to either hasten or impede the mineralization process. Some of the plant residues, for example, hemp residues, are rich in lignin. Lignin slows down the mineralization of residues [23,34]. An additional nitrogen input promoted the rate of decomposition, but had no significant influence on carbon release from the hemp residues [35]. Our study confirmed other researchers' reports, where plant residue mineralization with a very low lignin content occurs if sufficient nitrogen is available in the soil [26,34]. Therefore, using additional materials as an N input can accelerate the digestion of residues rich in lignin compounds, such as hemp residues [34,36].

4.4. Carbon Content in the Soil

Organic matter plays a very important role in assessing soil health and vitality and is an essential consideration in determining the functions of soil ecosystems [26]. The results of this study affirm the role of crop residue for the preservation of soil organic carbon stocks. Incorporating hemp residues into the soil plays an important role in the dynamics of carbon change. The accumulation, transfer, and content of soil carbon involves the dynamic interplay of microbial processes, climatic factors, and the physicochemical properties of the soil [37,38]. The hemp residues mixed into the soil enhanced the carbon content; the direct persistence of hemp residues will cause the retention of carbon in the surrounding soil environment. Essentially, the placement of the hemp residues is a factor in the decomposition process. Incorporated residues tend to slow down the decomposition process due to reduced exposure to microbial activity, oxygen, temperature fluctuations, and moisture variations [39]. An abundance of C and other nutrients are returned to the soil through thew decomposition of residues facilitated by microbes acting on the additional N sources. Xiangru Xu used corn straw in his research, which he inserted into the soil, and then observed what happened to its carbon content [40]. For the variants where the carbon content was the lowest, after the experiment, they noticed that the carbon content in the soil had leached and decreased, while in the variants with the highest carbon content, the residual carbon content in the soil did not increase significantly [19]. Organic carbon has a significant impact on soil fertility and microorganisms. In this study, the hemp residues in soil had no effect on carbon formation, which aligned with the previous studies [10,41].

4.5. Nitrogen Content in the Soil

Although, there are not many studies on the decomposition of hemp residues in soil, significant changes in nitrogen content have been reported when comparing the studies conducted by other researchers [26]. Our study demonstrates a significant increase in the amount of nitrogen in the soil due to the additional application of nitrogen fertilizers, which promoted the mineralization of hemp residues. The immobilization of nitrogen may have occurred in the soil as a result of the hemp residues, partly due to the influence of their C:N ratio. This, in turn, requires an additional N source addition [31,42]. Hence, the mineralization of hemp residues with additional nitrogen significantly increased the soil's nitrogen amount. Furthermore, the availability of the mineral N during decomposition influences the rate of decomposition. As affirmed in the previous studies, N-rich residues contain and release N in sufficient amounts to sustain decomposition, even if a little N is available in the soil; in contrast, the decomposition of N-poor residues is dependent on soil N, which, if not available (for example, when the surface placement limits contact with the soil), becomes a limiting factor for decomposition [39]. Notably, any potential direct N_2O emissions from the additives can be primarily mitigated by the action of the soil microbes that consume N_2O. The organic carbon added by the hemp residues stimulates the growth of soil microbes. These microbes use carbon as an energy source to carry out denitrification.

5. Conclusions

This study proposes accelerating the mineralization of hemp residues by mixing them with soil (incorporation) or leaving them on the soil surface as mulch. These research results confirmed the hypothesis that different nitrogen sources as additives applied to hemp residues can accelerate the decomposition of hemp residues in the soil and on its surface. The higher mass loss of hemp residues, when incorporated into soil alongside the organic fertilizer (pig digestate) and the nitrogen fertilizer pellet treatments, are of particular interest. Readily available N in these additives accelerates the decomposition process. Furthermore, the results of this work show that supplemental nitrogen not only breaks down hemp residues, but also increases the soil nitrogen levels, which is likely to positively impact the cultivation of other crops that require additional nitrogen. Although the amount of carbon in the soil did not change during the experimental period, it may likely increase when the hemp residues are completely mineralized in soil. The fastest mineralization of hemp residues occurred when the hemp residues were mixed into the soil with organic fertilizers or liquid nitrogen fertilizers used as additives. In general, the favorable results obtained in our study show the promising attributes of hemp residues as a bioresource material that can be used to sustain soil health. However, the high amount of lignin in plant waste can be a problem for residue mineralization. Hence, it is necessary to use additional nitrogen or other mineralization-promoting agents to accelerate the decomposition of hemp residue waste.

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