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Assessment of the impact of a digestate additive with biochar and zeolite on soil carbon dioxide flux and organic carbon mineralization

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ABSTRACT

In the context of contemporary agriculture, there is an imperative to curtail greenhouse gas emissions, including carbon dioxide, while concurrently enhancing the stability of organic caarbon within the soil. The objective of this study was to ascertain the impact of digestate augmented with biochar and zeolite on the emission of carbon dioxide from the soil and the process of organic carbon mineralization. The experiment was conducted on soils with three distinct variants: a control group (without additives), a group receiving digestate and biochar, and a group receiving digestate and zeolite. The study's findings demonstrated that both biochar and zeolite effectively curtailed the flux of carbon dioxide (CO_2) in comparison to the control soil. An augmentation in the total organic carbon and soluble organic carbon content was observed in the plot with digestate and biochar, while in the plot with digestate and zeolite, the forms of this carbon were stable. Kinetic models of carbon mineralization indicated a reduction in its decomposition in the plots with additives. The findings of this study substantiate the efficacy of the amalgamation of digestate with biochar and digestate with zeolite as a strategy to curtail carbon losses in soil and mitigate CO_2 emissions. Nevertheless, further research is warranted to optimize dosages and ascertain the long-term implications of employing these additives in diverse soil conditions.

Keywords: digestage, biochar, zeolite, carbon dioxide flux.

INTRODUCTION

The contemporary agricultural sector is confronted with the imperative to curtail carbon dioxide (CO_2) emissions, whilst concomitantly endeavoring to sustain or enhance soil quality. Within the European Union, the agricultural sector is accountable for approximately 14.3% of aggregate greenhouse gas emissions. Within the composition of these emissions, CO_2 constitutes approximately 27%, with the residual gases comprising nitrous oxide (36.5%) and methane (35.8%). In Poland, between 2005 and 2020, an increase in greenhouse gas emissions from agriculture was recorded by 7.4% (Bocean, 2025). A range of innovative strategies to reduce CO_2 emissions are currently under investigation, including, but not limited to, regenerative farming techniques, precision fertilization management, cover crops and the implementation of advanced agricultural technologies (Bocean, 2025). The aim of this research is to increase the efficiency of agricultural production while limiting the negative impact on the environment. A proposed solution to reduce greenhouse gas emissions involves the sequestration of carbon in the soil, which can be accomplished by augmenting the organic matter content and minimizing mechanical cultivation. The reduction in the utilization of nitrogen fertilizers and their replacement with natural, waste organic materials, in conjunction with the incorporation of nitrogen-fixing crops, contributes to a decrease in CO_2 emissions (Nazir et al., 2024). Microbial activity plays a crucial role in CO_2 flux, as both prokaryotic and eukaryotic microorganisms significantly contribute to carbon mineralization processes (Jaromin-Gleń et al., 2020). One solution that has been proposed is the utilization of organic and mineral materials, such as biochar and zeolite, which have the capacity to modify microbiological and chemical processes in the soil. This, in turn, has the potential to influence CO_2 emissions and organic carbon stability.

Digestate, a by-product of the methane fermentation process, is a rich source of organic matter and minerals that have the capacity to improve soil properties. However, its rapid biodegradation can lead to intensive carbon mineralization and increased CO_2 emissions (Lee et al., 2021). The addition of biochar, a by-product of biomass pyrolysis, has been demonstrated to possess the capacity to stabilize carbon in soil by means of organic substance sorption. This process has been shown to limit the availability of nutrients to microorganisms and to enhance the physicochemical properties of soil (Pandian et al., 2024). Zeolite has been demonstrated to possess a high ion exchange capacity and a porous structure. These properties enable the material to affect carbon retention and control microbiological processes, thereby reducing carbon losses in the form of CO_2 (Grifasi et al., 2024).

A plethora of studies have been conducted on the effect of biochar and zeolite on soil CO_2 emissions and organic carbon mineralization. The results of these studies indicate their potential to stabilize organic carbon and reduce greenhouse gas emissions. In an experiment conducted on orchard soils, it was found that the addition of biochar from cassava stems in the amount of 4% significantly increased the organic carbon content and reduced the activity of catalase and urease enzymes. This suggests increased stability of organic matter (Xiao et al., 2024). Another study, undertaken in field conditions on arable soils, demonstrated that the incorporation of biochar, in conjunction with the optimization of nitrogen fertilization, resulted in a substantial reduction in CO_2 emissions and an augmentation in the content of organic carbon forms within the soil (Yang et al., 2024). In addition, zeolites can help immobilize nutrients and contaminants in the soil, improving its structure and carbon retention capacity (Kukowska and Szewczuk-Karpisz, 2024). The mechanisms by which organic carbon is stabilized include changes in the activity of microbes in the soil. Biochar has been shown to promote the accumulation of stable forms of carbon; however, its interactions with microorganisms can also accelerate the mineralization of organic carbon in the short term (He et al., 2024). The findings of this study indicate that the utilization of digestate-biochar-zeolite mixtures has the potential to serve as an effective strategy for mitigating CO_2 emissions and enhancing organic carbon retention in agricultural and forest soils. However, there is a paucity of research concerning the synergistic or antagonistic effects of combining additives or organic wastes, or whether there may be interactions between them that modify the rate of carbon release from soil.

The objective of the present study was to ascertain the impact of digestate mixtures, incorporating zeolite and biochar, on the CO_2 flux from soil and the process of organic carbon mineralization. The study sought to evaluate the way these additives influence the stability of carbon within the soil, the rate of its mineralization, and the potential for mitigating carbon losses in the form of CO_2 flux. Furthermore, the objective was to make a comparison between the dynamics of changes in dissolved organic carbon (DOC) and total organic carbon (TOC) in soil in different experimental variants. This was done to determine whether biochar and zeolite can act as organic matter stabilizers and support soil carbon sequestration.

MATERIALS AND METHODS

The research was conducted on an experimental plot at the University of Life Sciences in Lublin in Czesławice Dziedzice, Lublin (Poland). The study employed a randomized block design, with three replicates. The experiment was conducted from 12 May to 22 October 2022. Three soil variants were tested in the experiment: a control consisting of soil without additives, and two variants with digestate and biochar, respectively. The second variant incorporated digestate at a rate of 5% w/w and biochar at a dose of 1% w/w. The third variant involved the introduction of digestate at a rate of 5% w/w and zeolite at a dose of 1% w/w into the soil. Biochar was obtained from a biogas plant in Piaski (Poland), while zeolite (clinoptilolite) was sourced from the Dylągówka deposit. Fluid brand biochar was produced from plant biomass because of the pyrolysis process, which was carried out at a temperature of 300 °C. The TOC, DOC and organic matter (OM) were determined in the plots on the selected measurement days.

The total organic carbon and dissolved organic carbon were determined by use of the RC 62 LECO apparatus (LECO, St Joseph, MO, USA). The determination of dissolved organic carbon was achieved by water extraction. Soil samples were suspended in deionized water at a ratio of 1:10 (g soil/ml water) and shaken for 24 h at room temperature. Following this, the suspension was subjected to centrifugation (4000 rpm, 15 min), and the obtained pellet was filtered through a membrane filter with a pore diameter of 0.45 µm. The organic matter content in the soil samples was determined by the loss on ignition method. Dried and weighed soil samples were placed in a muffle furnace and calcined at 550 °C for 4 hours. Following the completion of the process, the samples were cooled in a desiccator and then weighed again. The loss of mass of the sample after ignition was considered as the organic matter content, and the result was expressed as a percentage of the sample mass before combustion.

The measurement of CO_2 flux was conducted by means of a CO_2 probe (model GMP 343, manufactured by Vaisala Oy, Helsinki, Finland). The methodology employed in the measurement and calculation of CO_2 flux was consistent with that of previous studies (Kujawska et al., 2025).

Pursuant to the results obtained, the net mineralization ($c_{min,net}$) (Equation 1) and the carbon mineralization kinetics model (Equation 2) were calculated.

$$c_{min,net} = (c_{min,treatment} - c_{min,control}) \cdot \cdot (c_{soil} + c_{treatment}) \tag{1}$$

where: $c_{min,net}$ – net carbon mineralization, $c_{min,treatment}$ – total CO_2 from soil with additives, $c_{min,control}$ – total CO_2 from control soil, c_{soil} – soil organic matter, $c_{treatment}$ – carbon content in soil with additives (Zhu et al., 2017).

$$c_{min}t = c_0(1 - e^{-kt}) \tag{2}$$

where: $c_{min,net}$ – net carbon mineralization, c_0 – potentially mineralization carbon, k –mineralization rate constant, t – incubation time (de Figueiredo et al., 2019).

RESULTS AND DISCUSSION

An increase in temperature accelerates the metabolic rate of soil organisms, which in turn leads to an increase in carbon dioxide emissions. The role of humidity is significant, as it affects both microbial activity and the solubility of CO_2 in the soil (Mavrovic et al., 2023). The range of soil temperature was from 289.15K (17 May) to 309.51K (22 June). Research conducted in the spring and summer months, when higher temperatures were recorded, indicated that there was a corresponding increase in CO_2 emissions. The

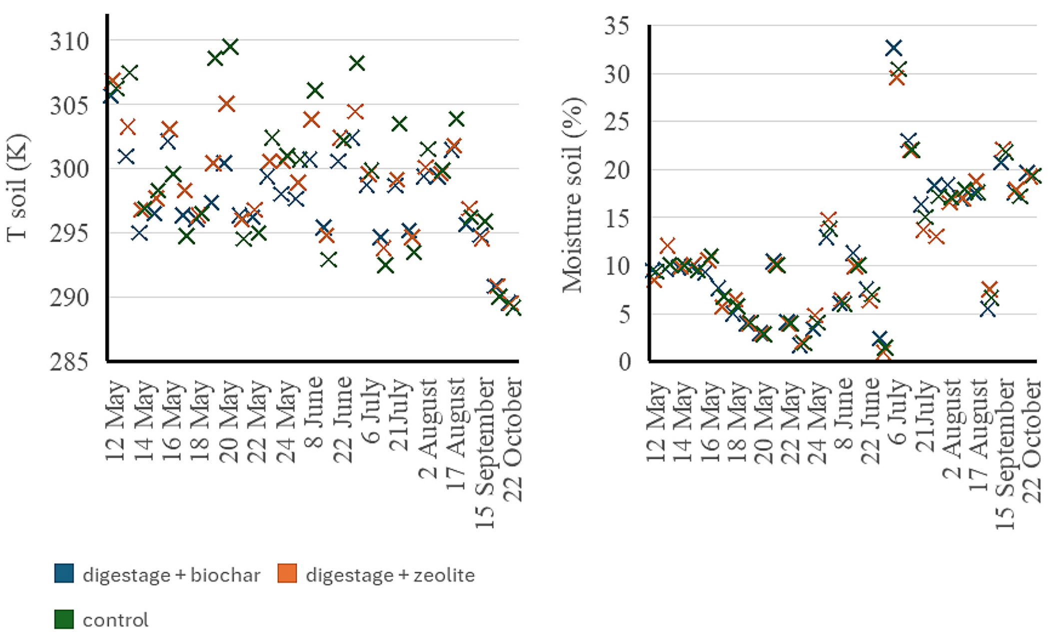

Figure 1. Moisture and temperature soil on individual measurement days

moisture content of the soil varied from 1.5% (29 June) to 32.6% (6 July) (Figure 1).

In the presented studies, the addition of biochar and zeolite with digestate increases the content of organic matter (Figure 2), total organic carbon (Figure 3), and dissolved organic carbon (Figure 4). Biochar-induced priming effects in soil via modifying the status

Furthermore, the plot that has received digestate in conjunction with zeolite has achieved OM and TOC values that are approximately 1.5 times higher than those recorded in soil that has not received any additives.

Biochar, a material with a high carbon content, has been demonstrated to enhance the total carbon content of soil, as evidenced by an increase in total organic carbon values. Research has indicated that the incorporation of biochar into soil leads to a substantial augmentation in soil organic carbon sequestration (Kumar et al., 2025). The influence of biochar on soil carbon accumulation is the result of several mechanisms. Firstly, biochar introduces stable forms of carbon into the soil directly. This limits the decomposition of existing organic matter, reducing its mineralization and CO_2 emissions. This reduction is known as the so-called negative primary effect (Rasul et al., 2022). Secondly, biochar has been demonstrated to modify soil properties by enhancing its pH, water and nutrient retention capacity. This, in turn, impacts the structure of soil microorganisms and their carbon metabolism, consequently

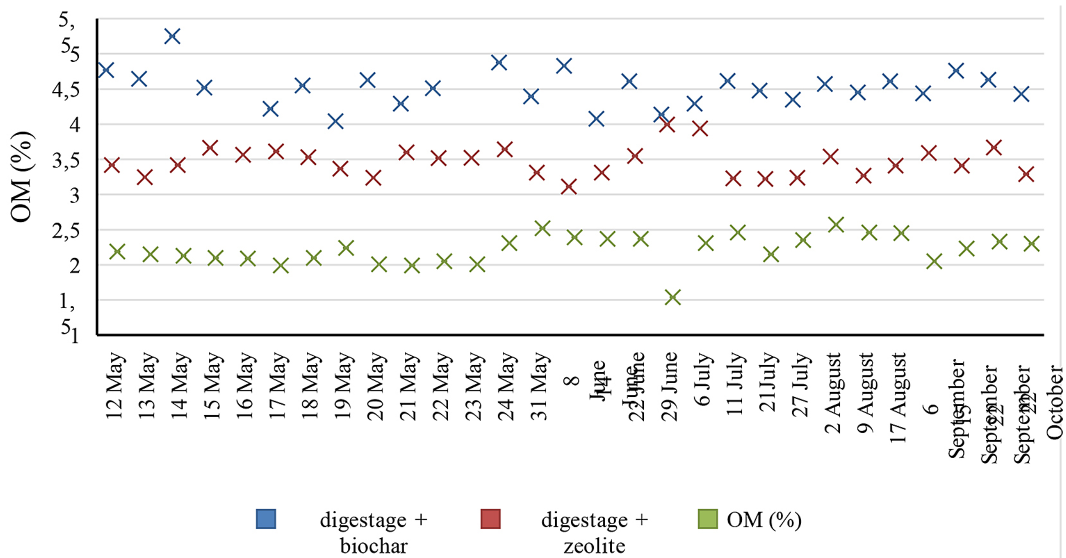

Figure 2. Organic matter in soil on individual measurement days

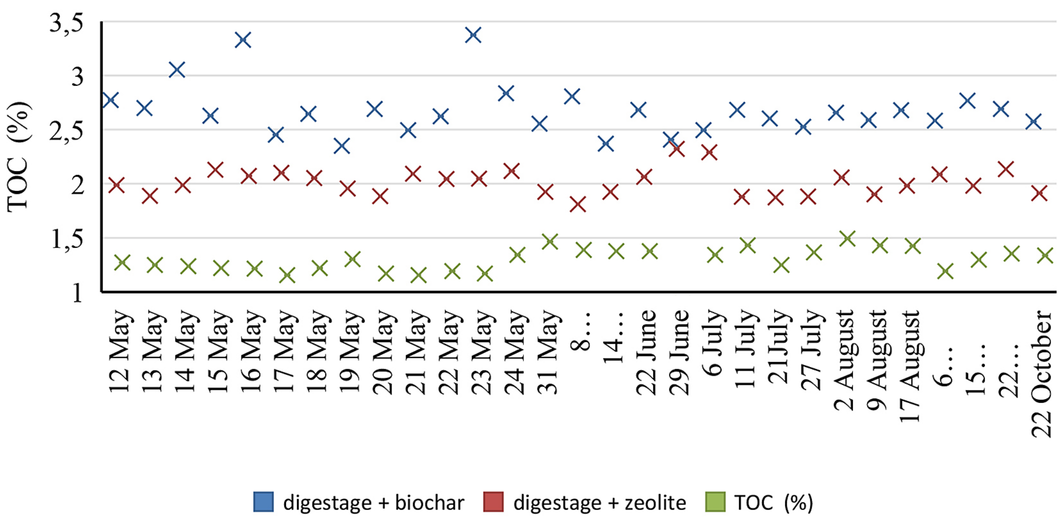

Figure 3. Total organic carbon in soil on individual measurement days

resulting in a reduced rate of organic matter decomposition (Zhao et al., 2024). Thirdly, biochar has been demonstrated to support the formation of stable complexes between organic matter and soil minerals, thereby increasing the resistance of organic carbon to decomposition and enabling its prolonged stabilization in the soil (Zhang et al., 2023). Thanks to these properties, biochar not only supplies additional carbon to the soil ecosystem but also contributes to its long-term retention.

In addition, zeolite, although it does not increase TOC as significantly as biochar, maintains its level at a stable level that is higher than in the control variant. While biochar significantly increases TOC, zeolite primarily functions to maintain a stable level of nutrients. Recent studies have demonstrated that the amalgamation of zeolite and biochar can enhance metal immobilization and nutrient retention. This suggests that the zeolite enhances the biochar's effects rather than competing with them (Zheng et al., 2020).

Analogous tendencies were identified in the case of soluble organic carbon. The highest concentrations of DOC were recorded in the digestate plot that incorporated biochar, a factor that promotes the release of soluble forms of carbon. The digestate plot with zeolite exhibited lower DOC values than the digestate plot with biochar, yet higher than those observed in the soil control. The addition of zeolites and biochar to soils has been shown to enhance their properties, thereby impacting the dynamics of retention and decomposition of organic carbon. Biochar, which are frequently characterized by an alkaline pH, have been observed to increase the solubility of organic substances, thereby facilitating their transfer to the soil solution. However, it should be noted that biochar, despite its initial capacity to absorb DOC, becomes saturated over time and begins to release some of the accumulated carbon (Blenis et al., 2023). However, zeolite provides stability. However, its reduced capacity to augment TOC in comparison with biochar may constrain its efficacy in the context of soil remediation (Martelletti et al., 2019). This observation underscores the necessity for further research to be conducted into the development of optimal rates of input materials and their combinations.

Figure 5 shows the CO_2 flux values on the plots tested with different doses of digestate, biochar and zeolite. The CO_2 flux values on the plots differ between the plots tested. The highest CO_2 fluxes (195.5 mg CO_2 m^{-2}) were observed on the control soil. The addition of organic matter, both biochar and zeolite, slightly reduced CO_2 fluxes. During the first weeks of the experiment (May–June), the CO_2 fluxes on the experimental plots were similar at around 150 mg CO_2 m^{-2}. In June and July, a rapid increase in CO_2 flux was observed on the control plot, reaching its highest value on 27 July (195.95 mg CO_2 m^{-2}). Meanwhile, the CO_2 flux values reached 170 mg CO_2 m^{-2} on the digestate plots with the addition of biochar and zeolite.

When comparing the plots with additives, the CO_2 flux values are similar, but in the plot with zeolite addition, similar CO_2 flux values can be observed on individual measurement days, especially in the later months of the experiment. The lowest emission during the whole measurement

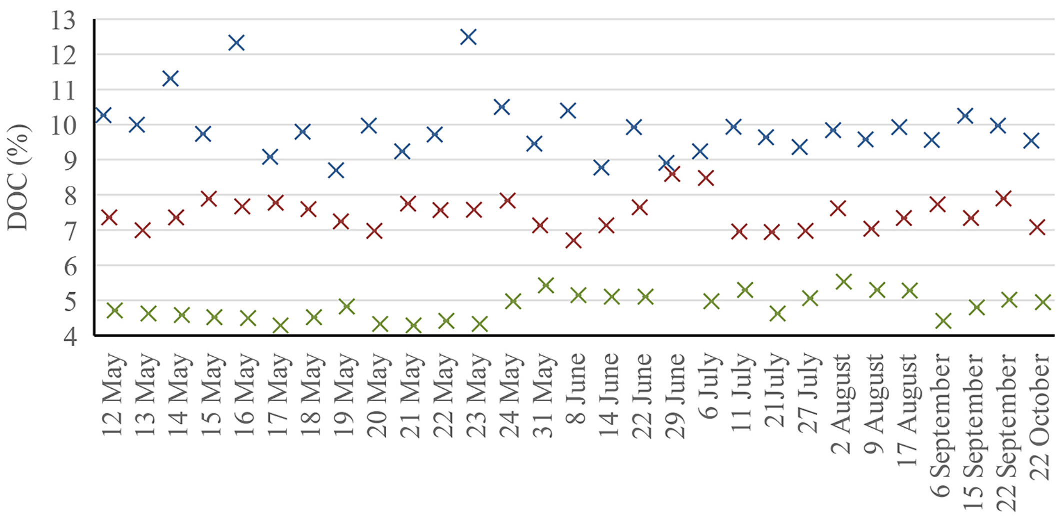

Figure 4. Dissolved organic carbon in soil on individual measurement days

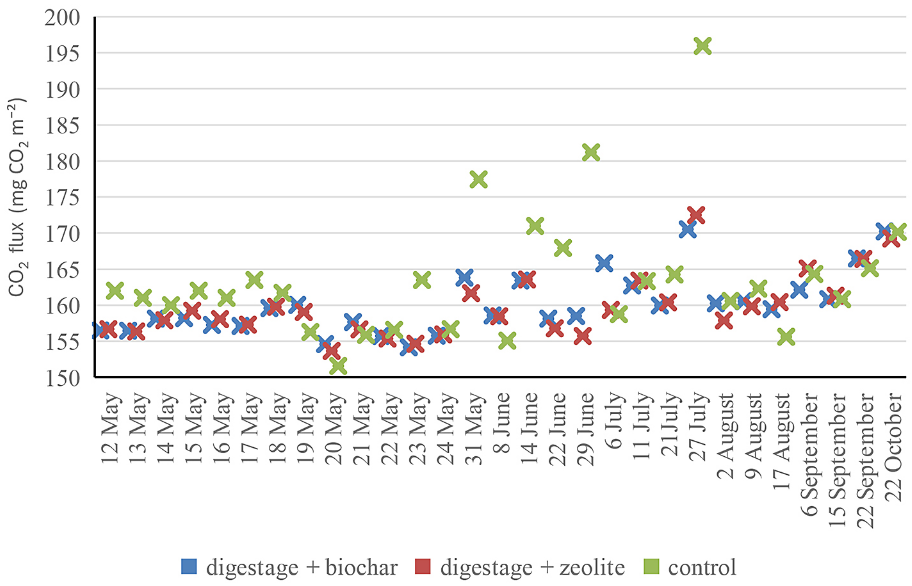

Figure 5. CO_2 flux in soil on individual measurement days

period was recorded in the control plot on 20 May (151.57 mg CO_2 m^{-2}), while the highest - also in the control group - was recorded on 27 July (195.95 mg CO_2 m^{-2}). This may indicate that without organic amendments, CO_2 flux values are more variable and responsive to changing conditions.

The results of the studies conducted showed that CO_2 flux values differed between the plots studied, with the highest values observed in the control soil. Both the addition of biochar and zeolite effectively reduced CO_2 emissions from the soil, confirming previous studies on the effect of these materials on greenhouse gas emissions. Similar results were obtained in the Cardelli et al. (2018) experiment, where CO_2 emissions were monitored for 100 days, analyzing different combinations: control soil without additives, soil with 1% and 5% digestate, soil with 1% biochar and their combination. In the plot with digestate, an increase of more than 60% in CO_2 emissions was observed compared to the control. The combination of biochar and digestate reduced CO_2 emissions by 20% compared to the soil with digestate (Cardelli et al., 2018). Mukherjee et al. (2016) showed that the addition of 1% biochar to digestate reduced CO_2 emissions by 11 times compared to digestate alone. Cardelli et al. (2018) confirmed this effect by showing that biochar reduced the availability of DOC, leading to reduced microbial activity and lower CO_2 emissions.

Ali et al. (2022) showed that the combination of biochar and zeolite significantly reduced emissions of NH_3 and CH_4 gases by 50% compared to the control soil. However, they observed an increase in CO_2 emissions of up to 110% at a dose of 6 t ha^{-1} biochar with 5 t ha^{-1} zeolite, and in the plot with the addition of zeolite alone, they observed a 12% reduction in CO_2 emissions. However, the studies by Chen et al. (2015) suggest that the effect may depend on soil conditions and the type of fertilizer used.

Studies show that biochar can reduce CO_2 emissions from soil. Hu et al. (2023) showed that biochar from sewage sludge added to soil reduced CO_2 emissions by 51% compared to unamended soil, while the addition of sewage sludge reduced CO_2 emissions by 20% compared to soils to which sewage sludge was added. Again, our results show that the effect of reducing CO_2 emissions was more pronounced, which may indicate a beneficial effect of combining digestate with biochar and zeolite. Case et al. (2012) in their study showed that cumulative CO_2 production from soils with 1% and 2% biochar addition was 40% higher than the control. While in the study by Cross & Sohi (2011) there was no change in CO_2 emissions from soils with 5% and 10% biochar addition.

An important aspect that should be considered in research is the selection of appropriate proportions of organic materials and the long-term effects of the additives used on the soil carbon cycle. Research by Verdi et al. (2024) showed that biochar added to digestate can significantly reduce CO_2 emissions, but this effect depends on the dose and incubation time. In the long term, biochar can be expected to contribute to the stabilization of organic matter in soils, with beneficial effects on soil fertility and carbon balance.

CONCLUSIONS

Recent studies have demonstrated that the incorporation of biochar and zeolite digestate can serve as an effective method to mitigate CO_2 flux.

Decomposition rate coefficient values were found to be lower in the amended plots compared to the control soil, indicating limited mineralization of organic carbon.

An increase in total organic carbon and dissolved organic carbon content was observed in the digestate and biochar plots. In contrast, the digestate and zeolite plot demonstrated the capacity to enhance the stability of these carbon forms.

Further research is necessary to optimize rates and ascertain the long-term implications of their utilization.

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