Soil Use and Management

RESEARCH ARTICLE

Soil Health and Nitrogen Dynamics as Affected by Organic Amendments in Monocropping and Intercropping of Maize and Mung Bean Systems

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Received: 16 December 2024 | **Revised:** 28 July 2025 | **Accepted:** 4 August 2025

Keywords: agronomic management | crop yield | intercropping | organic farming | soil fertility | sustainable agriculture

ABSTRACT

This study, conducted over 2 years (2021 and 2022), evaluated the effects of returning sheep manure (RM) and wheat residues (RR) as organic amendments on nitrogen (N) dynamics and soil properties in maize and mung bean monocultures and their intercropping systems within a semi-arid environment. Significant variations in soil N levels were observed, with RM enhancing mineral N content and nitrate availability across all cropping systems, particularly benefiting mung bean monocultures and intercropped systems compared to RR treatments. The nitrate/ammonium ratio varied according to crop type and amendment type, influencing N availability. Nitrous oxide emissions were significantly higher in RM, peaking in monocultures of maize and mung bean. The highest grain and straw yields were observed in maize monocultures (6.22 and 8.18 t ha^{-1}, respectively). Mung bean monoculture exhibited the lowest C/N ratio in grain (15.8) and straw (21.2), which provided a better balance of grain yield and N content. Soil nutrient levels, including essential macronutrients (N, P and K) and micronutrients (Fe, Mn and Zn), were affected by the cropping system and type of organic amendment. Mung bean monoculture showed the highest soil N and P levels (0.062% and 21.5 mg kg^{-1} dry soil, respectively), while intercropping improved micronutrient availability and soil structure, enhancing water content and aggregate stability. These findings underscore the significance of selecting suitable organic amendments and cropping systems to manage N dynamics, crucial for maintaining soil health and boosting crop productivity in semi-arid regions. Moreover, the results are vital for agricultural decision-makers, advocating for sustainable practices that enhance soil fertility, mitigate greenhouse gas emissions and contribute to food security and environmental sustainability.

1 | Introduction

Nowadays, the continuous reliance on synthetic fertilisers applied in large quantities in agricultural lands supports high crop yield to supply human needs, even if it is mainly responsible for the detrimental effect on both soil health and crop productivity, threatening the sustainability of agroecosystems in the long-term period (Derdour et al. 2022; Noor et al. 2023). Among the synthetic fertilisers, mineral nitrogen (N) fertilisers are overused compared to the effective needs of the crops, reducing their agronomical use efficiency. In addition, the application of elevated rates of mineral N fertiliser is responsible for the abundant loss of N forms from agroecosystems, mainly via leaching as nitrate (NO_3^-) and denitrification as nitrous oxide (N_2O). Agricultural soil serves as a primary contributor to N_2O emissions, a greenhouse gas (GHG) with a global warming potential (GWP) 298 (on a 100-year time horizon) times greater than carbon dioxide (CO_2) (IPCC 2013), which significantly contributes to GWP and stratospheric ozone depletion. It has been estimated that global N_2O emissions ranged from 12.2 to 23.5 Tg of N per year (bottom-up estimate) and 15.9 to 17.7 Tg of N per year (top-down estimate) with human-induced emissions, primarily stemming from N additions to croplands, increasing by 30% over the past four decades (Tian et al. 2020). In addition, this trend is expected to persist in the coming decades due to escalating demand for food, feed, fibre and energy, coupled with increasing sources from waste generation and industrial processes (Reay et al. 2012). Converting agricultural production systems worldwide, by employing sustainable approaches able to mitigate GHG emissions and environmental risks while concurrently improving soil health and crop yields, is urgently needed. However, the efforts aimed at reducing N_2O emissions from agricultural soils not only contribute to environmental sustainability but also have implications for food security (Grados et al. 2022). Mineral fertiliser application should be reduced as it primarily leads to short-term high yields without promoting long-term soil health, which is essential for sustainable agriculture. The use of organic amendments presents an alternative; however, their effectiveness must also be evaluated in terms of GHG emissions. While organic amendment can enhance soil health, it may also contribute to significant N_2O emissions, which would undermine its sustainability. Therefore, it is crucial to quantify gaseous N_2O losses associated with the application of organic amendments under various treatments to ensure that these practices contribute positively to both soil restoration and GHG mitigation (Hénault et al. 2012). By assessing the balance between improved soil health and potential increases in N_2O emissions, we can better design agricultural systems that are both productive and environmentally sustainable. Among these alternative approaches, the application of organic amendment, as carbon-based compounds, based on the concept of circular economy with the valorisation of wastes of other human activities, has emerged as a promising, sustainable and economically viable strategy to enhance agricultural production systems (Dubey et al. 2020). The application of organic amendment as a substitute for synthetic fertilisers can serve as a strategy to enhance soil health and carbon (C) sequestration. Specifically, these organic materials contribute to the formation of soil organic matter (SOM), which is crucial for building soil structure and improving nutrient retention. By feeding soil microorganisms across all trophic levels, organic amendments help reduce nutrient loss from agroecosystems. This multifaceted approach not only mitigates on-field N_2O emissions but also enhances soil organic C sequestration and crop yields. Therefore, it is essential to assess the impact of organic amendment on N_2O emissions to ensure that its benefits in improving soil health do not come at the cost of increased GHG (Al-Shammary, Al-Shihmani, et al. 2023; Al-Shammary, Lahmod, et al. 2023). In addition, the replenishment of SOM through the application of exogenous organic amendments stands as an eco-friendly approach to bolster soil fertility and agricultural productivity (Esmaeilian et al. 2023; Boudjabi and Chenchouni 2023). Organic amendments, such as manure and crop residues, serve as vital sources of plant nutrients and organic matter, offering manifold benefits and ecosystem services (Greff et al. 2022).

Several studies observed how organic amendments, such as animal manure and crop residues, represent a promising avenue for augmenting soil fertility, increasing crop yields and mitigating GHG emissions (Waldrip et al. 2020). Crop residues serve as significant inputs of C and N to soils, directly influencing plant nutrient availability and GHG emissions, including N_2O and CO_2. Specifically, the decomposition of crop residues releases nutrients that enhance microbial activity, which in turn affects soil nutrient cycling processes. This microbial activity can lead to increased N mineralisation, making nutrients more accessible to plants while also contributing to GHG emissions through processes such as nitrification and denitrification. Therefore, understanding these processes is essential for evaluating the overall impact of crop residues on soil health and GHG emissions in agricultural systems (Olesen et al. 2023). Organic residues are well-established sources of SOM that contribute to improved soil health and biological activity (Brichi et al. 2023; Lozano-Parra et al. 2023). Their application enhances nutrient availability for plants and supports various soil processes, thereby playing a crucial role in sustainable agricultural practices. By increasing SOM content, organic residues not only improve soil structure and water retention but also foster beneficial microbial communities that enhance overall soil fertility. This established understanding highlights the importance of integrating organic residues into agricultural systems to promote long-term soil health and productivity. The application of organic amendment, such as sheep manure, has been shown to improve soil aggregation and enhance physicochemical properties in 2-year experiments involving maize cultivation under arid conditions (Al-Shammary, Al-Shihmani, et al. 2023; Al-Shammary, Lahmod, et al. 2023).

Furthermore, the application of crop residues in agricultural lands aligns with several of the United Nations' Sustainable Development Goals (SDGs), including food security, water resource preservation, climate change mitigation and biodiversity conservation (Brichi et al. 2023; Moussaoui et al. 2023; Smith et al. 2019). Despite their manifold benefits, organic amendments can also influence biogeochemical processes related to GHG emissions (Thangarajan et al. 2013). By providing C and N substrates and enhancing microbial growth and activities for soil nitrification and denitrification processes, organic amendments can significantly enhance N_2O emissions (Charles et al. 2017; Thangarajan et al. 2013). Due to several factors, including the lower pH and bulk density of organic residues compared to synthetic fertilisers, as well as their higher content of SOM, microbial biomass C and microbial biomass N, these organic inputs can significantly influence soil health and nutrient dynamics (Parlak et al. 2022; Zhang et al. 2022). Various factors, including the type of organic inputs and cropping systems, have led to differing results regarding the impact of organic amendments on N_2O emissions. For example, while straw incorporation in maize cropping systems has been associated with higher N_2O emissions, it has reduced emissions in wheat cropping systems (Liu et al. 2019). Similarly, the retention of crop residues has been reported to both increase and decrease N_2O emissions, depending on the specific circumstances (Congreves et al. 2017).

Zhang et al. (2022) attributed the greater crop yield in the organic amended plots to the enhanced SOM content. Pu et al. (2022) found that retaining crop residue in the wheat–maize cropping system led to increases in N_2O emissions by 28.1% during winter wheat and 26.7% during summer maize compared to when residues were removed. In contrast, lower N_2O emissions were observed in soils treated with liquid manure compared to those treated with urea in wheat and barley cropping systems (Adelekun et al. 2021). This highlights the complex interactions between organic amendment and N_2O emissions, indicating that different management practices can significantly influence GHG outputs. Recognising the significant role of organic amendment and intercropping systems in shaping soil properties, crop yield and GHG emissions, this study hypothesises that returning post-harvest wheat residues will enhance soil properties and reduce N_2O emissions compared to sheep manure in maize and mung bean intercropping systems. There is the need for a comprehensive understanding of how different organic amendments, specifically post-harvest wheat residues versus sheep manure, influence soil N dynamics and soil properties in maize and mung bean and their intercropping, given the conflicting findings on the impact of organic inputs on GHG emissions across various cropping systems.

The study aims to assess the effects of wheat residues and sheep manure, applied as organic amendment for sole cropping and intercropping of maize and mung bean, on soil N dynamics, soil properties and crop yield. The specific objectives are: (i) to evaluate the changes in N dynamics influenced by different organic amendments (sheep manure and wheat residues) under maize and mung bean monocropping and intercropping systems; and (ii) to assess the impact of these treatments on soil properties. It is important to note that baseline data for N dynamics will be established from pre-treatment soil assessments, ensuring a comprehensive evaluation of changes resulting from the organic amendment.

2 | Materials and Methods

2.1 | Site Description

Field experiments were carried out in the 2021 and 2022 growing seasons in the Shabab region, Chardavol county, Iran (33°44′36.5″ N 46°38′32.6″ E, 982 m a.s.l.). The experimental site is characterised by a semi-arid climatic condition with mean annual (2006–2022) temperature and rainfall of 11.8°C and 422 mm, respectively. The weather parameters (minimum and maximum air temperature and rainfall) during the experimental period have been collected by a meteorological station placed near the field trials and data are reported in Table 1. The experimental site is in a typical area managed under conventional practices for cultivation of different crops such as wheat, lentil, barley, rice, corn, sugar beet and okra. The soil is classified as Calcic Aridisol with the following characteristics: sand (180 $g\,kg^{-1}$ of dry soil), silt (600 $g\,kg^{-1}$ of dry soil), clay (220 $g\,kg^{-1}$ of dry soil) content, pH (7.2), total N content (0.48 $g\,kg^{-1}$ of dry soil, Kjeldahl method), organic C content (5.0 $g\,kg^{-1}$ of dry soil, Walkley and Black method), bulk density (1.46 $g\,cm^{-3}$), respectively. The study was conducted under irrigated conditions.

2.2 | Experimental Design and Treatments Application

The present study focuses on the growing seasons of maize and mung bean crops following the harvesting of previous winter wheat. The size of the experimental area was 4750 m^2 (50 × 95 m) allowing for all mechanised farming operations to be carried out during the experiment. In both experimental growing seasons, the following experimental treatments were applied: (i) three cropping systems (maize [Ma], mung bean [Mu] and intercropping of maize and mung bean [Ma + Mu]); and (ii) two organic amendments (returning of wheat residues in the soil [RR] and returning of sheep manure [RM]). The field trial was arranged in six distinct treatments replicated three times for a total of 18 main plots according to a randomised complete block design. The size of each experimental plot was 100 m^2 (10 × 10 m). In both growing seasons in all plots, at the end of June, wheat was harvested mechanically, and residues were carefully removed from the experimental plots. On July 5, 2021, 5 $t\,ha^{-1}$ of wheat residues (C/N ratio of 72.9) were

TABLE 1 | Weather data (monthly average of the daily minimum [Min, °C], maximum [Max, °C] and average [Mean, °C] temperatures) over the two cropping seasons (2021 and 2022) for the studied area.

	2021			2022		
Month	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**
July	23.01	41.10	33.26	23.96	41.28	33.42
August	22.92	40.18	32.45	24.80	42.07	34.25
September	17.92	36.77	28.54	19.69	37.98	29.33
October	12.78	30.10	22.55	15.40	32.86	25.34

added in the Ma_RR, Mu_RR and Ma + Mu_RR plots, while 5 t ha^{-1} of RM (C/N ratio of 15.0) were added in the Ma_RM, Mu_RM and Ma + Mu_RM plots, respectively. Subsequently, all plots were tilled to a depth of 25 cm using a mouldboard plough. Mung beans were seeded in Mu_RM and Mu_RR at a rate of 30 kg ha^{-1}, while maize was seeded in Ma_RM and Ma_RR plots at the same rate on July 8, 2021. For plots under Ma + Mu_RM and Ma + Mu_RR treatments, a combination of 15 kg ha^{-1} of mung bean and 15 kg ha^{-1} of maize was seeded using the broadcasting method. In addition to organic amendment, mineral fertilisation was performed to maize, mung bean and their intercropping according to the common practices adopted by the farmers of the area and to avoid interference of synthetic fertiliser with organic amendment tested in this experiment. The following application rates were used: 40 kg N ha^{-1}, 40 kg P_2O_5 ha^{-1} and 60 kg K_2O ha^{-1}, respectively. Furrow irrigation was administered every 10–12 days depending on the environmental conditions. The experiment was repeated for the second year following the same procedures and timings as the first year on the same plots.

2.3 | N_2O Flux Measurements

The N_2O flux was measured at six events at 15-day intervals throughout the entire growing season of tested crops in both experimental years, spanning from July 20 to October 3, 2021, and from July 22 to October 5, 2022, respectively. Totally six N_2O measurements were performed during the growing seasons of all crops indicated as follows: T1, T2, T3, T4, T5 and T6 as the measurements performed at 15, 30, 45, 60, 75 and 90 days after crops sowing. For the N_2O measurements, a static closed chamber technique was employed adopting the method suggested by Oertel et al. (2012). The sampling protocol of GRACEnet Chamber-based Trace Gas Flux Measurement (Parkin and Venterea 2010). At crop sowing, PVC collars were inserted to a depth of 5 cm in each plot, with a 7-day acclimation period prior to the first N_2O flux measurement. This period helped to reduce the impact of soil disturbance from collar installation on the initial N_2O flux readings. During sample collection, chambers were sealed for 40 min, with gas samples collected at 0, 20 and 40 min through a sampling port using a 20 mL HSW HENKE-JECT syringe (HENKE SASS WOLF, Tuttlingen, Germany) and needle. Flux measurements were conducted between 11 and 12 a.m. and collected gas samples were injected into 12 mL pre-evacuated screw-cap septum glass vials (Labco, High Wycombe, UK). The concentration of N_2O in gas samples inside the vials was determined with a gas chromatograph (Teif Gostar Faraz, TG 2552, Iran; Brucker, Germany) equipped with an electron capture detector (ECD) in the lab. Temperatures of the column, injector and detector were set at 65°C, 100°C and 280°C, respectively (de Klein et al. 2020). The concentrations of N_2O were converted from volumetric (μL) to mass-based (μmol) units using the ideal gas law (de Klein and Harvey 2015):

$$PV = nRT \quad (1)$$

where P = pressure (atmospheres), V = volume (μL), n = the number of moles of gas (μmoles), R = 0.082 the gas law constant (L atm mol^{-1} K^{-1}) and T = temperature (Kelvin). Air temperature and atmospheric pressure were obtained from the nearest meteorological station. Hourly fluxes of N_2O (mg m^{-2} h^{-1}) were calculated based on the slope of the linear regression between gas concentrations during the enclosure period, and the ratio between chamber volume and the ground area enclosed by the chamber, as described by de Klein et al. (2020).

2.4 | Crop Yield Measurement, C and N Content in Grain and Straw

In all plots, at crop physiological maturity, plant samplings were performed on October 8, 2021, and October 10, 2022, respectively. The aboveground biomass of maize, mung bean crops and their intercropping were collected using a sampling area of 1 m^2 (1 m × 1 m) placed in the centre of each plot. Crop samples were harvested by hand at the soil surface and processed in the laboratory. The crop samples were manually threshed to separate the straw and grain, and their respective yields were measured. Crop samples were carefully separated for seeds and straw and oven-dried at the temperature of 70°C until constant weight. The mean weight across all samples within each plot was calculated to determine the average biomass produced by each crop type. For each sample, dried grain and straw samples were finely ground and analysed to determine C (Walkley and Black method) and N content (Jones 2001), respectively. For each experimental treatment, the C/N ratio was calculated by dividing the concentration of C by that of N separately for grain and straw.

2.5 | Soil Sampling and Analyses

During each flux sampling event throughout the growing seasons, composite soil samples were collected from depths between 0.00 and 0.05 m using soil cores measuring 0.05 m × 0.05 m. Mineral N (NH_4^+ and NO_3^-) in the soil samples was determined using the KCl extraction method (Page 1982). Additionally, after the experiment on October 12, 2021, composite soil samples were obtained using an auger sampler from depths of 0–25 cm in each plot. Soil samples were collected from four locations within each plot and mixed uniformly to create one composite sample. The collected soil samples were air-dried and divided into two parts for subsequent analyses. One portion of the soil sample was utilised to determine P and K concentrations in samples using spectrophotometric and flame photometric methods, respectively (Jones 2001). In addition, atomic absorption spectrophotometry was used to determine Fe, Mn and Zn in soil samples (Jones 2001). One portion of the soil sample was utilised to measure soil available water (Aw) and water-stable aggregates (WSA), while the other part was used to determine SOM and nutrient contents. Aw was calculated from the difference in moisture content between field capacity and wilting point (Cassel and Nielsen 1986), with moisture contents being estimated using a pressure plate and pressure membrane apparatuses. The wet sieving method was employed to determine WSA. In this procedure, a 50-g air-dried (4 mm sieved) soil sample was placed on top of a 2-mm sieve and submerged in deionised water at room temperature for 3 min to facilitate slaking. Sieving was conducted by vertically moving the sieves up and down by 3 cm, 50 times in 2 min to separate aggregates. A series of five sieves (2, 1, 0.5, 0.25 and 0.125 mm) were utilised, with aggregates larger than 0.25 mm considered water-stable aggregates (WSA > 0.25 mm in %) (Elliott 1986; Kemper and Rosenau 1986).

2.6 | Statistical Analyses

All collected parameters were subjected to analysis of variance (ANOVA) using the JMP statistical software package version 4.0 (SAS 1996). Before conducting statistical analysis, the data were evaluated for equal variance to check if transformations were necessary. For percentage-based data, angular transformations were applied to ensure homogeneity of variance, as recommended by Gomez and Gomez (1984). For clarity in reporting, transformed data were back-transformed in tables. For each year, effects of applied treatments on variables such as soil NO_3^-, soil ammonium, soil total N, soil nutrient content and crop yield and yield characteristics were assessed with a randomised complete block mixed model analysis of variance with treatment as the fixed effect and blocks within year as random effects. Main treatment effects and their interactions were compared using Fisher's protected least significant difference (LSD) test at a significance level of 5% ($p < 0.05$). To further explore soil responses, we performed canonical discriminant analysis (CDA) on soil chemical and physical properties at crop harvest. CDA, a method for evaluating multivariate data by creating canonical plots, helps in visualising and interpreting group similarities and differences based on measured characteristics. Following the procedures outlined by Gomez and Gomez (1984), we used CDA to combine the canonical coefficients of soil characteristics from the functions for both cropping seasons. This procedure resulted in a single canonical plot illustrating soil properties across six experimental groups defined by cropping system and residue source. Here, soil properties were represented as vectors, with vector length indicating association strength with each group, and vector direction illustrating the ordination of characteristics in multivariate space. This analytical approach helped in assessing soil characteristic similarities among groups and provided insight into the effects of organic amendment on soil properties across two seasons.

3 | Results

3.1 | Soil N Dynamics

The interaction of crop type with organic amendment on total soil mineral N content ($NO_3^- + NH_4^+$) and the NO_3^-/NH_4^+ ratio is presented in Table 2. Significant differences in response to organic amendment for each crop type were observed, underscoring the complexity of these factors within maize and mung bean intercropping systems. In both 2021 and 2022 growing seasons, soil mineral content progressively declined from T1 (initial stage) to T6 (final stage). This decline was more pronounced in 2022, highlighting the impact of annual variation on soil nutrient dynamics. The 2021 season showed notably higher soil mineral N concentrations, with relative increases of +6.6%, +9.1% and +12.7% at T2, T3 and T5, respectively, compared to 2022. Over time, soil mineral N concentrations decreased from T1 to T6 by 53.9% in 2021 and 54.2% in 2022. Plots treated with RM displayed significantly higher soil mineral N content than those treated with RR in both years. Sheep manure had a more substantial positive effect on mineral N content, particularly in mung bean monoculture (Mu) and in maize-mung bean intercropping (Ma + Mu). RM-treated plots showed consistently higher mineral N content over the growing seasons in both 2021 and 2022. The reduction in soil mineral N concentration from T1 to T6 was greater with RM application than RR across cropping systems in both years. In 2022, the maize + mung bean intercropping system showed the largest reduction (55.5% for RR and 66.1% for RM), while in maize monoculture, soil mineral N decreased by −38.9% with RR and −55.9% with RM. Differences in soil mineral N concentrations were also significant between treatments, with RM-treated plots consistently showing higher values. Mung bean monoculture had notably higher mineral N levels than maize monoculture in the first four measurements (T1–T4) under RR, with an average increase of +26.1%, and consistently higher across all dates under RM, averaging +27.9%. Differences in soil mineral N content were noted between maize monoculture and maize + mung bean intercropping at T4 and T5 under RR and from T1 to T4 under RM in both years. The NO_3^-/NH_4^+ ratio, an indicator of N availability, also varied across years, remaining relatively stable in 2021 but showing a significant decrease in 2022. In maize monoculture (Ma), both organic amendments affected the ratio, with RM application resulting in a notable increase, suggesting higher NO_3^- availability, while RR created a more balanced N profile. In mung bean monoculture (Mu), RM significantly increased the NO_3^-/NH_4^+ ratio, whereas RR had a more limited effect. Similarly, in the intercropping system, RM induced a shift towards greater NO_3^- availability compared to RR. These findings highlight the complex interplay of organic amendment, crop types and annual variability in shaping soil properties, specifically the NO_3^-/NH_4^+ ratio and bulk mineral N content.

Soil N_2O emissions showed significant differences by treatment in both years, with RM-treated mung bean (2021) and maize (2022) monocultures displaying elevated emissions across all measurement dates, as illustrated in Figure 1. Soil NO_3^- levels were consistently higher with RM application, especially in 2021 in Mu and Ma + Mu treatments during the first three measurements (T1–T3) and in Mu in 2022. Conversely, maize monoculture with RR had the lowest NO_3^- levels during the first four measurements (T1–T4), especially in 2022. NH_4^+ measurements revealed that RR-treated mung bean plots had the highest average NH_4^+ levels, while maize + mung bean intercropping with RR had the lowest levels. These results illustrate the influence of negative (NO_3^-) and positive (NH_4^+) charges in response to organic amendment, crop type and cropping system across different years. They emphasise the distinct impact of amendment, particularly RM, on N availability, soil mineral content and N_2O emissions in these cropping systems.

3.2 | Crop N Accumulation

Significant variations in crop N accumulation were observed between the two experimental years (Table 3). In 2021, grain yield was considerably higher, showing a +7.3% increase compared to 2022. Additionally, N content in grain, straw yield and straw N content were all markedly elevated in 2021, with increases of +35.4%, +7.2% and +28.3%, respectively, above 2022 values. Across both organic amendments, maize monoculture

TABLE 2 | The interaction effect of crop type × organic amendment on the total soil mineral content ($NO_3^- + NH_4^+$) and NO_3^-/NH_4^+ ratio during each growing season.

	T1		T2		T3		T4		T5		T6	
	Soil mineral N concentration (mg mineral N kg^{-1} of dry soil)											
2021 growing season												
Crop type	**RR**	**RM**	**RR**	**RM**	**RR**	**RM**	**RR**	**RM**	**RR**	**RM**	**RR**	**RM**
Ma	53.8 cA	58.8 cA	50.5 bA	53.2 bA	42.2 bA	46.8 cA	33.8 cA	40.6 cA	36.3 b	31.7 b	33.3 aA	27.8 bA
Mu	71.5 aB	90.7 aA	62.3 aB	69.5 aA	55.9 aB	71.3 aA	44.9 bB	49.8 bA	46.7 ab	42.3 a	35.7 aB	41.2 aA
Ma + Mu	60.6 bB	78.5 bA	56.8 abB	72.5 aA	47.2 aB	60.4 bA	55.8 aB	61.7 aA	52.8 a	35.5 b	27.3 bA	25.4 bA
2022 growing season												
Crop type	**RR**	**RM**	**RR**	**RM**	**RR**	**RM**	**RR**	**RM**	**RR**	**RM**	**RR**	**RM**
Ma	51.2 bA	64.6 bA	46.7 cA	46.4 cA	43.1 bA	44.2 bA	35.6 cA	37.3 cA	31.4 bA	35.4 bA	30.9 abA	26.5 bA
Mu	68.4 aA	75.8 abA	63.8 aB	79.3 aA	58.4 aA	61.5 aA	55.9 aB	60.8 aA	35.8 bA	42.8 aA	39.6 aA	32.1 aA
Ma + Mu	60.6 abB	84.3 aA	56.3 bA	61.3 bA	53.1 aA	48.3 bA	44.9 bB	50.1 bA	42.0 aA	30.6 bB	26.7 bA	29.7 abA
	NO_3^-/NH_4^+ ratio											
2021 growing season												
Crop type	**RR**	**RM**	**RR**	**RM**	**RR**	**RM**	**RR**	**RM**	**RR**	**RM**	**RR**	**RM**
Ma	0.38 aB	0.46 aA	0.57 aA	0.39 aB	0.60 aA	0.41 aB	0.93 aA	0.43 aB	0.73 aA	0.66 aA	0.67 aA	0.69 aA
Mu	0.38 aB	0.46 aA	0.53 abA	0.30 bB	0.50 abA	0.37 aB	0.67 bA	0.42 aB	0.57 bA	0.52 abA	0.51 bA	0.42 bA
Ma + Mu	0.39 aA	0.40 bA	0.52 bA	0.28 bB	0.40 bA	0.23 bB	0.34 cA	0.26 bA	0.46 bA	0.43 bA	0.58 abB	0.77 aA
2022 growing season												
Crop type	**RR**	**RM**	**RR**	**RM**	**RR**	**RM**	**RR**	**RM**	**RR**	**RM**	**RR**	**RM**
Ma	0.36 bB	0.51 aA	0.55 aA	0.44 aB	0.47 aA	0.37 aB	0.69 aA	0.46 aB	0.83 aA	0.56 aB	0.81 aA	0.66 aB
Mu	0.51 aA	0.50 aA	0.35 bA	0.22 bB	0.38 bA	0.27 bB	0.57 bA	0.28 bB	0.57 bA	0.37 bB	0.53 bA	0.45 bA
Ma + Mu	0.37 bA	0.28 bA	0.42 bA	0.29 bB	0.42 abA	0.34 abA	0.40 cA	0.33 bA	0.44 bA	0.56 aA	0.72 aA	0.76 aA

Note: Values belonging to the same measurement time without common letters in columns are statistically different between crops (lower-case letters) and in rows for organic amendment (upper-case letters) according to LSD ($p \leq 0.05$). T1, T2, T3, T4, T5 and T6 are the 15-day intervals of measurements.
Abbreviations: Ma, maize; Ma + Mu, maize + mung bean; Mu, mung bean; RM, sheep manure; RR, wheat residues.

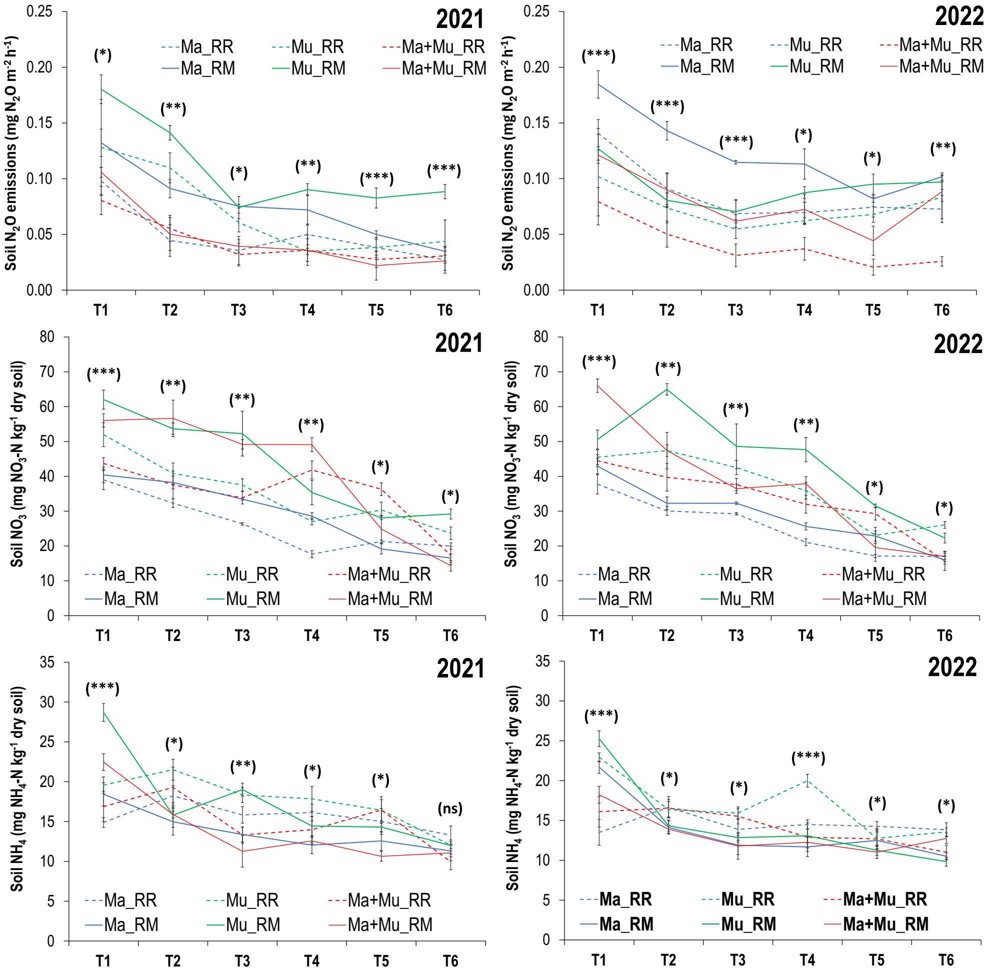

FIGURE 1 | Effects of crop type × organic amendment interaction on soil N_2O emission, soil NO_3 content and soil NH_4 content during crop cultivation. Data correspond to 2021 and 2022 growing seasons. Error bars represent ± standard error from the mean ($n = 6$ for the crop × organic amendment). The asterisks indicate the significant level of treatments *, ** and *** are significant at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively. Ma, maize; Ma + Mu, maize + mung bean; Mu, mung bean; RM, sheep manure; RR, wheat residues. T1, T2, T3, T4, T5 and T6 are the 15-day intervals of measurements.

consistently demonstrated significantly higher grain yield compared to mung bean monoculture, with an average increase of +75.3% and +76.5% for RR and RM, respectively, and compared to maize + mung bean intercropping, which showed yield increases of +46.3% and +46.7% for RR and RM, respectively. The C/N ratio in harvested grain was also notably higher in maize monoculture compared to mung bean monoculture (on average +56.3% for RR and +54.0% for RM) and maize + mung bean intercropping (on average +40.4% for RR and +38.2% for RM). Straw yield followed a similar pattern, with maize monoculture outperforming mung bean monoculture by +43.8% for RR and +47.3% for RM, and outperforming maize + mung bean intercropping by +37.6% for RR and +36.1% for RM. The C/N ratio in straw was likewise significantly higher in maize monoculture than in mung bean monoculture (+72.5% for RR and +72.2% for RM) and in maize + mung bean intercropping (+67.3% for RR and +60.7% for RM). Overall, RM application consistently produced significantly higher values in grain yield, straw yield and N content in both grain and straw, as well as in the C/N ratios, across all cropping systems (maize monoculture, mung bean monoculture and maize + mung bean intercropping). The N content in both grain and straw (Figure 2) was significantly higher in 2021 compared to 2022. In 2022, the N content in grain and straw was −27.4% and −22.0% lower, respectively, than in 2021. The N content in grain for maize monoculture was substantially lower than in mung bean monoculture and in maize + mung bean intercropping (Figure 2). Similarly, N content in straw was significantly lower in maize monoculture compared to mung bean monoculture and maize + mung bean intercropping. Notably, the differences in N content observed across crop type were consistent for both organic amendments, as no significant differences were generally detected in N content between RR and RM applications, except in N content in grain yield in 2021 where it was higher in RM than RR organic amendments (Figure 2).

3.3 | Soil Chemical and Physical Characteristics at Crop Harvesting

At crop harvest, significant year-based differences were observed across all measured variables (Table 4). Specifically, in the first year (2021), soil nutrient levels and soil physical properties were substantially higher compared to the second year

TABLE 3 | The interaction effect of crop type × organic amendment on grain yield and crop plant characteristics in each growing season.

Crop type	Grain yield (t ha^{-1})		N in grain yield (kg ha^{-1})		C/N ratio in grain		Straw (t ha^{-1} of DM)		N in straw (kg ha^{-1})		C/N ratio in straw	
2021 growing season												
Crop type	**RR**	**RM**	**RR**	**RM**	**RR**	**RM**	**RR**	**RM**	**RR**	**RM**	**RR**	**RM**
Ma	6.21 aB	6.53 aA	90.3 aA	83.6 bB	26.8 aA	26.2 aA	8.32 aA	8.39 aA	57.3 cB	67.5 bA	70.4 aA	54.8 aB
Mu	1.51 cA	1.63 cA	37.4 bA	43.1 cA	14.0 bA	12.2 bA	4.55 bA	4.86 cA	84.3 bB	96.8 aA	19.3 bA	16.4 bA
Ma + Mu	3.40 bB	3.68 bA	93.0 aA	98.8 aA	13.6 bA	13.3 bA	5.33 bA	5.42 bA	107.7 aA	101.5 aA	19.9 bA	20.5 bA
2022 growing season												
Crop type	**RR**	**RM**	**RR**	**RM**	**RR**	**RM**	**RR**	**RM**	**RR**	**RM**	**RR**	**RM**
Ma	5.95 aA	6.18 aA	57.8 aB	69.0 aA	38.7 aA	28.2 aB	7.84 aB	8.17 aA	46.7 bB	53.2 bA	78.2 aA	64.7 aB
Mu	1.40 cA	1.46 cA	30.4 cA	32.9 cA	14.5 cA	12.7 cA	3.99 cA	4.31 cA	62.8 aB	78.0 aA	21.6 bA	16.9 cA
Ma + Mu	2.93 bB	3.32 bA	42.2 bB	56.2 bA	25.4 bA	20.3 bB	4.74 bB	5.17 bA	60.2 aB	73.1 aA	28.7 bA	26.5 bA

Note: Values belonging to the same characteristic without common letters in columns are statistically different between crops (lower-case letters) and in rows for organic amendment (upper-case letters) according to LSD ($p \leq 0.05$).
Abbreviations: Ma, maize; Ma + Mu, maize + mung bean; Mu, mung bean; RM, sheep manure; RR, wheat residues.

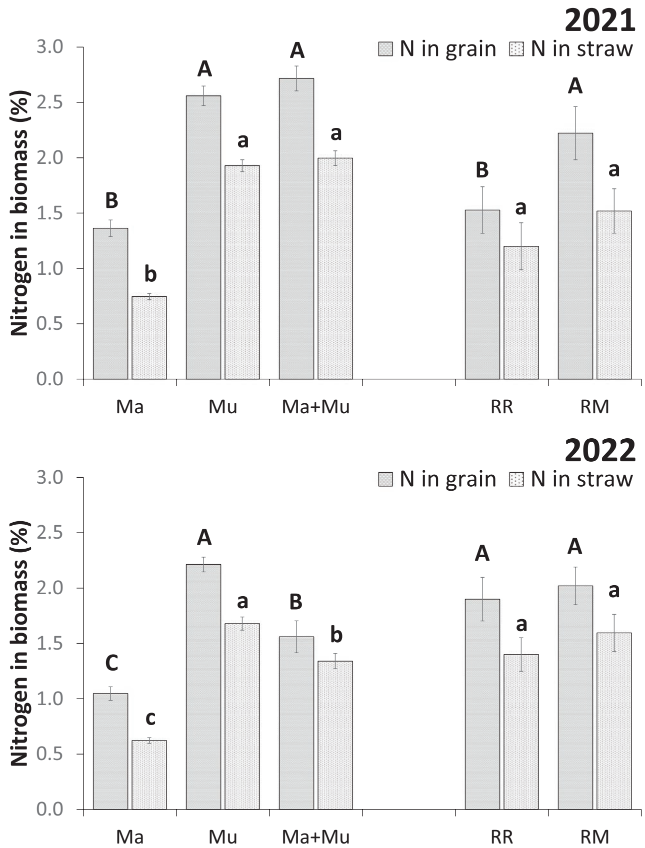

FIGURE 2 | Main effects of crop type and organic amendment on nitrogen content in grain and straw in 2021 and 2022 growing seasons. Values belonging to the same characteristic without common letters are statistically different according to LSD ($p \leq 0.05$). Lower-case letters and upper-case letters refer to N content in grain and straw, respectively. Ma, maize; Ma + Mu, maize + mung bean; Mu, mung bean; RM, sheep manure; RR, wheat residues.

(2022). Soil total N (N) was +15.4% higher in 2021, with increases in phosphorus (P) of +13.7%, potassium (K) of +8.9%, iron (Fe) of +31.3%, manganese (Mn) of +22.2% and zinc (Zn) of +23.5%. Additionally, available water content and aggregate stability were notably elevated in 2021, with increases of +14.8% and +3.9%, respectively, over 2022. In terms of crop type, mung bean monoculture exhibited significantly higher soil total N than both maize monoculture and maize + mung bean intercropping in both experimental years (Table 4). Soil P was also significantly higher in mung bean monoculture (22.1 and 20.8 mg kg^{-1} dry soil in 2021 and 2022, respectively), exceeding levels found in maize monoculture, which showed the lowest soil P content in both years. Conversely, the maize + mung bean intercropping system outperformed both monocultures in terms of soil K, Fe, Mn and Zn content. Soil K levels were on average +7.2% and +5.5% higher compared to maize and mung bean monocultures in both years, respectively, while Fe, Mn and Zn were on average +22.6%, +39.9% and +44.3% higher than maize monoculture values, and +21.6%, +20.3% and +31.3% higher than mung bean monoculture values, respectively. The intercropping system also demonstrated superior available water content (26.1% and 23.6% in 2021 and 2022, respectively) and aggregate stability (79.9% and 76.9% in 2021 and 2022, respectively), with an average increase of +9.5% and +16.2% over maize monoculture, and

TABLE 4 | Main effects of crops and organic amendment on the soil chemical and physical characteristics measured at crop harvesting in 2021 and 2022 growing seasons.

	STN	Soil P	Soil K	Soil Fe	Soil Mn	Soil Zn	Soil available water	Aggregate stability
	%	$mg\,kg^{-1}$ dry soil					%	
2021 growing season								
Crop type								
Ma	0.059 b	18.5 b	220.4 b	22.1 b	18.6 c	3.9 b	24.5 ab	67.2 b
Mu	0.064 a	22.1 a	225.3 b	21.5 b	25.4 b	4.7 b	23.3 b	72.9 b
Ma + Mu	0.055 b	19.7 b	236.4 a	27.4 a	31.3 a	6.7 a	26.1 a	79.9 a
Organic amendment								
RR	0.058 b	19.0 a	231.8 a	22.6 a	24.3 a	4.9 a	23.2 b	70.8 b
RM	0.061 a	21.2 a	223.0 b	24.7 a	25.9 a	5.2 a	26.1 a	75.9 a
2022 growing season								
Crop type								
Ma	0.046 b	14.9 c	202.2 b	15.7 b	15.7 c	3.0 b	20.5 b	64.2 b
Mu	0.060 a	20.8 a	205.0 b	16.8 b	20.1 b	3.8 ab	20.2 b	70.6 b
Ma + Mu	0.049 b	17.3 b	219.1 a	21.5 a	25.8 a	5.6 a	23.6 a	76.9 a
Organic amendment								
RR	0.050 b	19.6 a	216.8 a	19.4 a	22.4 a	4.4 a	20.0 b	68.1 b
RM	0.054 a	15.8 b	200.7 b	16.7 a	18.7 b	4.0 a	22.9 a	73.1 a

Note: Values belonging to the same characteristic for each experimental factor without common letters in columns are statistically different according to LSD ($p \leq 0.05$).
Abbreviations: Ma, maize; Ma + Mu, maize + mung bean; Mu, mung bean; RM, sheep manure; RR, wheat residues; STN, soil total nitrogen.

+12.4% and +8.9% over mung bean monoculture, respectively. Regarding organic amendments, in both experimental years, RM showed significantly higher soil total N, available water content, and aggregate stability compared to RR (Table 4). In contrast, RR-treated soils had a significantly higher K content than RM-treated soils and, in 2022, soil Mn, while no significant differences were noted between RM and RR treatments for the remaining parameters (Table 2).

3.4 | Synthetic View

The results of CDA performed for both 2021 and 2022 experimental years provide a comprehensive visualisation of relationships among soil chemical and physical characteristics at crop harvest (Figure 3). For both seasons, CDA incorporates key parameters including available soil water (ASW), water aggregate stability (WAS), average soil NO_3^-, average soil ammonium (NH_4^+) and average soil N_2O emissions. Plots reveal a similar trend between the years with distinct groupings of data points, showing how varying combinations of crop types and organic amendments influence soil properties. Notably, the analysis distinguishes between the effects of maize (Ma) and mung bean (Mu) and their intercropping on soil characteristics, as well as the differential impacts of organic amendments such as RR and RM. Data point proximities within the plot indicate potential correlations among specific soil attributes, highlighting the complex relationships within this multivariate dataset. As illustrated in Figure 3, these CDA results offer valuable insights into how crop selection and organic amendments jointly impact soil properties, providing a useful guide for sustainable agriculture and soil management practices. In 2021, the first two canonical variables explained 43.2% of the total variance. Indeed, the CDA analysis showed that the vectors of ASW, WAS, Soil P, Soil K, Soil Fe, Soil Mn and Soil Zn were generally associated with Ma + Mu crop type, while N_2O, NO_3^- and NH_4^+ vectors resulted in the same position of mung bean, particularly NO_3^- with Mu-RM. In 2022, the first two canonical variables explained 54.7% of the total variance, and the vectors indicate a similar trend to that described in 2021 (Figure 3).

4 | Discussion

The results of this study demonstrate how total soil mineral N ($NO_3^- + NH_4^+$) and the NO_3^-/NH_4^+ ratio varied significantly between the two cropping seasons, primarily due to differences in agro-climatic conditions. These seasonal variations can be attributed to the semi-arid environment of the study area, marked by low precipitation levels. These conditions, alongside the experimental treatments, had a substantial impact on crop responses, affecting both crop yield and soil chemical and physical characteristics at harvest. The second year of the study (2022) experienced slightly warmer conditions than the first (2021), with higher average temperatures contributing to enhanced crop development. Additionally, rising air temperatures led to lower soil moisture levels, particularly notable given the study area's silty loam soil with a relatively low clay content (22%) yet high water-holding capacity.

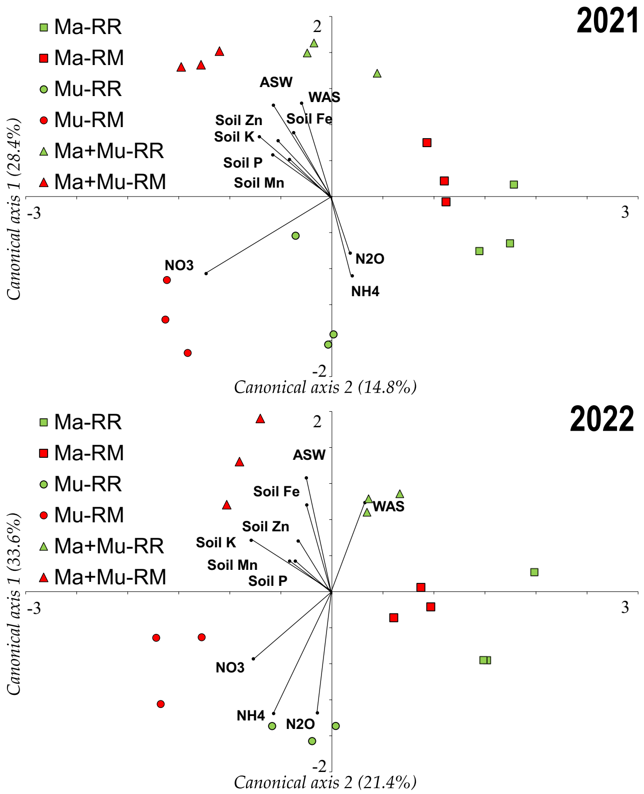

FIGURE 3 | Canonical discriminant analysis (CDA) of the soil chemical and physical characteristics at crop harvesting among the crop type × organic amendment interaction for 2021 and 2022 years. ASW, available soil water; Ma, maize; Ma + Mu, maize + mung bean; Mu, mung bean; N_2O, average soil nitrous oxide emissions during the crop growing season; NH_4, average soil ammonium content during the crop growing season; NO_3^-, average soil nitrate content during the crop growing season; RM, sheep manure; RR, wheat residues; WAS, water aggregate stability.

Such environmental factors play a critical role in soil N dynamics, influencing crop productivity and GHG emissions. In line with our findings, Cai et al. (2013) identified soil moisture and temperature as key determinants of soil denitrification and N_2O emissions. The application of RM resulted in a significant increase in grain yield, likely due to its higher N content and improved soil microbial activity, which facilitated better nutrient availability (Diacono and Montemurro 2010). Similarly, RR, while contributing to SOM, may have led to temporary N immobilisation, potentially explaining lower yield improvements compared to RM treatments (Liu et al. 2006). These findings align with previous studies indicating that organic amendments enhance yield stability, particularly in intercropping systems, by promoting N cycling and improving soil structure (Gattinger et al. 2012; Lal 2020). Moreover, the yield advantage observed in intercropping compared to monocultures supports the hypothesis that diversified cropping systems optimise resource use efficiency and complementarity in nutrient uptake, as reported by Zhao et al. (2023). The RR treatment affected also soil Mn availability likely through the production of some decomposition by-products that enhance nutrient solubility. In fact, the decomposition of RR, particularly under aerobic conditions, can lead to the release of chelating compounds that mobilise soil nutrients, increasing their bioavailability for plant uptake (Montreemuk et al. 2024). Furthermore, the high carbon-to-nitrogen (C:N) ratio of RR may induce temporary N immobilisation, which slows N release while promoting the activity of Mn-reducing microorganisms that facilitate Mn solubilisation in the rhizosphere (Zhu et al. 2022).

The results suggest that the integration of organic amendments with intercropping strategies can be an effective approach to sustain productivity under semi-arid conditions while improving soil health over time. The observed variations in grain yield across different cropping systems and organic amendments treatments highlight the role of soil fertility enhancement in semi-arid conditions. The observed higher grain yield in Ma monoculture compared to intercropping systems can be attributed to reduced interspecific competition for light, water and nutrients. In monoculture, Ma plants can fully exploit available soil resources without interference from another crop, leading to enhanced biomass accumulation and grain production (Tilman et al. 2011). However, the lower N content in monoculture maize may be explained by the higher overall N demand of dense maize stands, leading to increased nutrient uptake but also potential soil N depletion over time (Chen et al. 2014). The lower N concentration in monoculture maize suggests that despite higher yields, the efficiency of N utilisation may be suboptimal, possibly due to rapid nutrient uptake without sufficient replenishment from organic amendments or N fixation, leading to lower tissue N concentration (Congreves and Van Eerd 2015). Conversely, Mu monoculture exhibited higher STN and P levels compared to Ma and Ma + Mu due to several agronomic and physiological factors. Firstly, mung bean, as a leguminous crop, has a well-documented ability to enhance soil N through biological N fixation that led to an accumulation of STN over time (Adesemoye and Kloepper 2009). In contrast, maize relies solely on soil N uptake and does not contribute to N enrichment, which may explain the lower STN levels observed in monoculture maize. Additionally, intercropping systems often exhibit N competition between species, reducing the net accumulation of N in the soil compared to legume monocultures (Chamkhi et al. 2022). In addition, Mu has a relatively lower nutrient demand than Ma and is less likely to cause P depletion in the soil. Furthermore, legumes have been reported to enhance P availability by increasing root exudation of organic acids, which mobilise bound phosphorus in the soil (Richardson et al. 2009). This mechanism improves P bioavailability, contributing to the elevated P levels in mung bean monoculture plots. Conversely, Ma has a high P demand, leading to greater P depletion in monoculture and intercropping systems (Xia et al. 2013). As a consequence, intercropping systems with legumes, such as Mu, contribute to enhanced soil N availability through biological N fixation, which not only benefits the legume but also improves N uptake efficiency in the associated maize crop (Ladha et al. 2022). Overall, these results underscore the role of leguminous crops in sustainable soil fertility management, supporting their inclusion in cropping systems to improve soil nutrient status. Although inorganic N fertiliser controls were not included in this experiment, findings indicate that RM application likely enhanced soil N_2O emissions in maize and mung bean monocultures. Meta-analyses, such as that by Fan et al. (2023), indicate that replacing inorganic N with organic sources generally reduces N_2O emissions, with manure fertilisers associated with lower emission factors than ammonium and urea. The effectiveness of organic amendments for N_2O mitigation depends largely on their physicochemical characteristics and their substitution rate for N fertiliser (Ren et al. 2017). Nonetheless, crop residues present a challenge, as they can sequester C while also potentially increasing N_2O emissions (De Notaris et al. 2022). The impact of crop residues on soil C and N accumulation is shaped by initial soil properties that influence residue decomposition and SOM mineralisation (Liu et al. 2023). This study's results reinforce this understanding, especially in maize and mung bean monocultures, where the NO_3^-/NH_4^+ ratio was significantly lower under RM application from T2 to T6. Wheat residue acted as a water-retentive organic material, providing a buffering effect against moisture loss. Interestingly, no significant differences were observed in N contents in grain and straw or in soil phosphorus (P), potassium (K), iron (Fe) and zinc (Zn) at harvest. Prior research supports these findings, as low NO_3^-/NH_4^+ ratios are known to inhibit plant growth and modify the ion exchange, while elevated NH_4^+ levels can reduce the absorption of essential inorganic cations like K^+, Ca^{2+} and Mg^{2+} (Britto and Kronzucker 2002). Nitrification and denitrification are essential biochemical processes driving soil N_2O production in agricultural systems, influenced by factors such as N fertiliser substrate availability, soil acidity, moisture and temperature (Janssens-Maenhout et al. 2019). Studies have shown that organic materials, including manure and composts, can act as C sources for denitrifiers, accelerating denitrification and subsequently increasing N_2O emissions (Fernández-Luqueño et al. 2009). In this study, RM application in Ma and Mu monocultures significantly increased soil N_2O emissions across all measurement dates. Soil amendments with high C/N ratios, such as wheat straw, may deplete the soil mineral N pool for microbial assimilation, reducing mineral N availability for N_2O production unless supplemented by fertilisation (Olesen et al. 2023). Chen et al. (2013) observed that crop residues with C/N ratios between 45 and 100 (72.9 ratio in this study) slightly increased soil N_2O emissions compared to unamended controls. Organic amendments are integral to microbial processes, promoting N_2O emissions (Lazcano et al. 2021). Soil microbial processes underpinning N_2O production are sensitive to variations in soil aeration, moisture, structure, organic matter distribution and temperature (Ball 2013). Incorporating crop residues into the N cycle is vital for enhancing agricultural sustainability in semi-arid regions (Berhane et al. 2020). However, some agroecological practices, like organic amendment use, can inadvertently increase N_2O release if not properly managed (Grados et al. 2022). Crop residues serve as organic N sources and undergo microbial mineralisation and nitrification, contributing to N_2O emissions (Chen et al. 2013). Returning crop residues to the soil can modify soil GHG emissions and alter GWP. The residue C/N ratio, an indicator of residue quality, is critical for predicting N_2O emissions post-harvest, as it affects net N immobilisation or mineralisation from residues (Chen et al. 2013; Essich et al. 2020). As Lashermes et al. (2022) highlighted, understanding residue quality is essential for predicting N_2O emissions and evaluating their environmental impacts. Methods such as straw mulching or incorporation enhance SOM, promote biological activity and improve nutrient availability (Huang et al. 2021). Chen et al. (2013) found that crop residue incorporation generally raised N_2O emissions compared to unamended soils, with high C/N residues being more effective in moderating these emissions (Shan and Yan 2013). In an incubation study, Reichel et al. (2018) demonstrated that readily available C from residues, such as wheat or maize straw, increases N_2O emissions by stimulating heterotrophic microbial growth and enhancing denitrification, which consumes oxygen. High soil mineral N content combined with increased C from residues, particularly those with high, easily accessible C like wheat straw, can amplify N_2O emissions (Yue et al. 2017). In addition, as this experiment was conducted under irrigated conditions, it is likely that nitrous oxide emissions increased following the transition to aerobic soil conditions after irrigation, and the sampling performed at 15-day intervals may underestimate N_2O emissions; therefore, future studies could benefit from a higher-frequency sampling strategy immediately following irrigation to capture transient emission spikes more accurately.

A global meta-analysis by Liu et al. (2023) confirmed that residue return compared to no residue addition increases soil C stocks by 8%–13%, especially in the topsoil (0–20 cm), and raises soil N and P stocks by 9% and 5%, respectively. The accumulation of soil C depends on a balance of C inputs (e.g., residues, root exudates) and losses (e.g., microbial respiration), which are influenced by residue quality, quantity and decomposition rates (Almagro et al. 2021). Diatta et al. (2023) also observed enhanced mung bean growth following organic amendment applications, attributed to high nutrient content in manure, including N, P, K and trace elements. Contrasting findings exist regarding RR effect on N_2O emissions; while Shan and Yan (2013) found no significant impact, Schmatz et al. (2020) also observed no influence of RR with high C/N ratios. Agronomic practices, such as selecting organic amendments and choosing cropping systems, notably influence soil chemistry and structure. The maize + mung bean intercropping system showed the most pronounced decline in soil mineral N concentration over time, and it also resulted in significantly higher N content in grain and straw compared to maize monoculture. Within the same cropping system, intercropping led to significant increases in soil available water and aggregate stability compared to monocultures. This finding aligns with the efficiency of intercropping systems in optimising resource use, including light and nutrients, by utilising previously unoccupied niches in traditional monocultures (Chai et al. 2021; Liu et al. 2019). The feasibility related to the adoption of sheep manure and wheat residues as organic amendment is influenced by several factors such as input costs, crop yield responses and long-term soil fertility benefits. Although the initial costs of organic amendment may exceed those of synthetic fertilisers, their application enhances soil structure, water retention and microbial activity, thereby improving nutrient-use efficiency and reducing long-term fertiliser dependency (Diacono and Montemurro 2010). Several studies have demonstrated that the integration of organic amendments into cropping systems can lead to increased profitability by enhancing crop yields and reducing synthetic fertiliser inputs (Lal 2020). In semi-arid regions, where soil degradation and water scarcity are critical challenges, the use of organic amendments has been shown to improve soil organic carbon content and nutrient cycling, contributing to both agronomic and economic sustainability (Soria et al. 2021).

5 | Conclusions

This finding highlights the potential of organic amendments to improve nutrient cycling, emphasising the importance of aligning inputs with site-specific conditions to balance fertility and GHG emissions. The results indicate that the selection between monoculture and intercropping systems notably influences soil properties, particularly water availability and aggregate stability. Intercropping with maize and mung bean significantly improved resource utilisation efficiency by enhancing soil water retention and stability, likely due to improved root structure and nutrient cycling. In addition, the application of organic amendments, particularly returning sheep manure (RM), resulted in a significant increase in grain yield, underscoring the direct agronomic benefits of enhanced nutrient availability and soil health. Although Ma monoculture achieved higher grain production due to reduced interspecific competition, intercropping with Mu offered complementary advantages by contributing to long-term soil fertility and improved moisture retention. These findings highlight that managing SOM through residue retention or incorporation can effectively enhance soil nutrient levels and moderate N_2O emissions, while also supporting sustainable grain production. Future research should continue exploring the interactions among crop types, organic amendments and residue management to develop refined, context-specific agricultural strategies that improve soil health, mitigate GHG emissions and promote environmental sustainability in semi-arid regions, where soil fertility and water retention are critical for agricultural resilience.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Adelekun, M., O. Akinremi, P. Nikièma, B. Sparling, and M. Tenuta. 2021. "Nitrous Oxide Fluxes From Liquid Pig Manure and Urea Fertilizer Applied to Annual Crops." *Agriculture, Ecosystems and Environment* 313: 107393. https://doi.org/10.1016/j.agee.2021.107393.

Adesemoye, A. O., and J. W. Kloepper. 2009. "Plant-Microbes Interactions in Enhanced Fertilizer-Use Efficiency." *Applied Microbiology and Biotechnology* 85: 1–12. https://doi.org/10.1007/s00253-009-2196-0.

Almagro, M., A. Ruiz-Navarro, E. Díaz-Pereira, J. Albaladejo, and M. Martínez-Mena. 2021. "Plant Residue Chemical Quality Modulates the Soil Microbial Response Related to Decomposition and Soil Organic Carbon and Nitrogen Stabilization in a Rainfed Mediterranean Agroecosystem." *Soil Biology and Biochemistry* 156: 108198. https://doi.org/10.1016/j.soilbio.2021.108198.

Al-Shammary, A. A. G., L. S. S. Al-Shihmani, A. Caballero-Calvo, and J. Fernández-Gálvez. 2023. "Impact of Agronomic Practices on Physical Surface Crusts and Some Soil Technical Attributes of Two Winter Wheat Fields in Southern Iraq." *Journal of Soils and Sediments* 23, no. 11: 3917–3936. https://doi.org/10.1007/s11368-023-03585-w.

Al-Shammary, A. A. G., N. R. Lahmod, J. Fernández-Gálvez, and A. Caballero-Calvo. 2023. "Effect of Tillage Systems Combined With Plastic Film Mulches and Fertilizers on Soil Physical Properties in a Wheat-Agricultural Site in Southern Iraq." *Cuadernos de Investigación Geográfica* 49, no. 2: 51–63. https://doi.org/10.18172/cig.5544.

Ball, B. C. 2013. "Soil Structure and Greenhouse Gas Emissions: A Synthesis of 20 Years of Experimentation." *European Journal of Soil Science* 64, no. 3: 357–373. https://doi.org/10.1111/ejss.12013.

Berhane, M., M. Xu, Z. Liang, J. Shi, G. Wei, and X. Tian. 2020. "Effects of Long-Term Straw Return on Soil Organic Carbon Storage and Sequestration Rate in North China Upland Crops: A Meta-Analysis." *Global Change Biology* 26, no. 4: 2686–2701. https://doi.org/10.1111/gcb.15018.

Boudjabi, S., and H. Chenchouni. 2023. "Comparative Effectiveness of Exogenous Organic Amendments on Soil Fertility, Growth, Photosynthesis and Heavy Metal Accumulation in Cereal Crops." *Heliyon* 9, no. 4: e14615. https://doi.org/10.1016/j.heliyon.2023.e14615.

Brichi, L., J. V. M. Fernandes, B. M. Silva, J. D. F. Vizú, J. N. G. Junior, and M. R. Cherubin. 2023. "Organic Residues and Their Impact on Soil Health, Crop Production and Sustainable Agriculture: A Review Including Bibliographic Analysis." *Soil Use and Management* 39: 686–706. https://doi.org/10.1111/sum.12892.

Britto, D. T., and H. J. Kronzucker. 2002. "NH_4^+ Toxicity in Higher Plants: A Critical Review." *Journal of Plant Physiology* 159, no. 6: 567–584. https://doi.org/10.1078/0176-1617-0774.

Cai, Y., W. Ding, and J. Luo. 2013. "Nitrous Oxide Emissions From Chinese Maize-Wheat Rotation Systems: A 3-Year Field Measurement." *Atmospheric Environment* 65: 112–122. https://doi.org/10.1016/j.atmosenv.2012.10.038.

Cassel, D., and D. Nielsen. 1986. "Field Capacity and Available Water Capacity." In *Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods*, Vol. 5, edited by A. Klute, 901–926. Soil Science Society of America.

Chai, Q., T. Nemecek, C. Liang, et al. 2021. "Integrated Farming With Intercropping Increases Food Production While Reducing Environmental Footprint." *Proceedings of the National Academy of Sciences of the United States of America* 118, no. 38: e2106382118. https://doi.org/10.1073/pnas.2106382118.

Chamkhi, I., S. Cheto, J. Geistlinger, et al. 2022. "Legume-Based Intercropping Systems Promote Beneficial Rhizobacterial Community and Crop Yield Under Stressing Conditions." *Industrial Crops and Products* 183: 114958. https://doi.org/10.1016/j.indcrop.2022.114958.

Charles, A., P. Rochette, J. K. Whalen, D. A. Angers, M. H. Chantigny, and N. Bertrand. 2017. "Global Nitrous Oxide Emission Factors From Agricultural Soils After Addition of Organic Amendments: A Meta-Analysis." *Agriculture, Ecosystems and Environment* 236: 88–98. https://doi.org/10.1016/j.agee.2016.11.021.

Chen, H., X. Li, F. Hu, and W. Shi. 2013. "Soil Nitrous Oxide Emissions Following Crop Residue Addition: A Meta-Analysis." *Global Change Biology* 19, no. 10: 2956–2964. https://doi.org/10.1111/gcb.12274.

Chen, X., Z. Cui, and M. Fan. 2014. "Producing More Grain With Lower Environmental Costs." *Nature* 514: 486–489. https://doi.org/10.1038/nature13609.

Congreves, K. A., S. E. Brown, D. D. Németh, K. E. Dunfield, and C. Wagner-Riddle. 2017. "Differences in Field-Scale N_2O Flux Linked to Crop Residue Removal Under Two Tillage Systems in Cold Climates." *GCB Bioenergy* 9, no. 4: 666–680. https://doi.org/10.1111/gcbb.12354.

Congreves, K. A., and L. L. Van Eerd. 2015. "Nitrogen Cycling and Management in Intensive Horticultural Systems." *Nutrient Cycling in Agroecosystems* 102: 299–318. https://doi.org/10.1007/s10705-015-9704-7.

de Klein, C., and M. J. Harvey. 2015. *Nitrous Oxide Chamber Methodologies–Evolving Issues and Collection of Ancillary Data to Enhance Flux Interpretations*. ASA-CSSA-SSSA.

de Klein, C. A. M., M. A. Alfaro, D. Giltrap, et al. 2020. "Global Research Alliance N_2O Chamber Methodology Guidelines: Statistical Considerations, Emission Factor Calculation, and Data Reporting." *Journal of Environmental Quality* 49, no. 5: 1156–1167. https://doi.org/10.1002/jeq2.20127.

De Notaris, C., D. Abalos, M. H. Mikkelsen, and J. E. Olesen. 2022. "Potential for the Adoption of Measures to Reduce N_2O Emissions

From Crop Residues in Denmark." *Science of the Total Environment* 835: 155510. https://doi.org/10.1016/j.scitotenv.2022.155510.

Derdour, A., N. Belam, and W. Chebab. 2022. "Traditional Irrigation System and Methods of Water Harvesting in the Oasis of Sfissifa Ksour Mountains—Algeria." *Larhyss Journal* 2022, no. 49: 17–35.

Diacono, M., and F. Montemurro. 2010. "Long-Term Effects of Organic Amendments on Soil Fertility: A Review." *Agronomy for Sustainable Development* 30: 401–422. https://doi.org/10.1051/agro/2009040.

Diatta, A. A., C. Bassène, A. G. B. Manga, et al. 2023. "Integrated Use of Organic Amendments Increased Mungbean (*Vigna radiata* (L.) Wilczek) Yield and Its Components Compared to Inorganic Fertilizers." *Urban Agriculture & Regional Food Systems* 8, no. 1: e20048. https://doi.org/10.1002/uar2.20048.

Dubey, R. K., P. K. Dubey, R. Chaurasia, H. B. Singh, and P. C. Abhilash. 2020. "Sustainable Agronomic Practices for Enhancing the Soil Quality and Yield of *Cicer arietinum* L. Under Diverse Agroecosystems." *Journal of Environmental Management* 262: 110284. https://doi.org/10.1016/j.jenvman.2020.110284.

Elliott, E. T. 1986. "Aggregate Structure and Carbon, Nitrogen, and Phosphorus in Native and Cultivated Soils." *Soil Science Society of America Journal* 50, no. 3: 627–633. https://doi.org/10.2136/sssaj1986.03615995005000030017x.

Esmaeilian, Y., M. Babaeian, and A. Caballero-Calvo. 2023. "Optimization of Castor Bean (*Ricinus communis* L.) Cultivation Methods Using Biostimulants in an Arid Climate." *Euro-Mediterranean Journal for Environmental Integration* 8, no. 4: 823–834.

Essich, L., P. M. Nkebiwe, M. Schneider, and R. Ruser. 2020. "Is Crop Residue Removal to Reduce N_2O Emissions Driven by Quality or Quantity? A Field Study and Meta-Analysis." *Agriculture (Switzerland)* 10, no. 11: 1–20. https://doi.org/10.3390/agriculture10110546.

Fan, X., X. Chen, T. Chen, et al. 2023. "Effects of Substituting Synthetic Nitrogen With Organic Amendments on Crop Yield, Net Greenhouse Gas Emissions and Carbon Footprint: A Global Meta-Analysis." *Field Crops Research* 301: 109035. https://doi.org/10.1016/j.fcr.2023.109035.

Fernández-Luqueño, F., V. Reyes-Varela, C. Martínez-Suárez, et al. 2009. "Emission of CO_2 and N_2O From Soil Cultivated With Common Bean (*Phaseolus vulgaris* L.) Fertilized With Different N Sources." *Science of the Total Environment* 407, no. 14: 4289–4296. https://doi.org/10.1016/j.scitotenv.2009.04.016.

Gattinger, A., A. Muller, M. Haeni, et al. 2012. "Enhanced Top Soil Carbon Stocks Under Organic Farming." *Proceedings of the National Academy of Sciences of the United States of America* 109, no. 44: 18226–18231. https://doi.org/10.1073/pnas.1209429109.

Gomez, K. A., and A. A. Gomez. (1984) *Statistical Procedures for Agricultural Research*, 2nd edn. John Wiley & Sons.

Grados, D., K. Butterbach-Bahl, J. Chen, et al. 2022. "Synthesizing the Evidence of Nitrous Oxide Mitigation Practices in Agroecosystems." *Environmental Research Letters* 17, no. 11: 114024. https://doi.org/10.1088/1748-9326/ac9b50.

Greff, B., J. Szigeti, Á. Nagy, E. Lakatos, and L. Varga. 2022. "Influence of Microbial Inoculants on Co-Composting of Lignocellulosic Crop Residues With Farm Animal Manure: A Review." *Journal of Environmental Management* 302: 114088. https://doi.org/10.1016/j.jenvman.2021.114088.

Hénault, C., A. Grossel, B. Mary, M. Roussel, and J. LéOnard. 2012. "Nitrous Oxide Emission by Agricultural Soils: A Review of Spatial and Temporal Variability for Mitigation." *Pedosphere* 22, no. 4: 426–433. https://doi.org/10.1016/S1002-0160(12)60029-0.

Huang, T., N. Yang, C. Lu, X. Qin, and K. H. M. Siddique. 2021. "Soil Organic Carbon, Total Nitrogen, Available Nutrients, and Yield Under Different Straw Returning Methods." *Soil and Tillage Research* 214: 105171. https://doi.org/10.1016/j.still.2021.105171.

IPCC. 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Janssens-Maenhout, G., M. Crippa, D. Guizzardi, et al. 2019. "EDGAR v4.3.2 Global Atlas of the Three Major Greenhouse Gas Emissions for the Period 1970–2012." *Earth System Science Data* 11, no. 3: 959–1002. https://doi.org/10.5194/essd-11-959-2019.

Jones, J. B. 2001. *Laboratory Guide for Conducting Soil Tests and Plant Analysis*. CRC Press.

Kemper, W. D., and R. C. Rosenau. 1986. "Aggregate Stability and Size Distribution." In *Methods of Soil Analysis: Part 1. Physical and Mineralogical Methods*, Vol. 5, edited by A. Klute, 425–442. Soil Science Society of America.

Ladha, J. K., M. B. Peoples, P. M. Reddy, et al. 2022. "Biological Nitrogen Fixation and Prospects for Ecological Intensification in Cereal-Based Cropping Systems." *Field Crops Research* 283: 108541. https://doi.org/10.1016/j.fcr.2022.108541.

Lal, R. 2020. "Regenerative Agriculture for Food and Climate." *Journal of Soil and Water Conservation* 75, no. 5: 123A–124A. https://doi.org/10.2489/jswc.2020.0620A.

Lashermes, G., S. Recous, G. Alavoine, et al. 2022. "N_2O Emissions From Decomposing Crop Residues Are Strongly Linked to Their Initial Soluble Fraction and Early C Mineralization." *Science of the Total Environment* 806: 150883. https://doi.org/10.1016/j.scitotenv.2021.150883.

Lazcano, C., X. Zhu-Barker, and C. Decock. 2021. "Effects of Organic Fertilizers on the Soil Microorganisms Responsible for N_2O Emissions: A Review." *Microorganisms* 9: 983. https://doi.org/10.3390/microorganisms9050983.

Liu, J., L. Fang, T. Qiu, et al. 2023. "Crop Residue Return Achieves Environmental Mitigation and Enhances Grain Yield: A Global Meta-Analysis." *Agronomy for Sustainable Development* 43, no. 6: 78. https://doi.org/10.1007/s13593-023-00928-2.

Liu, X., S. J. Herbert, A. M. Hashemi, X. Zhang, and G. Ding. 2006. "Effects of Agricultural Management on Soil Organic Matter and Carbon Transformation—A Review." *Plant, Soil and Environment* 52: 531–543. https://doi.org/10.17221/3544-pse.

Liu, X., J. Ren, Q. Zhang, and C. Liu. 2019. "Long-Term Effects of Biochar Addition and Straw Return on N_2O Fluxes and the Related Functional Gene Abundances Under Wheat-Maize Rotation System in the North China Plain." *Applied Soil Ecology* 135: 44–55.

Lozano-Parra, J., C. F. Maldonado-Clavelle, A. Caballero-Calvo, M. Pulido-Fernández, Y. Gyasi-Agyei, and J. Rodrigo-Comino. 2023. "Estimation of Soil Mobilization Rates by a Rainy Period and Intense Tillage Practices in Vineyards—A Case Study in the Maule Region (Chile)." *Hydrological Processes* 37, no. 4: e14829.

Montreemuk, J., T. N. Stewart, and B. Prapagdee. 2024. "Bacterial-Assisted Phytoremediation of Heavy Metals: Concepts, Current Knowledge, and Future Directions." *Environmental Technology and Innovation* 33: 103488. https://doi.org/10.1016/j.eti.2023.103488.

Moussaoui, T., A. Derdour, A. Hosni, M. Ballesta-de los Santos, P. Legua, and M. Á. Pardo-Picazo. 2023. "Assessing the Quality of Treated Wastewater for Irrigation: A Case Study of Ain Sefra Wastewater Treatment Plant." *Sustainability (Switzerland)* 15, no. 14: 11133. https://doi.org/10.3390/su151411133.

Noor, R. S., F. Hussain, I. Abbas, M. Umair, and Y. Sun. 2023. "Effect of Compost and Chemical Fertilizer Application on Soil Physical Properties and Productivity of Sesame (*Sesamum Indicum* L.)." *Biomass*

Conversion and Biorefinery 13, no. 2: 905–915. https://doi.org/10.1007/s13399-020-01066-5.

Oertel, C., K. Herklotz, J. Matschullat, and F. Zimmermann. (2012). "Nitric Oxide Emissions From Soils: A Case Study With Temperate Soils From Saxony, Germany." *Environmental Earth Sciences* 66, no. 8: 2343–2351. https://doi.org/10.1007/s12665-011-1456-3.

Olesen, J. E., R. M. Rees, S. Recous, et al. 2023. "Challenges of Accounting Nitrous Oxide Emissions From Agricultural Crop Residues." *Global Change Biology* 29, no. 24: 6846–6855. https://doi.org/10.1111/gcb.16962.

Page, A. L. 1982. *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties*. Soil Science Society of America.

Parkin T. B., and R. T. Venterea. (2010) "Chamber-Based Trace Gas Flux Measurements." In *Sample Protocols GRACEnet*, edited by R. F. Follett, 1–39. USDA.

Parlak, M., T. Everest, T. Tunçay, A. Caballero-Calvo, and J. Rodrigo-Comino. 2022. "Soil Losses due to Leek and Groundnut Root Crop Harvesting: An Unstudied Regional Problem in Turkey." *Land Degradation & Development* 33, no. 11: 1799–1809.

Pu, C., J. S. Chen, H. D. Wang, A. L. Virk, X. Zhao, and H. L. Zhang. 2022. "Greenhouse Gas Emissions From the Wheat-Maize Cropping System Under Different Tillage and Crop Residue Management Practices in the North China Plain." *Science of the Total Environment* 819: 153089. https://doi.org/10.1016/j.scitotenv.2022.153089.

Reay, D. S., E. A. Davidson, K. A. Smith, et al. 2012. "Global Agriculture and Nitrous Oxide Emissions." *Nature Climate Change* 2: 410–416. https://doi.org/10.1038/nclimate1458.

Reichel, R., J. Wei, M. S. Islam, et al. 2018. "Potential of Wheat Straw, Spruce Sawdust, and Lignin as High Organic Carbon Soil Amendments to Improve Agricultural Nitrogen Retention Capacity: An Incubation Study." *Frontiers in Plant Science* 9: 900. https://doi.org/10.3389/fpls.2018.00900.

Ren, F., X. Zhang, J. Liu, et al. 2017. "A Synthetic Analysis of Greenhouse Gas Emissions From Manure Amended Agricultural Soils in China." *Scientific Reports* 7, no. 1: 8123. https://doi.org/10.1038/s41598-017-07793-6.

Richardson, A. E., P. J. Hocking, R. J. Simpson, and T. S. George. 2009. "Plant Mechanisms to Optimise Access to Soil Phosphorus." *Crop and Pasture Science* 60: 124–143. https://doi.org/10.1071/CP07125.

SAS. 1996. *SAS User's Guide: Statistics*. SAS Institute.

Schmatz, R., S. Recous, D. Adams Weiler, et al. 2020. "How the Mass and Quality of Wheat and Vetch Mulches Affect Drivers of Soil N_2O Emissions." *Geoderma* 372: 114395. https://doi.org/10.1016/j.geoderma.2020.114395.

Shan, J., and X. Yan. 2013. "Effects of Crop Residue Returning on Nitrous Oxide Emissions in Agricultural Soils." *Atmospheric Environment* 71: 170–175. https://doi.org/10.1016/j.atmosenv.2013.02.009.

Smith, P., J. Adams, D. J. Beerling, et al. 2019. "Land-Management Options for Greenhouse Gas Removal and Their Impacts on Ecosystem Services and the Sustainable Development Goals." *Annual Review of Environment and Resources* 44: 255–286. https://doi.org/10.1146/annurev-environ-101718-033129.

Soria, R., R. Ortega, F. Bastida, and I. Miralles. 2021. "Role of Organic Amendment Application on Soil Quality, Functionality and Greenhouse Emission in a Limestone Quarry From Semiarid Ecosystems." *Applied Soil Ecology* 164: 103925. https://doi.org/10.1016/j.apsoil.2021.103925.

Thangarajan, R., N. S. Bolan, G. Tian, R. Naidu, and A. Kunhikrishnan. 2013. "Role of Organic Amendment Application on Greenhouse Gas Emission From Soil." *Science of the Total Environment* 465: 72–96. https://doi.org/10.1016/j.scitotenv.2013.01.031.

Tian, H., R. Xu, J. G. Canadell, et al. 2020. "A Comprehensive Quantification of Global Nitrous Oxide Sources and Sinks." *Nature* 586: 248–256. https://doi.org/10.1038/s41586-020-2780-0.

Tilman, D., C. Balzer, J. Hill, and B. L. Befort. 2011. "Global Food Demand and the Sustainable Intensification of Agriculture." *Proceedings of the National Academy of Sciences of the United States of America* 108, no. 50: 20260–20264. https://doi.org/10.1073/pnas.1116437108.

Waldrip, H. M., P. H. Pagliari, and Z. He. 2020. *Animal Manure: Production, Characteristics, Environmental Concerns, and Management*. John Wiley & Sons.

Xia, H. Y., Z. G. Wang, J. H. Zhao, et al. 2013. "Contribution of Interspecific Interactions and Phosphorus Application to Sustainable and Productive Intercropping Systems." *Field Crops Research* 154: 53–64. https://doi.org/10.1016/j.fcr.2013.07.011.

Yue, K., D. A. Fornara, W. Yang, et al. 2017. "Effects of Three Global Change Drivers on Terrestrial C:N:P Stoichiometry: A Global Synthesis." *Global Change Biology* 23, no. 6: 2450–2463. https://doi.org/10.1111/gcb.13569.

Zhang, X., H. Qian, K. Hua, et al. 2022. "Organic Amendments Increase Crop Yield While Mitigating Greenhouse Gas Emissions From the Perspective of Carbon Fees in a Soybean-Wheat System." *Agriculture, Ecosystems & Environment* 325: 107736. https://doi.org/10.1016/j.agee.2021.107736.

Zhao, J., L. Bedoussac, J. Sun, et al. 2023. "Competition-Recovery and Overyielding of Maize in Intercropping Depend on Species Temporal Complementarity and Nitrogen Supply." *Field Crops Research* 292: 108820. https://doi.org/10.1016/j.fcr.2023.108820.

Zhu, R., C. Liu, Y. D. Xu, et al. 2022. "Ratio of Carbon and Nitrogen in Fertilizer Treatment Drives Distinct Rhizosphere Microbial Community Composition and Co-Occurrence Networks." *Frontiers in Microbiology* 13: 968551. https://doi.org/10.3389/fmicb.2022.968551.