

ORIGINAL ARTICLE

Agrosystems

Impacts of organic input application strategies on soil greenhouse gas emissions in diverse cropping systems in a semiarid region

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Abstract

Organic amendments enhance soil quality in agroecosystems, although they may modify the dynamics of greenhouse gas (GHG) emissions, highlighting complex interactions between soil management and environmental sustainability. A field experiment was conducted in the semiarid region of Iran to evaluate the effects of barley residues (BR), sheep manure (SM), and their combination (BR+SM) on soil carbon dioxide (CO₂) and nitrous oxide (N₂O) emissions under maize and mungbean. In mungbean, both SM and BR+SM resulted in higher CO₂ fluxes than BR. Conversely, in maize, cumulative CO₂ emissions were similar among treatments. Under mungbean, BR+SM exhibited higher soil N₂O values than SM and BR. The lowest cumulative CO₂ (4.77 ± 0.24 and 5.29 ± 0.37 Mg ha⁻¹ year⁻¹ for maize and mungbean, respectively) and N₂O (4.73 and 3.00 kg ha⁻¹ year⁻¹ for maize and mungbean, respectively) values were measured in the BR, whereas the BR+SM resulted

Abbreviations: BR, barley residues; ECD, electron capture detector; GHG, greenhouse gas; MBC, microbial biomass carbon; SM, sheep manure; ST, soil temperature; VIF, variance inflation factor; WFPS, water-filled pore space.

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in significantly high cumulative CO₂ and N₂O under both crops. Cumulative CO₂ fluxes were 21.5% and 53.5% lower in the BR than BR+SM under maize and mungbean, respectively. Similarly cumulative N₂O was 48% lower in the BR than in the BR+SM treatment under the mungbean cropping system. Application of BR can be considered as an effective alternative management strategy in terms of lowering GHG emissions under maize and mungbean. By exploring the impact of organic input management on soil carbon and nitrogen dynamics in semiarid cropping systems, our study provides key insights for enhancing agricultural sustainability, while reducing GHG emissions.

Plain Language Summary

Organic materials like crop residues and animal manure are commonly used to improve soil health, especially in dry farming regions. However, their impact on greenhouse gas emissions from soils is not well understood. This study aimed to evaluate how applying barley residues, sheep manure, or both affected emissions of carbon dioxide (CO₂) and nitrous oxide (N₂O) in maize and mungbean fields in semiarid western Iran. The study found that barley residues alone led to the lowest emissions, while combining them with manure significantly increased CO₂ and N₂O release, especially in mungbean crops. These results suggest that crop type and amendment combination strongly influence greenhouse gas outcomes. Choosing the right organic input—like barley residues—can help farmers reduce emissions while maintaining soil fertility, making agriculture more climate-friendly in semiarid areas.

1 | INTRODUCTION

Food security, maximizing profit, and mitigation of climate change are main concerns for the agricultural sector nowadays (Nsabiyeze et al., 2024; Smith et al., 2020; Viana et al., 2022). Intensification of agricultural systems and high input of synthetic fertilizers is commonly applied in order to satisfy the rapidly growing demand for food worldwide but can in the long run lead to unintended soil degradation and pollution of aquatic systems (L. Li et al., 2025; Rashmi et al., 2020). For example, intense fertilizer application can speed up soil organic matter depletion, lead to loss of biodiversity, groundwater contamination, and increased emissions of greenhouse gases (GHGs) (Abdo et al., 2025; Owusu et al., 2024). Techniques of sustainable management, such as the application of organic amendments in agriculture, are promising approaches for alleviating environmental degradation, increasing farmers' incomes, and mitigating GHGs emissions (Brenzinger et al., 2018; Owusu et al., 2024; Wu et al., 2020).

Worldwide, annual production of plant residues and animal manure is 3.8×10^9 and 7×10^9 Mg, respectively, while biosolids production is approximately 10×10^7 Mg (Thangarajan et al., 2013). Organic inputs to agricultural lands

can increase soil organic matter content and boost soil fertility by improving aggregate stability and soil structure as well as by increasing microbial biomass and activity (Annabi et al., 2011; Y. Li et al., 2021; X. Zhang et al., 2022). There is a rising interest in the utilization of organic inputs in agriculture due to environmental issues and the economic aspects related to the high cost of mineral fertilizers (Park et al., 2011).

Both, the application of mineral fertilizers and of organic amendments can lead to increased GHG emissions (Holka et al., 2024; IPCC, 2007; Lussich et al., 2024; Zhou et al., 2017). The three main GHGs, CO₂, CH₄, and N₂O are produced during different biogeochemical processes, namely aerobic and anaerobic respiration as well as nitrification and denitrification. Microbial breakdown of the organic matter in the amendments leads to GHG emissions by affecting the soil carbon and nitrogen cycles and creating more favorable conditions for GHG production and emissions (Holka et al., 2022; Lussich et al., 2024). Oxygen consumption, due to increased microbial growth and activity following the addition of organic amendments, can lead to the creation of temporarily oxygen-depleted zones within the soil and increased N₂O production during denitrification (Seshan

et al., 2024). Organic amendments applications affect drivers of GHG emissions such as temperature, water-filled pore space (WFPS), O₂ concentration, pH, mineral nitrogen content (NO₃⁻, NH₄⁺), and available soil organic carbon content (Lee et al., 2009; Owusu et al., 2024).

Addition of organic substances can change the microbial community dynamics, which can accelerate the decomposition of organic residues and increase the CO₂ fluxes (Lussich et al., 2024; Perelo & Munch, 2005). Appropriate management of organic inputs in farmlands is crucial for improving soil quality and farm profitability while avoiding unwanted environmental impacts like emissions of GHGs. Previous research mainly focused on the effects of either crop residues (X. Zhang et al., 2022) or animal manure (Adelekun et al., 2021; X. Zhang et al., 2022) addition on GHG emissions under single cropping systems. Although the individual application of crop residues and animal manure is common, their combined application, which could balance nutrient supply and optimize carbon-to-nitrogen ratios, has received less attention in the context of GHG emissions. Recent research has found no significant differences in GHG intensity between sole and combined application of straw, manure, and green manure in a wheat–maize–sunflower cropping system (Zhao et al., 2024). However, another study found that co-incorporation of hairy vetch and wheat straw significantly reduced cumulative N₂O emissions compared to their individual incorporation (Liu et al., 2024). Reduced N₂O emission was mainly attributed to the regulated nitrifier and denitrifier communities. Organic materials with lower C/N ratios typically provide more readily decomposable substrates, potentially enhancing short-term GHG emissions, whereas materials with higher C/N ratios might promote more gradual decomposition and carbon sequestration. It is therefore essential to investigate how these dynamics differ between cereal and leguminous crops, which interact uniquely with soil microbial communities (Abalos et al., 2022).

In previous studies, organic inputs with relatively low C:N ratios resulted in increased emissions of CO₂ and N₂O, while organic fertilizers with higher C:N ratios resulted in an increased amount of stabilized soil organic carbon (Deru et al., 2023; Rummel et al., 2021). Not enough data are available in literature to assess how this association is modulated by different crops. Therefore, it is imperative to assess the impact of organic amendments on GHG emissions across such contrasting crop types as cereal and legume cropping systems, particularly given their fundamentally different interactions with soil microbes, including legumes' unique impact on the nitrogen cycle through symbiotic nitrogen fixation, to characterize the sustainability of different agricultural practices. By optimizing organic input strategies to minimize GHG emissions while enhancing soil fertility, this study con-

tributes to sustainable development goal n. 13: climate action, supporting sustainable agricultural practices that mitigate climate change in vulnerable semiarid regions (Nsabiyeze et al., 2024).

In semiarid regions such as western Iran, croplands face several challenges including soil degradation, atmospheric water supply limitations, and declining environmental sustainability. These challenges are expected to escalate with climate change, necessitating adaptive agricultural management practices. One option to implement climate-smart agriculture in this region is the use of postharvest crop residue and animal manure as organic fertilizers. However, to the authors' best knowledge no information is available on the dynamics of GHG emissions from agricultural soils where organic residues were applied under diverse cropping systems typical for semiarid cropland like the ones in western Iran. Barley residues (BR) and sheep manure (SM) were selected for this study due to their high availability and traditional use in western Iran, where barley production generates substantial crop residues and SM is abundant from local livestock systems (Mirzaei, Holl, et al., 2025; Mirzaei, Saunders, et al., 2025). Based on the abovementioned considerations, the objectives of this research were to (1) quantify the CO₂ and N₂O emissions under maize and mungbean cropping systems amended with different organic inputs (postharvest BR, SM, and their mixed application) and (2) to understand the key drivers leading to soil GHG fluxes from the abovementioned systems.

2 | MATERIALS AND METHODS

2.1 | Study site and soil characteristics

The study was carried out in the 2020 growing season in two adjacent fields at agricultural farmlands of the Shabab region, Chardavol county located in Ilam province, western Iran (33°44'29.8" N 46°38'27.6" E 982 m a.s.l.). The climate of the area is semiarid, with annual long-term (30 years period) average precipitation of 422 mm and average annual temperature of 11.8°C. Soil samples ($n = 5$) (0–20 cm) were taken to determine the basic soil chemical and physical analyses before starting the trials (in July 2020) for both fields. The soil particle size distribution included 25% clay, 21% sand, and 54% silt (Bouyoucos hydrometer; Gee & Bauder, 1986). Soil pH (H₂O) was 7.21 (± 1.65) (saturated paste extract pH meter; Rhoades, 1982), and the total organic C was on average 0.45% (± 2.21) (wet oxidation method; Walkley & Black, 1934). Total N content was 0.04% (± 1.23) (Kjeldahl method; Bremner, 1996). Barley (*Hordeum vulgare* L.) was grown in both experimental fields in the year prior to the experimentation.

2.2 | Experimental setup

In each experimental field (maize and mungbean cropping systems), three treatments with different organic amendment addition types were set up as follows: (i) BR, (ii) SM, and (iii) mixture of BR and SM (BR+SM). In each field, experimental treatments were arranged in a randomized block design with three replicates for a total of nine plots of 50 m² size (5 m × 10 m) with 2 m distance between the plots. The treatments were applied manually after the harvesting the previous barley crop in July 2020. For this purpose, 6 t ha⁻¹ of BR, and 6 t ha⁻¹ of SM were added to BR and SM plots, respectively. Also, for the BR+SM plots, 3 t ha⁻¹ of BR, and 3 t ha⁻¹ of SM were added. Then all plots were conventionally ploughed up to a depth of 30 cm. Maize and mungbean were seeded at a rate of 30 kg ha⁻¹ per field using manual broadcasting sowing on July 15, 2020. The plots were fertilized with 30 kg N ha⁻¹ from urea source applied following common practices adopted in the region, including soil turning with a plow, mixing with a disk harrow, and levelling with a land leveler. Irrigation was carried out approximately every 8–10 days, depending on environmental conditions, as there was no rainfall during the experiment.

2.3 | GHG measurement and analysis

Gas flux measurements were performed using the closed static chamber technique (De Klein & Harvey, 2015). The 18 polyvinyl chloride opaque chambers (15 cm diameter, 12.5 cm height) consisted of a chamber base and a lid with ports for gas sampling. Since the chambers were opaque and no plants were included, we specifically measured soil respiration rather than net ecosystem exchange of CO₂. The chamber collars were inserted into the ground to a depth of 5 cm 1 week prior to commencing the experiment and remained in the field for the duration of the experiment. The chamber bases were only removed for farming operations and were returned immediately to the same position afterward. No fan was included in the chambers, as natural diffusion ensures adequate gas mixing during the short 40-min closure period in small-volume static chambers, minimizing biases (Pihlatie et al., 2013; Rochette, 2011).

Gas sampling was conducted from 10:00 a.m. to 12:00 p.m. to approximate daily mean fluxes, as soil temperature (ST) variability was minimal in the semiarid conditions during measurement periods. Flux calculations used linear regression recommended for short-duration chamber measurements with three sampling points (Venterea et al., 2020).

Gas samples were collected at 0 (immediately after closure), 20, and 40 min. Fluxes were calculated via linear regression of the three points, with data excluded if $R^2 < 0.7$ to account for nonlinearity or measurement errors (Venterea et al., 2020).

Measurements were conducted on six sampling campaigns separated by 7–10 days throughout the maize and mungbean growing seasons between July and October 2020. Gas samples were injected into 12 mL pre-evacuated glass vials (Labco) and were analyzed for CO₂ and N₂O concentrations using gas chromatography equipped with electron capture detector for N₂O and thermal conductivity detector for CO₂ (Bruker 430-GC). Gas concentration was converted from volumetric to mass using the ideal gas law. The fluxes of each gas were calculated using linear change in gaseous concentration inside the chamber over time and from the ratio between chamber volume and soil surface area (De Klein & Harvey, 2015). The linearity of CO₂ and N₂O accumulation in the chamber headspace was evaluated using the coefficient of determination (R^2). Flux measurements with an R^2 value below 0.7 were excluded from the dataset. Cumulative soil CO₂ and N₂O fluxes for the BR, SM, and BR+SM treatments in the maize and mungbean cropping systems were estimated by linearly interpolating between sampling dates. The process involved multiplying the average daily flux between two successive measurements by the time interval between them and then adding this amount to the previous cumulative total (Guardia et al., 2016). Measurements were carried out during six sampling campaigns, each spaced 7–10 days apart, spanning the main growing seasons of maize and mungbean from late July to early October 2020. In total, 108 individual chamber measurements were obtained (6 campaigns × 3 treatments × 3 replicates × 2 crops). Mungbean was harvested in late September and maize in early October, with measurements completed before harvest to prevent disturbance.

2.4 | Soil and organic residue sampling

In parallel to GHG measurements, soil samples were collected in the center of each plot. Three soil cores from the 0- to 10-cm depth were mixed, homogenized to one composite sample. Each soil sample was split in subsamples. One subsample was used to determine volumetric water content. The soil sample was oven-dried at 105°C for 24 h, and the dried soil weight was then multiplied by the soil bulk density to calculate the volumetric water content.

Soil bulk density was measured in the field using the core-ring method (Klute, 1986). The top 5 cm of soil was carefully removed, and stainless-steel rings (5 cm height, 5 cm inner diameter, 100 cm³) were inserted using a hammering ring holder. The rings were then dislodged and trimmed with a putty knife to achieve the correct volume. Each sample was oven-dried at 105°C for 48 h and weighed before and after drying. Another fresh soil subsample was used to measure soil microbial biomass carbon (MBC) using chloroform fumigation extraction method (Jenkinson et al., 2004). WFPS (dimensionless) was calculated using volumetric water content and soil porosity using the equation describe

by Farquharson and Baldock (2007).

$$\text{WFPS} = \frac{\theta_v}{\emptyset} = \frac{\theta_m \times \rho_d}{1 - \left(\frac{\rho_d}{\rho_s}\right)} \quad (1)$$

where θ_v is the volumetric water content (cm^3 water cm^{-3} total soil volume), \emptyset is the total soil porosity (cm^3 pores cm^{-3} total soil), θ_m is the gravimetric water content (g water g^{-1} total soil), ρ_d is the bulk density (g soil particles cm^{-3} total soil volume), and ρ_s is the particle density (2.65 g cm^{-3} soil particles).

ST was measured with a thermometer at a depth of 0–10 cm at each gas sampling in all plots. Furthermore, carbon and nitrogen contents of BR and SM were analyzed using the method described by Walkley and Black (1934) and Kjeldahl (Jones, 2001), respectively. The carbon content of BR and SM was found to be 62% (± 2) and 35% (± 2), respectively. The nitrogen content of BR and SM was determined to be 0.8% (± 1.1) and 1.7% (± 2.3), respectively.

2.5 | Statistical analyses

We performed the statistical analysis in the open-source software R, version 3.5.3 (R Development Core Team, 2017). We utilized linear mixed models in the lme4 package (Bates et al., 2014), with “CO₂ fluxes” (soil respiration) and “N₂O fluxes” as response variables, “Crop,” “Treatment,” “ST,” “WFPS,” and “MBC” as explanatory variables and “day [of the experiment]” and “replicate” as random effects. The statistical significance of each explanatory variable was determined by likelihood ratio tests performed with the Anova function between the full model and the model without the fixed factor. We tested for multicollinearity between the explanatory variables by checking the variance inflation factor (VIF) of the full model. The VIF for any variable was not higher than 2.9 and the diagnostic plots showed that the models were appropriate. In cases when the factors of “Crop” or “Treatment” were statistically significant, we applied the Tukey contrast multiple comparisons of means in the multcomp package (Hothorn et al., 2019) to test for significant differences in emissions of CO₂ or N₂O between the two crops and the three treatments. The total cumulative CO₂ and N₂O fluxes for the duration of the experiment (50 days) were calculated by interpolating the N₂O and CO₂ emissions between each sampling day.

3 | RESULTS

The daily CO₂ fluxes were significantly different between the two cropping systems (Table 1), being on average 35% higher from mungbean than from maize. However, the crop type had no effect on the daily N₂O fluxes. The treatment type had a

TABLE 1 Analysis of the effects of microbial biomass carbon (MBC), soil temperature (ST), water-filled pore space (WFPS), Crop, and Treatment on the daily CO₂ and N₂O fluxes.

	Effect	df	χ^2	p-value
CO ₂	MBC	1	4.180	0.041
	ST	1	56.301	<0.001
	WFPS	1	0.032	0.859
	Crop	1	14.972	<0.001
	Treatment	2	3.035	0.219
	MBC*Treatment	2	1.611	0.447
	MBC*Crop	1	4.163	0.041
	ST*Treatment	2	1.813	0.404
	ST*Crop	1	0.376	0.540
	WFPS*Crop	1	2.032	0.154
	WFPS*Treatment	2	0.537	0.765
	Crop*Treatment	2	0.636	0.728
N ₂ O	MBC	1	0.273	0.601
	ST	1	12.805	<0.001
	WFPS	1	84.72	<0.001
	Crop	2	0.6522	0.722
	Treatment	3	8.112	0.044
	MBC*Treatment	2	7.840	0.020
	MBC*Crop	1	0.211	0.646
	ST*Treatment	2	26.202	<0.001
	ST*Crop	1	0.152	0.696
	WFPS*Crop	1	9.883	0.002
	WFPS*Treatment	2	2.211	0.331
	Crop*Treatment	2	4.814	0.09

Note: * represents interaction term and χ^2 is the chi-squared test statistic from likelihood ratio tests. Significant values ($p < 0.05$) are highlighted in bold. Abbreviation: df, degrees of freedom.

significant effect only on the daily N₂O fluxes, with the difference being only between the SM and the BR+SM (Tables 1 and 2). The daily N₂O fluxes from SM were higher by 83% than from BR+SM.

The WFPS did not significantly influence the daily CO₂ flux; however, the daily N₂O fluxes were significantly higher with the higher WFPS values (Table 1). The MBC had a significant positive effect on the CO₂ flux, but not on N₂O fluxes. The ST had a significant positive effect on the daily fluxes of CO₂ and N₂O (Table 1). There were no interactions between ST, WFPS, MBC, and either Crop or Treatment in daily CO₂ fluxes; however, the statistically significant interaction between MBC and Crop (Table 1) indicated a possibly steeper increase of the CO₂ fluxes with rising MBC in mungbean than in maize. The only significant interactions in the N₂O flux models were between Treatment and MBC, between Treatment and ST, and between Crop and WFPS,

TABLE 2 Multiple comparisons of means: Tukey contrasts. The comparison of daily CO₂ fluxes between two crops (maize and mungbean) and of N₂O fluxes between three treatments (barley residue [BR], sheep manure [SM], and BR+SM).

CO ₂	Comparison	Standard error	z-value	p-value
	Mungbean–maize	3.873	4.426	<0.001
N ₂ O				
	BR+SM–BR	4.779	1.466	0.302
	SM–BR	4.217	−0.936	0.613
	SM–BR+SM	3.451	−3.175	0.004

Note: Significant contrasts ($p < 0.05$) are highlighted in bold.

indicating that not all treatments and crops were responding to changes in MBC, ST, and WFPS in the same way. The BR treatment was less responsive to ST increases than the other two treatments while mungbean was more sensitive to rising WFPS than maize (Table 1).

3.1 | Seasonal course of selected soil properties

The MBC, ST, and WFPS time series during the experimental period are shown in Figure 1. Averaged across measurements dates, ST shows a similar declining development over the observation period for both crop types. However, while ST stayed at a comparably stable level after Day 43 after sowing on the mungbean field, ST dropped further until the end of the observation period on the maize field (Figure 1A). ST ranged from $23 \pm 0.44^\circ\text{C}$ to $17 \pm 0.27^\circ\text{C}$ for maize, while from $25 \pm 0.21^\circ\text{C}$ to $19 \pm 0.41^\circ\text{C}$ for mungbean.

The WFPS during maize and mungbean growing season showed different trends under different organic treatments (Figure 1B). Although the WFPS showed a similar trend for both crops, the WFPS was larger on average and more variable for maize compared to mungbean. Under the maize cropping system, a reduction in WFPS after repeated application of the BR+SM treatment 26, 46, 76 days after sowing was observed, in comparison with other treatments. However, WFPS was lower on average for BR compared to other treatments under mungbean cropping system.

MBC during maize and mungbean growing season showed different trends under different treatments (Figure 1C). Applying SM alone or mixed with BR (BR+SM) increased MBC in comparison to sole BR application. However, MBC was higher on average in case of BR+SM application, in comparison with SM for both cropping systems. Similarly, MBC was lower for BR in comparison with other treatments under the mungbean cropping system.

3.2 | Soil CO₂ and N₂O fluxes during crop growing seasons

Soil CO₂ (A) and N₂O (B) flux time series for all treatments under the maize and mungbean cropping system are shown in Figures 2 and 3. The results show a similar course of CO₂ fluxes for all treatments under the maize cropping system (Figure 2). However, CO₂ fluxes were slightly higher for BR+SM treatment. Under the mungbean cropping system, SM alone or BR+SM resulted in higher soil CO₂ fluxes, compared with BR application. Under maize cultivation, soil N₂O fluxes generally decreased from crop sowing until harvesting (Figure 3). Similarly, under the mungbean cropping system, soil N₂O fluxes generally declined over the observation period; however, they were higher for BR+SM than SM or BR treatments. The soil N₂O fluxes were similar for both SM and BR under mungbean cropping system.

3.3 | Relationships between soil CO₂ and N₂O fluxes with soil properties

To characterize the variability of the observed gas fluxes in relation to the variability of potential flux drivers, correlation analysis between gas fluxes and ST, WFPS, and MBC were carried out for both crops. For both crops, the CO₂ fluxes significantly correlated with ST, and MBC (Figures 4 and 5). The strongest relationship under the maize cropping system ($R^2 = 0.65$, $p < 0.001$) was detected between CO₂ fluxes and ST, while under mungbean cropping system, the strongest relationship ($R^2 = 0.59$, $p < 0.001$) was detected between CO₂ fluxes rate and MBC.

For both crops, the results showed that the N₂O emission rate was significantly correlated with WFPS and ST (Figures 6 and 7). The strongest relationship was found between N₂O emission rate and WFPS under both maize cropping system ($R^2 = 0.60$, $p < 0.001$) and under mungbean cropping system ($R^2 = 0.56$, $p < 0.001$).

3.4 | Cumulative CO₂ and N₂O fluxes

The cumulative fluxes of CO₂ and N₂O for all treatments under the maize and the mungbean cropping system, respectively, are shown in Table 3. The BR treatment resulted in the lowest emissions of both GHGs, both under the maize and mungbean cropping system. SM application alone also resulted in a similar amount of cumulated GHG fluxes. However, combining BR with SM (BR+SM) resulted in significantly higher cumulative CO₂ fluxes under maize ($5.79 \text{ Mg ha}^{-1} \text{ year}^{-1}$), and mungbean ($8.11 \text{ Mg ha}^{-1} \text{ year}^{-1}$) cropping system compared to their individual applications. Cumulative CO₂ fluxes were 21.5% and 16.5% lower in BR

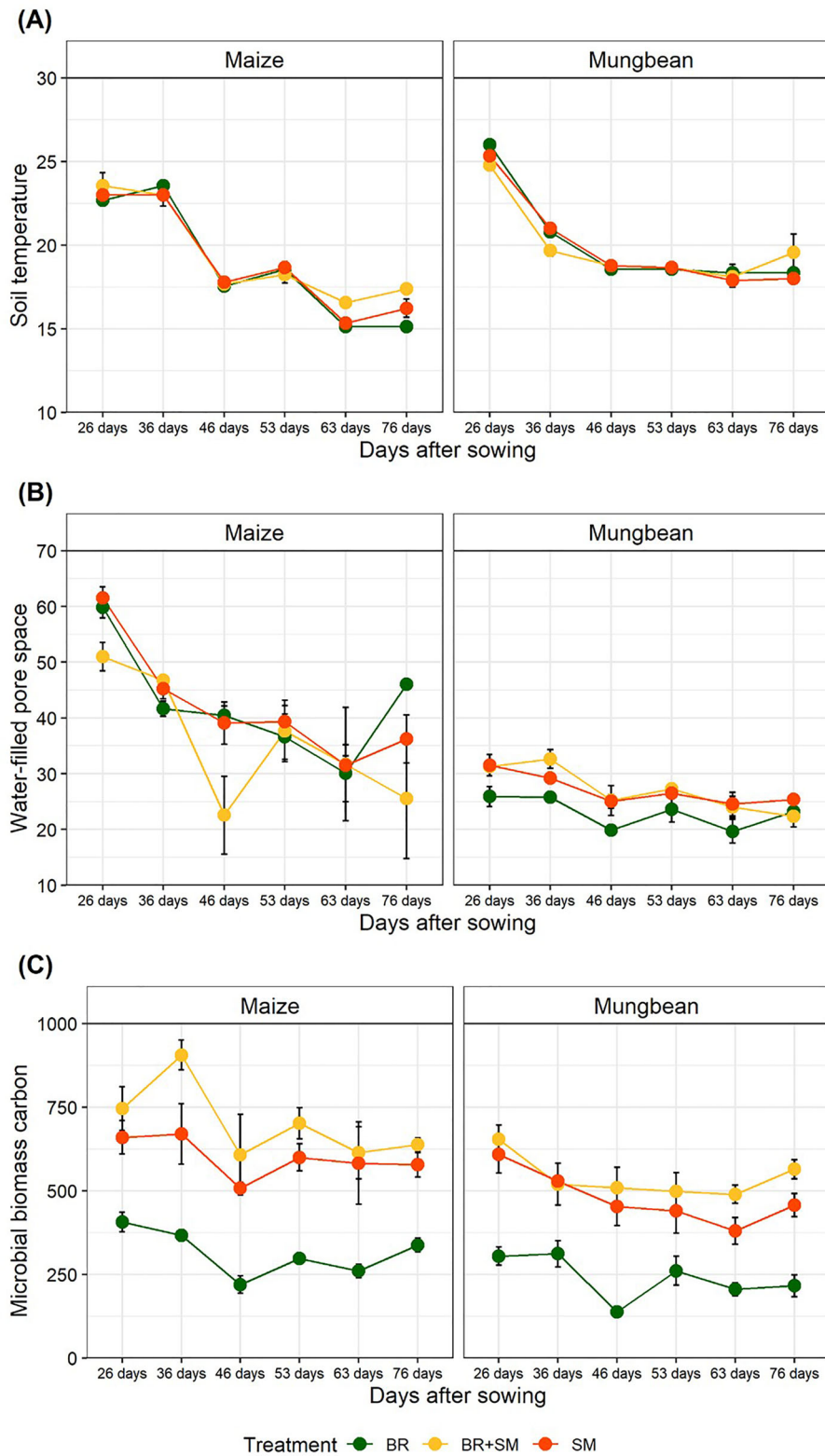


FIGURE 1 Soil temperature (ST), water-filled pore space (WFPS), and microbial biomass carbon (MBC), during the experimental period for the treatments of barley residues (BR), sheep manure (SM), and mixture of BR and SM (BR+SM) under maize and mungbean cropping systems.

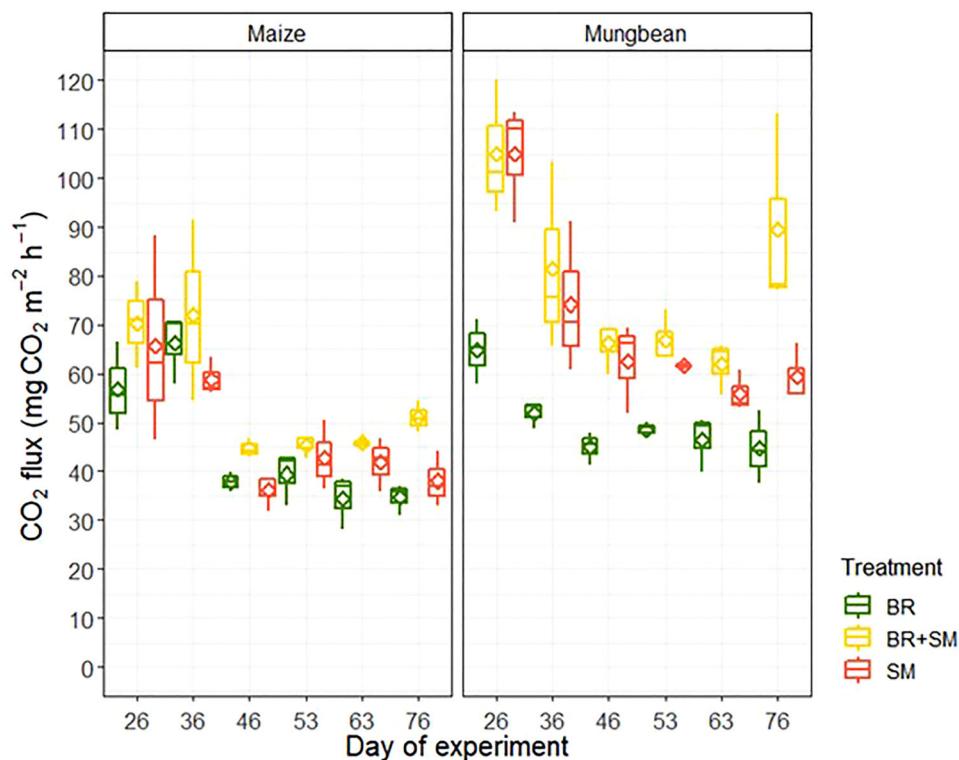


FIGURE 2 The CO₂ flux dynamics during the experimental period for the treatments barley residues (BR), sheep manure (SM), and mixture of BR and SM (BR+SM) under maize and mungbean cropping systems. Broad lines are medians, black dots are means, boxes show the interquartile range and whiskers extend to the last data point within 1.5 times the interquartile range.

TABLE 3 Cumulative soil CO₂ and N₂O fluxes for barley residue (BR), returning sheep manure (SM), and returning mixture of BR and SM (BR+SM) treatments under maize and mungbean cropping systems.

GHG	Crop	Treatment	Cumulative fluxes (CO ₂ : Mg
			ha ⁻¹ year ⁻¹ , N ₂ O: kg
			ha ⁻¹ year ⁻¹)
CO ₂	Maize	BR	4.77b
		BR+SM	5.79a
		SM	4.97b
	Mungbean	BR	5.29c
		BR+SM	8.11a
		SM	7.19b
N ₂ O	Maize	BR	4.73a
		BR+SM	5.09a
		SM	4.81a
	Mungbean	BR	3.00b
		BR+SM	4.44a
		SM	3.16b

Note: Values belonging to the same characteristic for each experimental factor without common letters in columns are statistically different according to LSD ($p \leq 0.05$).

Abbreviation: GHG, greenhouse gas.

and SM compared to BR+SM, respectively, under maize cropping system. Similarly, in the mungbean cropping system, cumulative CO₂ fluxes were about 54% and 13% lower in the BR and SM treatments, respectively, compared to BR+SM treatment. The highest N₂O cumulative fluxes (4.44 kg ha⁻¹ year⁻¹) were estimated with under the mixed application of organic residues (BR+SM) under mungbean cropping systems, showing a 48% and 1% increase in fluxes compared to individual BR and SM treatments, respectively. However, no significant differences in N₂O fluxes were observed among the treatments under the maize cropping system.

4 | DISCUSSION

Historically, agricultural practices have relied heavily on plant residues and animal manures since the origins of farming (Willoughby et al., 2023). Addition of organic amendments is a common practice in agriculture, with several recent studies reporting benefits in semiarid regions, such as improved soil structure and reduced GHG emissions (Goldan et al., 2023; Marín-Martínez et al., 2021; Mukhtiar et al., 2024; Xuan et al., 2023). Several studies demonstrated that organic amendments affect biogeochemical processes governing GHG emissions in water-limited agroecosystems and their management can

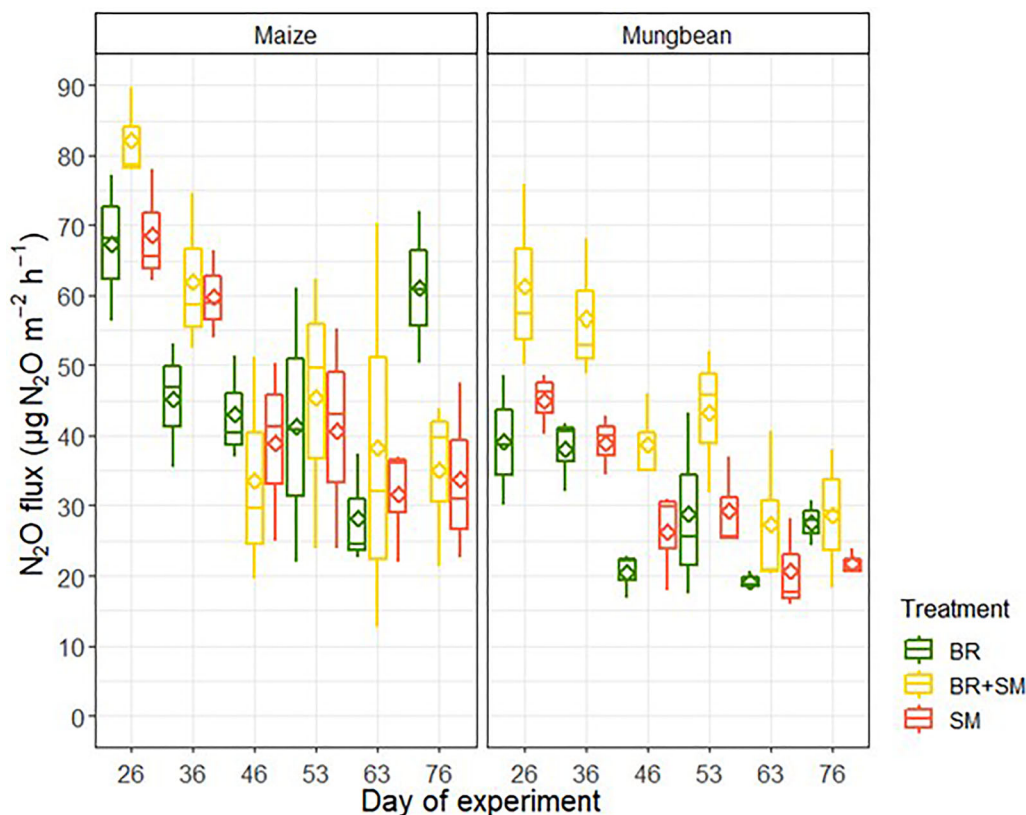


FIGURE 3 The N_2O fluxes dynamic during the experimental period for the treatments barley residues (BR), sheep manure (SM), and mixture of BR and SM (BR+SM) under maize and mungbean cropping systems. Broad lines are medians, black dots are means, boxes show the interquartile range and whiskers extend to the last data point within 1.5 times the interquartile range.

significantly improve agricultural sustainability while contributing to climate change mitigation efforts (Brenzinger et al., 2018; Marín-Martínez et al., 2021; X. Zhang et al., 2022).

In this study, organic amendments based on residues of barley cultivation and SM were applied to agricultural soil before the cultivation of maize and mungbean crops, either individually or in mixtures. CO_2 and N_2O emissions showed large variability and differences between the experimental treatments during the cultivation period of both crops. The daily CO_2 fluxes indicate distinct patterns depending on crop type and type of added organic amendments. Under maize cultivation, soil subjected to all three organic amendments exhibited similar trends in CO_2 emissions. Although not statistically significant, a slight elevation in CO_2 emissions observed in the BR+SM treatment, indicating a potential effect of combining BR and SM on microbial activity and carbon mineralization (Truong & Marschner, 2018). Under mungbean cultivation, higher CO_2 emissions were observed for SM applied alone or in combination with BR (BR+SM) compared to BR applied alone.

The observed differences in daily soil CO_2 fluxes between mungbean and maize crops, with mungbean exhibiting significantly higher fluxes compared to maize, highlight the

influence of crop type on soil carbon dynamics in agricultural ecosystems. Different crop species can have distinct impacts on soil carbon cycling due to variations in root exudates, residue quality, and microbial species associated with each crop (Huang et al., 2018; Shakoor et al., 2021). Understanding the factors driving these differences in soil CO_2 flux between crops in rotation is essential for optimizing carbon sequestration and mitigating GHG emissions in agricultural systems.

The data suggest an association between elevated soil water content in SM and BR+SM treatments and increased CO_2 emissions. This association may be attributed to the water-holding capacity of organic matter in manure, which could create more favorable moisture conditions for microbial activity in these water-limited soils. However, further research is needed to establish direct causal relationships between these variables. This observation aligns with previous studies indicating that increased soil water content can affect soil CO_2 fluxes directly by affecting plant root growth, the activity of soil microorganisms, and gas diffusion through the soil pores and indirectly by affecting soil nutrient availability and plant growth (Blazewicz et al., 2014; Curiel Yuste et al., 2007; Du et al., 2021; Göransson et al., 2013). However, Moyano et al. (2013) observed that excessive soil moisture can reduce

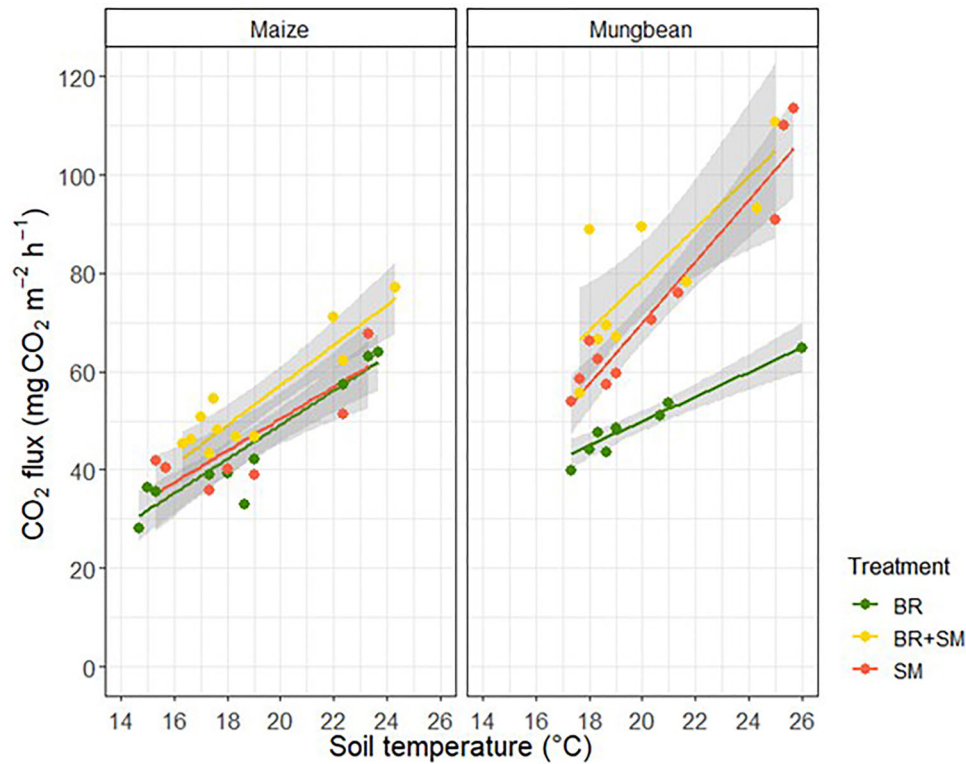


FIGURE 4 Results of linear regression between soil CO₂ fluxes and soil temperature for maize and mungbean cropping systems across treatments barley residues (BR), sheep manure (SM), and mixture of BR and SM (BR+SM) during the experimental period. Shaded areas represent the 95% confidence interval of the linear regression result.

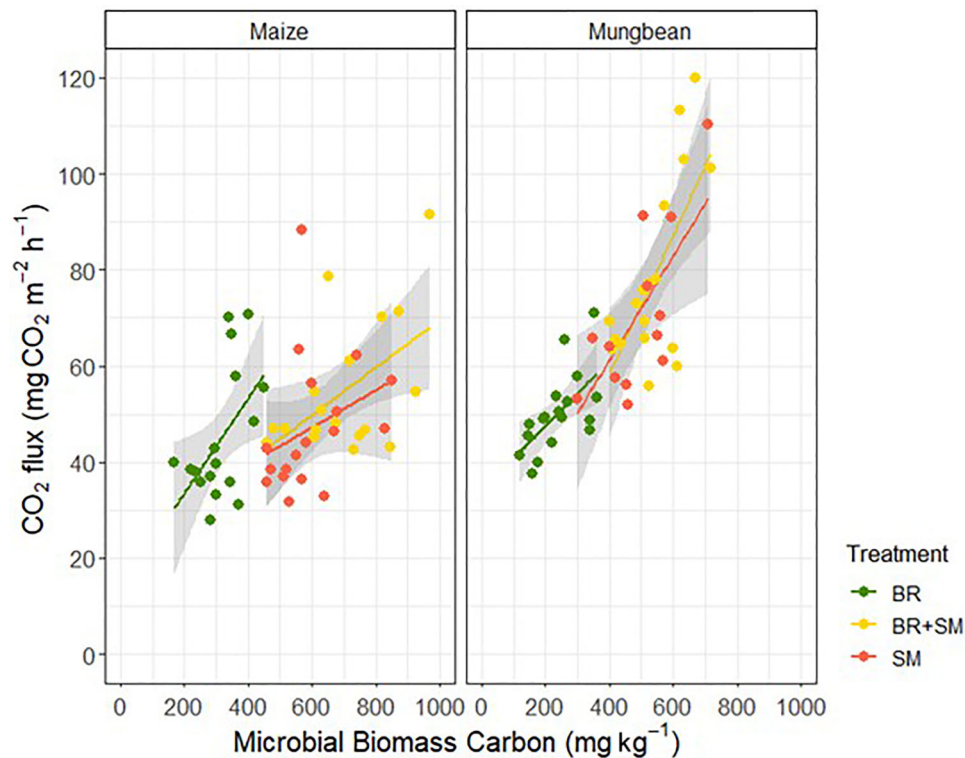


FIGURE 5 The relationships between soil CO₂ flux and soil microbial biomass carbon for maize and mungbean cropping systems across treatments barley residues (BR), sheep manure (SM), and mixture of BR and SM (BR+SM) during the experimental period.

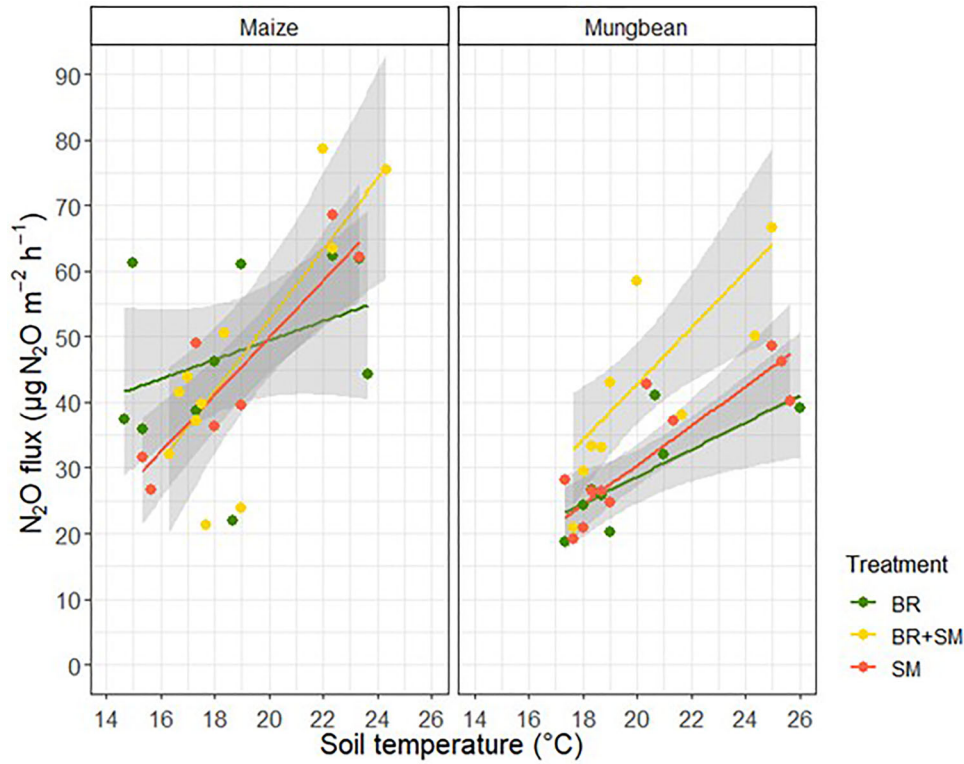


FIGURE 6 The relationships between soil N_2O emissions and soil temperature for maize and mungbean cropping system across treatments barley residues (BR), sheep manure (SM), and mixture of BR and SM (BR+SM) during the experimental period.

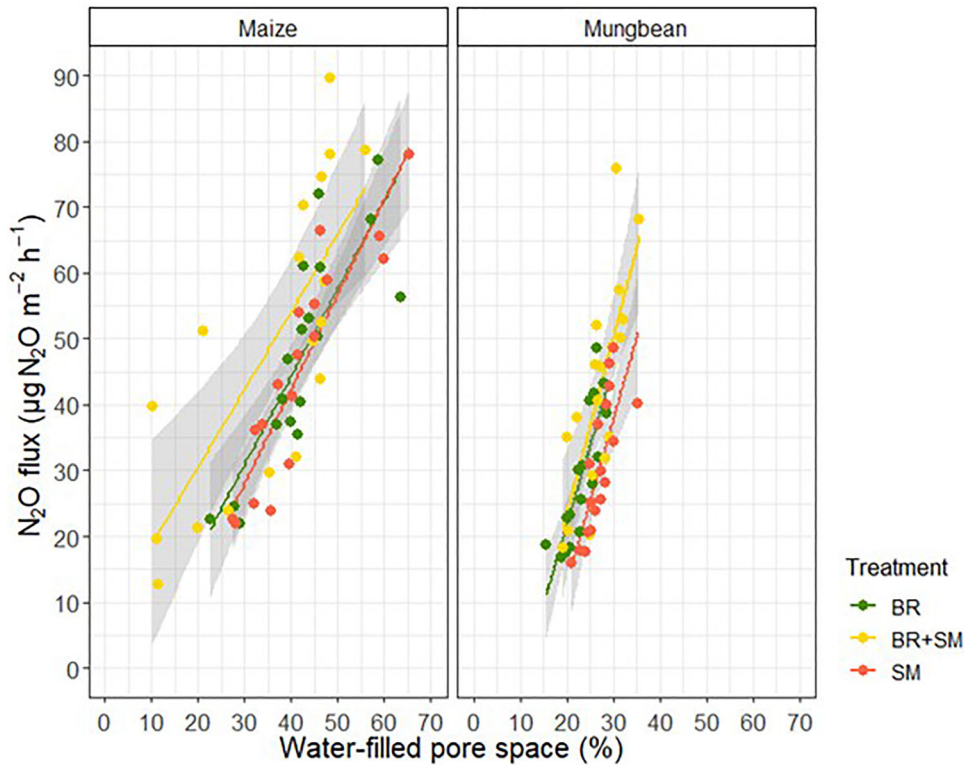


FIGURE 7 The relationships between soil N_2O emissions and water-filled pore space for maize and mungbean cropping system across treatments barley residues (BR), sheep manure (SM), and mixture of BR and SM (BR+SM) during the experimental period.

CO₂ fluxes by reducing oxygen diffusion as it is much slower in water compared to air. Consequently, high water contents can reduce the oxygen availability for respiration activities of soil microorganisms (Sierra et al., 2017; Skopp et al., 1990).

The linear regression analyses conducted for both crop species subjected to organic amendment treatments revealed significant correlations of soil CO₂ emission rates with soil physical and biological characteristics, such as temperature, and MBC. In both cropping systems, soil CO₂ emissions exhibited significant positive correlations with ST, indicating the strong influence of temperature on microbial activity for processing soil organic matter and carbon mineralization, which are in line with the study of La Scala et al. (2010). As STs rise, microbial metabolic rates increase, leading to enhanced decomposition of soil organic matter and subsequent CO₂ release into the atmosphere (Buchmann, 2000; Eliasson et al., 2005; Ray et al., 2020; L. Zhang et al., 2012). Significant interaction between MBC and crop species suggests differential responses of the microbial communities associated with mungbean and maize. The more pronounced increase in CO₂ flux with rising MBC under mungbean may be attributed to differences in rhizodeposition patterns and the presence of rhizobial associations supporting nitrogen fixation, which could foster distinct microbial community composition and activity between the two crops. Several factors such as crop species, soil properties, management practices, or environmental conditions, may play a more significant role in regulating N₂O emissions (Butterbach-Bahl et al., 2013; Chataut et al., 2023; Signor & Cerri, 2013). The significant effect of treatment type on N₂O flux highlights the importance of organic input management in modulating nitrogen dynamics and subsequent N₂O emissions.

In contrast to CO₂ fluxes, the trends in N₂O fluxes differed between the two cropping systems. In the maize cropping system, no discernible trend was observed among treatments, suggesting that organic inputs had minimal impact on N₂O emissions under maize cultivation. However, in the mungbean cropping system, higher N₂O fluxes were observed for the BR+SM treatment compared to SM or BR alone. This pattern may potentially be related to the nitrogen fixation capability of leguminous plants such as mungbean. The symbiotic relationship between legumes and rhizobia can lead to additional nitrogen inputs to the soil system, which could potentially contribute to substrate availability for nitrification and denitrification processes when combined with carbon sources from organic amendments (Rochette & Janzen, 2005). Additionally, mungbean crops tend to leave more residual nitrogen in the soil after uptake, unlike maize, which has higher nutrient uptake and leaves less residual nitrogen (Niranjan et al., 2023). This residual nitrogen further contributes to the elevated N₂O emissions observed in the mungbean system compared to the maize system.

The significant influence of WFPS on N₂O emissions suggests that while soil moisture content plays a crucial role in regulating N₂O production processes and subsequent N₂O emissions (Cardoso et al., 2017), higher WFPS values likely create anaerobic conditions favorable for denitrification, leading to increased N₂O emissions, whereas CO₂ flux may be less sensitive to changes in soil moisture (Franco-Luesma et al., 2022).

ST was found to positively correlate with N₂O fluxes, reflecting the temperature sensitivity of microbial activity and enzymatic processes involved in nitrogen transformations (Parton et al., 2001). Warmer temperatures can enhance microbial-mediated nitrification and denitrification processes, promoting N₂O production in the soil.

In both, maize and mungbean cropping systems, BR alone resulted in the lowest cumulative CO₂ and N₂O fluxes compared to other treatments. This could be attributed to the relatively lower nitrogen content (higher C/N ratio) of BR and lower microbial biomass in soils where BR was applied. Conversely, the mixed application of SM with BR resulted in significantly higher cumulative CO₂ and N₂O fluxes. This could be attributed to the relatively higher C/N ratio of BR (approximately 78:1) compared to SM (approximately 21:1) and the observed lower microbial biomass in soils where only BR was applied. Conversely, the mixed application of SM with BR created an intermediate C/N ratio with both readily available nitrogen from manure and carbon from residues, potentially providing optimal conditions for microbial activity. This balance appears to have stimulated decomposition processes and subsequently higher GHG emissions (Baggs et al., 2000, 2003; Lehtinen et al., 2014; Wang et al., 2011). The significant differences in N₂O fluxes between treatments under the mungbean cropping system underscore the importance of considering both the type and combination of organic inputs in mitigating N₂O emissions in agricultural systems. The absence of a no-amendment control limits interpretations to relative effects among treatments, potentially underestimating overall benefits such as net GHG reductions compared to bare soil. Future studies should incorporate controls to quantify absolute impacts. Measurements were carried out during six sampling campaigns, each spaced 7–10 days apart, spanning the main growing seasons of maize and mungbean from late July to early October 2020. In total, 108 individual chamber measurements were obtained (6 campaigns × 3 treatments × 3 replicates × 2 crops). Mungbean was harvested in late September and maize in early October, with measurements completed before harvest to prevent disturbance. This study was limited to a single growing season, which may not capture interannual variations in weather conditions, crop performance, and GHG fluxes. For instance, fluctuations in precipitation could influence soil WFPS and subsequent emissions. Although the measurements covered the main growing period, they do not represent full annual GHG dynamics

typical of semiarid climates. Therefore, multiyear studies are recommended to validate these findings and assess long-term trends.

5 | CONCLUSIONS

This study demonstrated that organic amendment composition significantly influences GHG emissions across contrasting cropping systems in semiarid agroecosystems. BR application consistently resulted in lower N₂O and CO₂ fluxes (21.5%–53.5% reduction in CO₂ and up to 48% reduction in N₂O compared to mixed applications), establishing crop residue management as a viable climate-smart agriculture strategy. The differential responses between leguminous and cereal crops, with mungbean showing greater sensitivity to amendment type than maize, highlights the necessity of crop-specific mitigation approaches. However, as this study was conducted over a 1-year period, further long-term research is needed to understand seasonal and interannual variability in emissions.

AUTHOR CONTRIBUTIONS

Morad Mirzaei: Conceptualization; data curation; formal analysis; investigation; methodology; validation; visualization; writing—original draft. **David Holl:** Data curation; formal analysis; investigation; methodology; validation; writing—original draft; writing—review and editing. **Magdalena Matysek:** Conceptualization; investigation; methodology; validation; writing—original draft. **Mary Harty:** Conceptualization; methodology; validation; writing—original draft. **Laura Cardenas:** Conceptualization; investigation; visualization; writing—original draft. **Yuan Li:** Data curation; formal analysis; methodology; writing—original draft. **Ján Horák:** Data curation; formal analysis; validation; writing—original draft. **Mohamed Allam:** Data curation; methodology; visualization; writing—review and editing. **Roberto Mancinelli:** Data curation; investigation; methodology; visualization; writing—original draft; writing—review and editing. **Emanuele Radicetti:** Conceptualization; data curation; investigation; supervision; validation; visualization; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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