Sustainable and Climate Resilient Biobased Solutions Tested in Microcosm Experiments For Their Effect on CO_2 Emissions

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Abstract. This study discusses the role of bio-stimulants, respectively alginate-derived beads, as an adaptation strategy in relation to GHGs, supporting soil carbon sequestration and nutrient cycling. Considering the current climate crisis, bio-stimulants enhance the resilience of agricultural ecosystems and facilitate the transition towards a low-emission regenerative agriculture. It has been observed that S_0 recorded the lowest CO_2 emissions, with the maximum values ranging from 0.4125 g m^{-2} h^{-1} to 2.1418 g m^{-2} h^{-1}, while the highest CO_2 emissions were recorded for the AZ and AZI treatments. The AZ treatment showed a range of CO_2 emissions between 1.1379 g m^{-2} h^{-1} and 3.0539 g m^{-2} h^{-1}, the latter representing the highest emission value observed throughout the entire monitoring period. AZI registered higher CO_2 values than S_0, ranging between 0.2083 g m^{-2} h^{-1} and 1.8368 g m^{-2} h^{-1}, while S_0 had a more spread distribution between 0.0548 g m^{-2} h^{-1} to 2.1352 g m^{-2} h^{-1}. Nonetheless, results indicate that the soil on which the alginate-zeolite suspension was applied had the highest water retention capacity, while the control pot registered the lowest values for soil moisture, emphasizing the climate resilience capacity to the dependent parameters, also considering the soil emission component of carbon balance.

1 Introduction

Recent climatic variations have determined significant challenges to agriculture, affecting crop yields, food security, and farming practices worldwide. As environmental factors such as temperature, precipitation level or wind fluctuate, it is essential to comprehend the impact on agricultural ecosystems in order to develop sustainable strategies, ensure resilience, and develop a synergistic agro-environmental approach [1,2]. Studies indicate the importance of

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nature-based agricultural practices and policies aiming to reduce carbon footprints, while considering the adaptation to climate change [3].

CO_2 emissions have risen above 408 ppm, according to data from the World Meteorological Organization [4]. The aforementioned climate driver, together with CH_4 and N_2O, contributes over 80% to the greenhouse effect, whereas agriculture is responsible for 30% of the GHGs generated by anthropogenic activities [5]. Therefore, it is of urgent need to implement bio-solutions that can improve water retention of soils, ensure gradual release of nutrients, and control soil pH. It has been demonstrated that alginate-derived beads enrich soil quality through their over-time progressive degradation [6]. Studies indicate that to achieve climate neutrality and transition to a sustainable agriculture, agroecological practices such as crop rotation, no-tillage or low-tillage, smart irrigation, organic fertilizers, and legume crops play an important role, strengthening, at the same time, the link between food security, economic efficiency, and GHG emissions [7]. Microbial bioengineering represents a non-invasive and eco-friendly practice that contributes to a more resilient agriculture. Thus, bio-stimulants aim to preserve soil quality and biodiversity while promoting healthy crops and improving plants' access to nutrients [8].

Despite its key role in organic matter degradation and soil health improvement, microbial activity can lead to increased emissions of CO_2 and N_2O [9]. Although advancements have been made in decreasing emissions associated with fertilizers and bio-stimulants, research gaps still exist, particularly regarding their long-term effects and the connection between fertilizing techniques and soil microbial communities [10,11]. Furthermore, variability in application methods and environmental conditions significantly hinders accurate emission quantification. Most research has concentrated on agronomic adaptation measures to increase crop productivity, while the effects of the applied amendments on the existing GHG balance from agricultural soils have received limited attention. It has been demonstrated that organic soil amendments, such as manure increase CO_2 emissions, registering higher values than mineral fertilisers. Thus, values corresponding to the manured soil were higher by 1431.9–2174.2 kg CO_2–C ha^{-1} than the soil ammended with mineral fertilisers [12].

In this context, the transition towards low-emission agriculture requires an evaluation of ecosystem services considering crop yields, farming costs, and the overall impact of agricultural practices on the environment, for reconciling economic viability with ecological balance. Therefore, implementing sustainable land management practices, such as adjusting sowing dates and planting climate-resilient crops, can increase the carbon sequestration potential of soil .

Thus, this study aims to analyse the contribution of the above-mentioned bio-stimulants to greenhouse gas mitigation effect and also address the climate adaptation by considering soil moisture and temperature variability. This research highlights that integrated agroecological practices, including the application of alginate-derived beads as a sustainable bio-stimulant, decrease the environmental footprint from agriculture, while supporting environmentally friendly practices.

2 Materials and Methods

To mimic the release profile in real agricultural fields, the developed materials were evaluated as potential soil conditioners in pot experiments for over 30 days, including a pre-treatment monitoring, under controlled temperature and humidity conditions, similar to those prevalent in common agricultural fields during the wheat seeding period. First, about 100 kg of soil was collected from agricultural land around Bucharest, homogenized, and uniformly dispersed in 4 pots of 50 L. After filling each pot with soil, the same quantity (50 g) of wheat seeds was spread on the soil surface and mixed with soil from a depth of 5 cm. Suspensions containing alginate (A), alginate–zeolite (AZ), and alginate–zeolite–inoculum (AZI) were

dispersed in soil in 3 pots, while the fourth pot was control with no treatments applied (S0). Throughout the experiment, the moisture content and the temperature of the soil were measured with a digital soil moisture meter sensor TRIME-PICO by inserting the instrument sensor into the soil to a specific depth. The soil moisture was daily monitored and kept at a humidity level above 10% by irrigation sessions when necessary.
A total of three fertilizations were applied during the experiment, using the alginate-derived beads: at the beginning of the experiment, 2 weeks, and 4 weeks after the start of the experiment.

In order to determine the physico-chemical indicators of soil, samples were collected at the beginning and at the end of the experiment for the control pot and for the 3 pots containing suspensions of alginate-derived amendments.

CO_2 emissions were monitored and evaluated as an essential soil health indicator. Thus, the potential co-benefit of CO_2 reduction/capture in soil by applying alginate-derived beads was considered. In this study, CO_2 emissions from soil in experimental pots have been measured in microcosms using two measuring devices: the GT500 by Eosense and the EGM-5 from PPSystems. At the same time, soil moisture and temperature parameters were monitored while analyzing the influence of wheat growth rate on these emissions.

The GT500 automatic gas analyzer is suitable for continuous measurements of CO_2 flux, providing high accuracy in quantifying soil emissions. It monitored the evolution of gas fluxes over a day, while the EGM-5 was used to allow rapid determinations of CO_2 concentration. The combined use of the two equipment provided a detailed picture of the temporal variations and factors influencing emissions. A pre-calibration protocol of the equipment was applied to avoid possible errors during the measurement cycle.

3 Results and discussions

The following section presents an overview of the effects and influence of alginate-derived beads, as bio-stimulants, on GHG fluxes. Table 1 presents the chemical indicators for soil at the beginning and at the end of the experiment for control pot and for the 3 pots with amendments applied.

The main soil characteristics were determined at the beginning of the experiment and then monitored throughout the experiment. As can be observed in Table 1, the soil used in the experiment is moderately acidic, and the pH of the soil decreased slightly for all soil samples. The decrease was smaller for soils treated with AZ and AZI, considering the slightly alkaline pH of these composites. The C/N ratio was positively influenced by the use of alginate-based composites.

Table 1. Principal characteristics of the soil used in the pot experiment

Characteristic	Samples collected at the beginning of the experiment				Samples collected at the end of the experiment			
	Control	A	AZ	AZI	Control	A	AZ	AZI
pH, pH units	5.82	5.93	5.66	5.89	5.68	5.81	5.57	5.85
Total nitrogen, %	0.19	0.17	0.17	0.18	0.14	0.15	0.15	0.15
Total phosphorus, mg/kg	442	482	425	436	436	427	431	432
Total potassium, mg/kg	504	1315	1718	1223	1275	1471	1696	1669
Organic carbon content, %	1.23	1.37	1.38	1.31	1.54	1.69	1.61	1.56

Electrical conductivity, mS/m	0.13	0.12	0.12	0.13	0.06	0.12	0.14	0.12
Ratio C/N	6.47	8.06	8.12	7.27	11	11.26	10.73	10.44

Considering the effects of climate change in agriculture, it is essential to establish a set of sustainable land management practices that improve soil health while adapting to climate change. In this context, GHG emissions will be assessed in correlation with the soil amendments used in this study.

Figure 1 presents the evolution of soil moisture for each pot, its corresponding treatment, and the control pot. Results indicate that the soil on which the alginate-zeolite suspension was applied had the highest water retention capacity, while the control pot registered the lowest values for soil moisture. After amendments were applied and the soil was irrigated, soil moisture increased for the three pots with alginate-derived beads, suggesting that by improving soil porosity, bio-stimulants enhance water infiltration and retention.

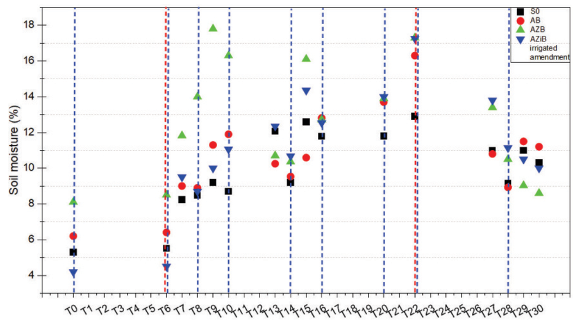

Fig. 1. Soil moisture depending on irrigation events and amendment application

Figure 2 assesses the CO_2 emissions of the control pot in comparison with the pots treated with alginate suspensions. S0 recorded the lowest CO2 emissions, with the maximum values ranging from 0.4125 g m^{-2} h^{-1} to 2.1418 g m^{-2} h^{-1} at T21. The highest CO_2 emissions were recorded for the AZ and AZI treatments. At T9, the AZ treatment showed a range of CO_2 emissions between 1.1379 g m^{-2} h^{-1} and 3.0539 g m^{-2} h^{-1}, the latter representing the highest emission value observed throughout the entire monitoring period. These results can be attributed to the fact that the applied treatments enhanced the development of soil microorganisms, thereby improving the decomposition of organic matter which determined an increase in CO_2 emissions. Zeolite contributed to this effect by improving soil water retention and aeration, stimulating microbial activity. Moreover, the application of alginate in combination with zeolite consistently resulted in higher CO_2 emissions compared to the treatment involving alginate, zeolite, and microbial inoculum. This suggests that the interaction between the treatment components may influence microbial dynamics and the rate of carbon sequestration in the soil.

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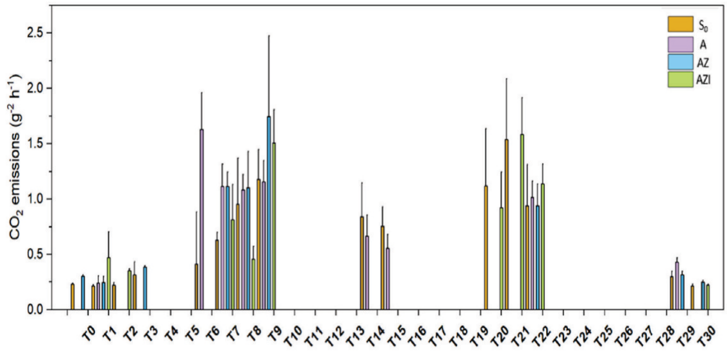

Fig. 2. Comparison of CO_2 fluxes between the control soil and the soil with alginate (A, AZ, AZI) applications under controlled conditions

Figure 3 presents the CO_2 emissions of the control soil and the soil treated with alginate. A recorded higher CO_2 emission compared with S0, being characterized by a more compact distribution during the monitoring period. Towards the end of the measurement, S0 registered higher values, whilst A indicated a decreasing trend for CO_2 emissions. The fluctuation of the CO_2 emissions for S0 highlights that the untreated soil is more reliant on environmental factors such as temperature and moisture, while A has a more stable emission pattern. Therefore, alginate is essential for stabilizing biogeochemical processes and the decomposition of soil organic matter.

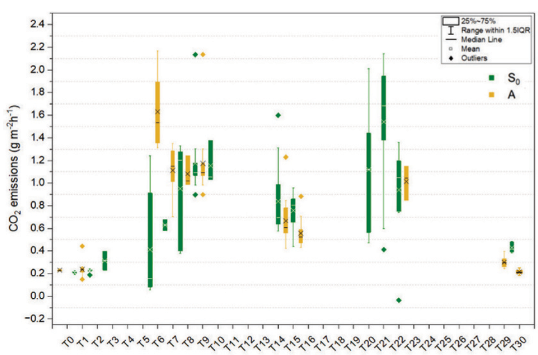

Fig. 3. CO_2 emissions from the control soil and the soil treated with alginate (A)

Figure 4 summarizes the difference between CO_2 emissions from control soil and soil treated with alginate-zeolite (AZ). A more compact distribution is observed for AZ with approximately constant values of the CO_2 emissions during the analyzed period, while S0 had significant fluctuations. Thus, the highest value registered for AZ was 3.0539 g m^{-2} h^{-1} and 2.1230 g m^{-2} h^{-1} for S_0 at T9. Moreover, at the same time period, it was observed the highest spread of the values corresponding to AZ, between 1.1379 g m^{-2} h^{-1} and 3.0539 g m^{-2} h^{-1}, highlighting the impact of alginate-derived beads.

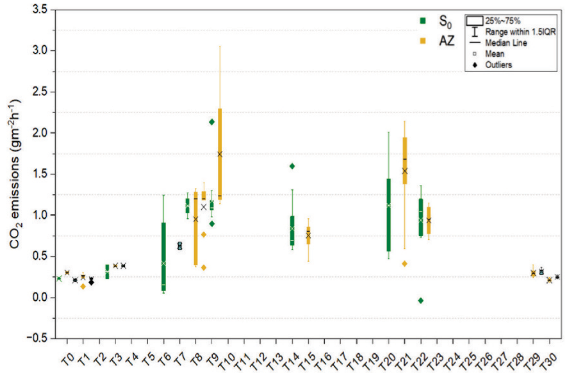

Fig. 4. CO_2 emissions from control soil and soil treated with alginate-zeolite (AZ)

Figure 5 illustrates the evolution of the CO2 emissions from control soil and soil treated with alginate-zeolite and inoculum (AZI). AZI registered higher CO2 values than S0 at the beginning of the analyzed period, while towards the end, AZI illustrates a decreasing trend, with a compact distribution of the dataset with values between 0.2083 g m^{-2} h^{-1} and 1.8368 g m^{-2} h^{-1}, while S0 had a more spread distribution ranging from 0.0548 g m^{-2} h^{-1} to 2.1352 g m^{-2} h^{-1}.

Table 2 presents the mean values and standard deviations of CO_2 emissions for the analyzed samples (A, AZ, AZI, and S0). The control sample (S0) exhibits the highest mean value (0.656) and the lowest standard deviation (0.422), indicating a tighter distribution of values. In contrast, the AZ sample has the lowest mean value (0.426) and a standard deviation relatively close to that of the other zones (0.542), which demonstrates greater variability and a lower trend compared to the other samples.

Table 4 presents the results of the t-test, comparing CO_2 emissions between the control sample S0 and the samples A, AZ, and AZI. The highest difference is observed between S0 and AZ (-0.263), followed by the difference from A (-0.154) and AZI (-0.110), indicating that the emissions recorded for S0 are on average lower than in the other samples. These results are strengthened by t-test.

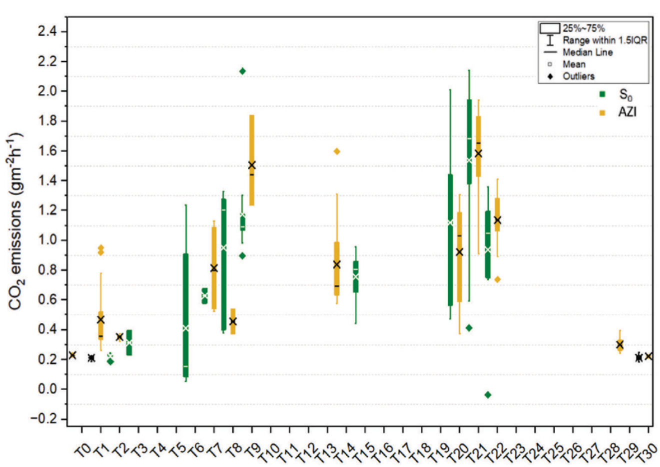

Fig. 5. CO_2 emissions from control soil and soil treated with alginate-zeolite and inoculum (AZI)

Table 2. Descriptive indicators of CO_2 emissions from the analyzed samples

	Bias	Std. Error	95% Confidence interval

					Minimum	Maximum
A	Mean	.5251750	-.0002385	.1347701	.2690333	.7897689
	Std. deviation	.55266423	-.02454954	.07190882	.38963372	.65891973
AZ	Mean	.4267537	.0028762	.1331699	.1801735	.7082799
	Std. deviation	.54213837	-.02759679	.10900992	.28915314	.71484832
AZI	Mean	.4974208	.0053025	.1426572	.2460655	.7837460
	Std. deviation	.56515769	-.02657814	.09072923	.34450500	.69077149
S0	Mean	.6562627	.0047823	.1049373	.4720691	.8748674
	Std. deviation	.42202695	-.01757781	.06187430	.28785441	.52147958

Table 3. Pearson correlation analysis for samples S_0, A, AZ, and AZI

	S_0	A	AZI
A	.873*		
AZ	.869*	.875*	
AZI	0.646	0.533	0.737

Additionally, the comparison between S0 and AZ indicated significance (unilateral p= 0.055), highlighting the effect of the applied treatment. Similarly, the analysis between S0 and A emphasized a trend towards significance (unilateral p = 0.071); however, differences between S0 and AZI were not statistically relevant.

Table 4. Results of the t-test applied to CO_2 emissions monitored in the four samples

	Mean	Std. Deviation	Std. Mean Error	95% Confidence interval Minimum	95% Confidence interval Maximum	t	One-sided p	Two-sided p
S_0 - A	-.154012	.188537	.084316	-.388112	.080087	-1.827	.071	.142
S_0 - AZ	-.2634827	.287042	.128369	-.619892	.092927	-2.053	.055	.109
S_0 - AZI	-.1104313	.349248	.156188	-.544080	.323217	-.707	.259	.519

4 Conclusions

This study evaluated the role of bio-stimulants, respectively alginate-derived beads, as an adaptation strategy to GHG dependent parameters (temperature and soil moisture), supporting soil carbon sequestration and nutrient cycling. Results indicate that S0 registered the lowest CO_2 emissions while having large fluctuations over time, being more sensitive to environmental factors like temperature and moisture. The alginate treatment (A) stabilized CO_2 emissions, showing a more compact and consistent pattern throughout the monitoring period. Zeolite-based suspensions (AZ and AZI) had the highest CO_2 emissions, as a result of enhanced decomposition of organic matter. In contrast to the treatment that also contained microbial inoculum (AZI), the combination of alginate and zeolite (AZ) resulted in increased CO_2 emissions, suggesting that interactions between treatment components can impact microbial dynamics and soil carbon sequestration, especially in higher soil moisture levels above 14%. In comparison with S0 which registered the lowest CO2 emissions ranging from 0.4125 g m^{-2} h^{-1} to 2.1418 g m^{-2} h^{-1}, AZ indicated the highest values with a range between 1.1379 g m^{-2} h^{-1} to 3.0539 g m^{-2} h^{-1}. As opposed to AZI which registered values between 0.2083 g m-2 h-1 and 1.8368 g m-2 h^{-1}, S0 had a more spread distribution ranging from 0.0548 g m-2 h-1 to 2.1352 g m-2 h-1. The Pearson correlation analysis indicates a significantly high correlation between A and AZ (r = 0.875), and significant correlations between S0 and A, as well as between S0 and AZ, with r = 0.873 and r = 0.869 ($p<0.05$).

However, correlations with AZI do not present significance. Results of the t-test applied to CO_2 emissions monitored in the four samples indicate that the highest difference is observed between S0 and AZ (-0.263), followed by the difference from A (-0.154) and AZI (-0.110), indicating that the emissions recorded for S0 are on average lower than in the other samples.

These findings indicate that alginate-derived beads, used as bio-stimulants, contribute to stabilizing biogeochemical processes and the decomposition of soil organic matter, providing a sustainable solution for transitioning towards a regenerative agriculture, by improving soil water retention and soil structure. Climate mitigation potential must be investigated in supplementary research by long-term monitoring of GHG and considering other carbon reservoirs (aboveground biomass, soil organic matter (SOM), and soil organic carbon (SOC)).

Although only four pots were used for the experiment (S0, A, AZ and AZI), minimal variability and comparable initial conditions were assured by utilising soil from a homogenized batch. Thus, considering the homogeneity of the soil and the experimental procedures, each pot served as a representative unit for the applied treatment. Consequently, several temporal measurements of CO_2 emissions within each treatment were subjected to statistical analysis, providing enough data points to assess trends and differences with an acceptable level of confidence. However, more replicates will be used in future research to improve statistical robustness while also taking micro-scale variability into consideration. Nonetheless, by analysing climate adaptation and mitigation, the present study aims to target two of the EU Taxonomy Principles, as stated in 2030 Agenda for Sustainable Development.

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