Journal of Agricultural Science and Technology (JAST), 29(5)
In Press, Pre-Proof Version

Combined Effects of Tillage, Crop Rotation, and Biochar on Estimated Net Global Warming Potential in a Rainfed Wheat Agroecosystem

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Abstract

Conservation-oriented management practices, such as reduced soil disturbance, diversified crop rotations, and biochar application, have been increasingly considered as potential approaches to reduce the environmental impact of cereal production systems. This study evaluated the effects of tillage system, crop rotation, and biochar application on soil carbon and estimated greenhouse gas balance in a rainfed wheat agroecosystem in Khosroshahr, northwestern Iran. A split–split plot experiment was conducted during 2020–2023 using three tillage systems (conventional tillage (CT), reduced tillage (RT), and no-tillage (NT)), three crop rotations (continuous wheat, wheat–fallow–wheat, and wheat–grass pea–wheat), and three biochar rates (0, 5, and 10 t ha^{-1}). Climate impacts were quantified using IPCC Tier 1 emission factors with management-specific adjustments. Management practices significantly affected soil carbon, grain yield, and estimated greenhouse gas balance. Soil organic carbon was 19.5 to 28.7 t C ha^{-1}, while estimated GWP_{net} varied from −11053 to +466 kg CO_2-eq ha^{-1} across treatments. Conservation-oriented systems, particularly NT and RT combined with biochar application, generally produced more negative estimated GWP_{net} values than CT systems.

Keywords: Conservation agriculture, Crop diversification, Field-scale greenhouse gas balance.

INTRODUCTION

Agriculture plays a dual role in this challenge: it is both a major source of greenhouse gas emissions and one of the sectors most vulnerable to climate variability and change. This dual role is particularly evident in arid and semi-arid regions, where agricultural production is constrained by limited water availability, high inter-annual climatic variability, and inherently fragile soil systems. Consequently, identifying management strategies that enhance climate resilience while mitigating environmental impacts has become a central focus of agro-environmental research.

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Within agricultural systems, rainfed wheat agroecosystems occupy a pivotal position due to their extensive global distribution and fundamental role in food security. Rainfed wheat accounts for more than 60% of the global wheat-cultivated area, with a substantial proportion located in dryland environments (FAO, 2022). Although rainfed cropping systems are often assumed to have a relatively low environmental footprint because they lack irrigation inputs, increasing evidence suggests that they can be important sources of GHG emissions, particularly nitrous oxide (N_2O). Pulses of N_2O emissions are frequently triggered by episodic rainfall events interacting with soil nitrogen availability and suboptimal soil physical conditions (Butterbach-Bahl et al., 2013). Moreover, conventional tillage practices accelerate SOC mineralization through increased soil disturbance and aeration, leading to enhanced carbon dioxide (CO_2) emissions and long-term depletion of soil carbon stocks (Poeplau and Don, 2015). As a result, rainfed wheat agroecosystems can contribute substantially to the global warming potential (GWP) of agricultural landscapes, especially in dry and semi-arid regions.

Mitigating greenhouse gas (GHG) emissions in rainfed wheat production can be effectively achieved through various management practices. The partial substitution of organic fertilizers, such as manure, has been shown to enhance soil quality and crop productivity while reducing nitrous oxide (N_2O) emissions by 10.6-15.3% and improving nitrogen recovery efficiency (Liu et al., 2023). However, practices that increase soil organic matter may also increase N_2O emissions, complicating the net GHG abatement potential (Palmer et al., 2017). Additionally, conservation tillage practices, particularly no-till, have demonstrated lower cumulative CO_2 emissions than intensive tillage, thereby promoting soil carbon change. Furthermore, crop rotation with break crops like canola and field peas can lower GHG emissions associated with wheat production by improving nitrogen use efficiency and reducing fertilizer inputs (Brock et al., 2016).

In recent decades, substantial research effort has been directed toward management-based adaptation strategies, including the use of stable organic amendments such as biochar. In this regard, research on the use of biochar in agriculture has attracted considerable attention. The effects of biochar on soil organic carbon (SOC), GHG emissions, and crop yield vary depending on biochar and soil characteristics, as well as management practices (El-Naggar et al., 2019). In this regard, biochar produced from lignin-rich feedstocks (such as pine biochar) may reduce methane and nitrous oxide emissions and, due to its stable aromatic structure, facilitate carbon change over a longer period (Bo et al., 2023).

A moderate pyrolysis temperature (400–550 °C) showed the best efficiency in reducing overall carbon intensity per crop yield (GHGI), with a 14.9 % decrease (Amirahmadi et al., 2025). No-till practices have been shown to reduce GWP and GHG intensity (GHGI) by 66-71% compared to conventional tillage (Sainju, 2016). Implementing conservation agriculture (CA) with reduced tillage and crop residue retention can minimize N_2O emissions without compromising crop yields (Namatsheve et al., 2025). Crop rotation, particularly with legumes, can reduce N_2O emissions and improve soil fertility. In a study, cumulative N_2O emissions were significantly lower in CA systems with crop rotation compared to continuous monocropping (Namatsheve et al., 2025). A meta-analysis indicated that crop rotation increased GWP and GHGI by 41-46% compared to monocropping, highlighting the need for careful management (Sainju, 2016).

Against this background, the present study integrates multi-year field observations to evaluate the combined effects of tillage intensity, crop rotation, and biochar application on GHG and GWP in a rainfed wheat agroecosystem under arid and semi-arid conditions. However, the interactive effects of tillage intensity, crop rotation complexity, and biochar application on net GHG balance remain insufficiently quantified in semi-arid rainfed wheat systems. The objective of this study was to evaluate the short-term effects of tillage systems, crop rotations, and biochar application on soil organic carbon dynamics and net global warming potential in a semi-arid rainfed wheat system.

MATERIALS AND METHODS

Study Area Description

This study was conducted at the Agricultural and Natural Resources Research Center of East Azerbaijan Province, located in Khosroshahr (15 km southwest of Tabriz, Iran), at an elevation of 1338 m above sea level (37°58′ N, 46°03′ E). A cold semi-arid climate characterizes the region, and rainfed wheat production systems dominate local agriculture.

Field experiments were conducted over three consecutive growing seasons (2020-2023). Long-term (1990–2022) mean annual precipitation is approximately 310 mm, with the majority occurring during winter and early spring. Mean annual temperature is 11.2 °C.

Experimental Design and Field Management

The field experiment was arranged as a split–split plot design based on a randomized complete block design with three replications. Main plots (Tillage system) were conventional tillage (CT): moldboard plowing + disk harrowing, reduced tillage (RT): disk harrowing only, and no-tillage (NT): direct seeding. Subplots (Crop rotation) include continuous wheat (W–W–W), wheat–fallow–wheat (W–F–W), and wheat–grass pea–wheat (W–G–W). The Sub-subplots (Biochar rate) including 0, 5, and 10 t ha^{-1}. Each main plot was divided into subplots (8 m × 4 m), and sub-subplots measured 2 m × 4 m. To avoid cross-contamination, 1 m buffer zones were maintained between plots.

Biochar Production, Characteristics, and Application

Biochar was produced from dried pine needles at 400 °C under oxygen-limited conditions using a laboratory-scale pyrolysis system. This temperature was selected based on previous studies indicating low pH and EC at 400 °C (Reyhanitabar et al., 2020). The physicochemical characteristics of the pine needle biochar were determined at the Soil and Water Research Institute, Tehran, Iran. The carbon (C), hydrogen (H), and nitrogen (N) contents were analyzed using a CHNS/O elemental analyzer (2400 Series II CHNS/O Analyzer, Perkin-Elmer, USA) based on the combustion method. The oxygen content was calculated by difference after considering C, H, N, and ash contents. The atomic H/C ratio was calculated from elemental composition according to the method described by Lehmann and Joseph (2015). The ash content was determined according to ASTM D2866. The specific surface area (BET), pore volume (PV), and acidic surface functional groups (carboxylic, phenolic, and lactonic groups) were determined according to Cerato and Lutenegger (2002) and Song and Guo (2012). The cation exchange capacity (CEC), pH, and mineral elements (K, P, and Mg) were determined using standard laboratory procedures at the Soil and Water Research Institute. Table 1 and Figure 1 show the biochar characteristics and microscopic image, respectively.

Biochar was manually applied at designated rates (0, 5, and 10 t ha^{-1}) and incorporated into the top 0–30 cm soil layer within a 0.5 m × 0.5 m central area of each sub-subplot.

Initial soil conditions were: 45% clay, 47% silt, and 8% sand, SOC 0.63%, pH 7.5, bulk density 1.23 g cm^{-3}. Soil samples were collected from the 0–30 cm layer at the end of the third growing season. SOC and total nitrogen were analyzed using the Walkley–Black (Schumacher, 2002) and Kjeldahl (Bremner et al., 1982) methods, respectively. Bulk density was measured using the core method, and total porosity was calculated accordingly (Blake and Hartge, 1986). Soil moisture content was determined by oven-drying at 105 °C for 24 h.

Table 1. Pine needles biochar characteristics.

Parameter	C	H	O	N	Ash	K	P	Mg	MSR	pH	CEC	CFG	PFG	LFG	BET	PV
Unit			%				mg g^{-1} biochar				mmol kg^{-1} biochar		mmol g^{-1} biochar		m^2 g^{-1} biochar	cm^3 g^{-1} biochar
Value	78	0.8	12.5	0.23	8.47	12.6	4.20	13.0	1.2	6.74	12	1.63	0.67	0.016	11.5	0.06

C, H, O, and N represent carbon, hydrogen, oxygen, and nitrogen contents, respectively; K, P, and Mg represent potassium, phosphorus, and magnesium contents, respectively. Ash represents ash content. CEC represents cation exchange capacity. CFG, PFG, and LFG represent carboxylic, phenolic, and lactonic functional groups, respectively. BET represents specific surface area, PV represents pore volume, and MSR represents the matrix-to-surface-area ratio.

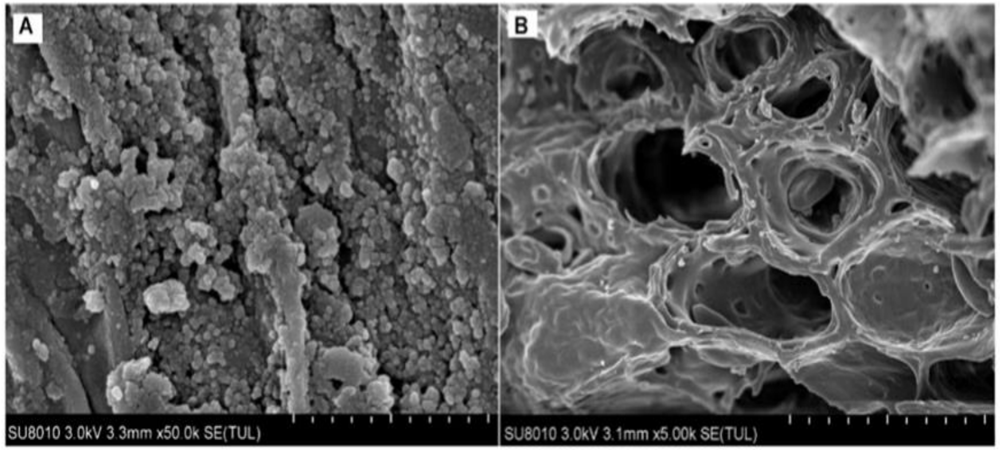

Figure 1. Scanning electron microscopy (SEM) images of the pine needle-derived biochar produced at 400 °C: (A) high magnification (×50,000) showing the porous surface structure, and (B) lower magnification (×500) displaying the overall morphology of the biochar particles

Mineral nitrogen (NH_4^+-N + NO_3^--N) was extracted from fresh soil samples using 2 M KCl (1:5 soil-to-solution ratio) and determined by the steam-distillation method.

Crop management and rotation implementation

Rainfed bread wheat (*Triticum aestivum* L.) cv. 'Varan', a high-yielding, early-maturing, and disease-resistant cultivar adapted to semi-arid cold environments, was grown as the main crop during the three-year experimental period (2020–2023). Wheat was sown at 20-cm row spacing and a depth of 3–5 cm on November 1 in each wheat-growing season. Nitrogen fertilizer was applied at a total rate of 40 kg N ha^{-1} in two equal applications at sowing and tillering, while phosphorus was applied at 15 kg P ha^{-1} at land preparation. A single supplementary irrigation was applied at sowing to ensure uniform crop emergence.

Three crop rotations were evaluated: continuous wheat (W–W–W), wheat–fallow–wheat (W–F–W), and wheat–grass pea–wheat (W–G–W). In the W–W–W rotation, wheat was grown in each of the three consecutive growing seasons. In the W–F–W rotation, wheat was grown in the first and third seasons, while the intervening second season was maintained as fallow. In the W–G–W rotation, wheat was grown in the first and third seasons, whereas a locally adapted ecotype of grass pea (*Lathyrus sativus* L.) was grown only during the second season. Thus, the rotation phases were implemented sequentially within the same experimental plots rather than being spatially staggered among neighboring plots.

Grass pea was sown on November 11 and was harvested at maturity in late May to early June. The harvested grass pea biomass was removed from the plots and was not incorporated into the soil. This residue management was maintained to avoid additional soil disturbance, particularly under no-tillage conditions.

Wheat harvest dates varied among years and treatments because the imposed tillage, crop rotation, and biochar treatments affected crop phenology and maturity. Therefore, wheat was harvested over a range of dates rather than on a single fixed date, generally from late June to late July. These differences in harvest timing were considered part of the treatment responses rather than a variation in the experimental protocol.

Weed management was conducted throughout the experimental period in wheat, fallow, and grass pea phases to minimize weed interference among treatments. Crop management practices were kept consistent among treatments except for the imposed tillage, crop-rotation, and biochar treatments.

Estimation of GHG emissions

GHG emissions from agricultural soils were estimated using an emission-factor-based approach following the Intergovernmental Panel on Climate Change (IPCC) guidelines, which are widely used when direct field measurements are unavailable. This approach enables consistent, transparent estimation of GHG fluxes across different management systems. It has been widely used in comparative assessments of tillage systems, crop rotations, and soil amendments such as biochar.

In the present study, nitrous oxide (N_2O) emissions were estimated based on mineral nitrogen availability and management-specific emission factors. In contrast, carbon dioxide (CO_2) emissions were incorporated indirectly through changes in SOC stocks. Methane (CH_4) emissions were assumed to be negligible due to the rainfed and non-flooded nature of the cropping system. N_2O emissions were estimated using the default emission factor (EF) approach recommended by the Intergovernmental Panel on Climate Change (IPCC). Accordingly, annual N_2O–N emissions (kg N ha^{-1}) were calculated by multiplying the amount of mineral nitrogen input by the emission factor. The resulting N_2O–N values were converted to N_2O emissions using a molecular weight conversion factor (44/28), and subsequently expressed in CO_2 equivalents by applying a GWP of 298 over a 100-year time horizon (Baasansuren et al., 2019).

Equation 1 $$N_2O - N(kg\ N\ ha^{-1}) = N_{mineral} \times EF$$

Where $N_{mineral}$ is mineral nitrogen input (kg N ha^{-1}) and EF is the direct N_2O emission factor. The default IPCC EF (0.01 kg N_2O-N kg^{-1} N) was adjusted to represent treatment-specific differences in N_2O emission potential associated with tillage intensity, crop rotation, and biochar application. These adjustments were based on reported effects of conservation tillage, legume-based rotations, and biochar amendment on soil nitrogen cycling and N_2O emissions (Cayuela et al., 2014; Rochette, 2008; van Kessel et al., 2012).

Accordingly, management-adjusted EF values were assigned for each tillage × crop rotation × biochar combination. The applied EF values ranged from 0.007 to 0.018 kg N_2O-N kg^{-1} N and are presented in Table 2Table 2. Management-adjusted emission factors (EF) used for estimating N_2O emissions under different tillage systems, crop rotations, and biochar application rates.. Compared with the default IPCC EF, lower values were assigned to biochar-amended treatments due to reduced N_2O emission potential, whereas higher values were assigned to systems with greater disturbance intensity or increased nitrogen availability. These treatment-specific EFs were subsequently used for calculating annual N_2O emissions and their CO_2-equivalent values.

Only direct N_2O emissions were estimated in this study, following the IPCC Tier 1 methodology (IPCC, 2006; 2019 Refinement). Indirect N_2O emissions arising from nitrogen leaching, runoff and atmospheric deposition were not quantified, because reliable site-specific values for the leaching fraction and volatilization fractions were not available for the rainfed semi-arid conditions of the experimental site. Consequently, the reported GWP_{N_2O} values represent direct emissions only.

Table 2. Management-adjusted emission factors (EF) used for estimating N_2O emissions under different tillage systems, crop rotations, and biochar application rates.

Tillage system	Crop rotation	Biochar (t ha^{-1})	Emission factor (EF)
No-tillage (NT)	W–W–W	0	0.009
NT	W–W–W	5, 10	0.007
NT	W–F–W	0	0.011
NT	W–F–W	5, 10	0.008
NT	W–G–W	0	0.012
NT	W–G–W	5, 10	0.009
Reduced tillage (RT)	W–W–W	0	0.011
RT	W–W–W	5, 10	0.008
RT	W–F–W	0	0.013
RT	W–F–W	5, 10	0.009
RT	W–G–W	0	0.014
RT	W–G–W	5, 10	0.010
Conventional tillage (CT)	W–W–W	0	0.015
CT	W–W–W	5, 10	0.010
CT	W–F–W	0	0.017
CT	W–F–W	5, 10	0.011
CT	W–G–W	0	0.018
CT	W–G–W	5, 10	0.012

N_2O–N emissions were converted to N_2O gas using the molecular weight ratio:

Equation 2

$$N_2O = N_2O - N \times \frac{44}{28}$$

Finally, N_2O emissions were converted to CO_2-equivalents using a 100-year global warming potential of 298 (IPCC AR4):

Equation 3

$$GWP_{N_2O} = N_2O \times 298$$

Direct CO_2 emissions from soil respiration and management operations were not estimated separately. Instead, net CO_2 exchange was quantified from changes in SOC stocks (ΔSOC) in accordance with IPCC good-practice guidelines. Changes in SOC represent the net balance between carbon inputs (crop residues, root biomass, and biochar additions) and carbon losses through microbial decomposition and mineralization.

The ΔSOC values (t C ha^{-1}) were converted to CO_2-equivalents using a molecular conversion factor (44/12) and incorporated into the net global warming potential (GWP_{net}). Negative ΔSOC values indicate estimated net carbon accumulation and result in a reduction of GWP, whereas positive values represent net carbon losses to the atmosphere.

Global Warming Potential (GWP)

GWP indices were calculated to integrate the combined climate impacts of estimated GHG emissions across different management scenarios and enable direct comparisons among tillage systems, crop rotations, and biochar application rates. All GWP indices were expressed as CO_2-equivalents using 100-year time horizon characterization factors in accordance with IPCC guidelines. Carbon dioxide emissions from field operations (CO_2 operations) were estimated based on diesel fuel consumption for different tillage systems.

Equation 4 $$\boldsymbol{CO_{2_{opetation}} = Fuel\ use\ (t\ ha^{-1}) \times \mathrm{EF_{diesel}}}$$

CO_2 operations were estimated from diesel fuel consumption using representative, conservative rates of 65, 40, and 20 L ha^{-1} for conventional, reduced, and no-tillage systems, respectively. These rates were not measured directly during the experiment but were selected to represent the relative operational intensity of the three tillage systems. The assumed values were slightly higher than fuel-use rates reported under Iranian field conditions by Akbarnia and Farhani (2014), who reported 59.33, 29.67, and 14.33 L ha^{-1} for conventional, reduced, and no-tillage systems, respectively. The higher rates adopted here were intended to conservatively account for differences in field conditions, soil resistance and compaction, machinery characteristics, and the number and duration of field operations, all of which can affect tractor fuel requirements (Akbarnia and Farhani, 2014). CO_2 emissions from diesel combustion were subsequently estimated using an emission factor of 2.68 kg CO_2 L^{-1} diesel. These emissions were included in the calculation of field-scale global warming potential (GWP_{field}) (IPCC, 2006).

Equation 5 $$\boldsymbol{GWP_{field} = GWP_{N_2O} + CO_{2_{operation}}}$$

In this study, the climate mitigation effect of biochar was accounted for through changes in SOC stocks (ΔSOC) and indirect effects on N_2O emissions. Emissions associated with biochar production and energy substitution were not included, as the analysis focused on field-scale GWP rather than a full life cycle assessment.

ΔSOC was calculated as the difference in final SOC stock between each management combination and a reference treatment (Conventional Tillage × Continuous Wheat × 0 t ha^{-1} biochar), which had a final SOC stock of 19.5 t C ha^{-1}. This reference treatment was selected because it represents the conventional management system widely practiced in the study region and maintained an SOC stock essentially identical to the initial field-average value (0.63% SOC, bulk density 1.23 g cm^{-3}, 0–30 cm depth). Consequently, the calculated ΔSOC values represent relative differences in final SOC stocks among treatments rather than absolute temporal changes from a plot-specific pre-experiment baseline. No plot-level initial SOC measurements were available. ΔSOC was calculated as Equation 6.

Equation 6 $$\Delta SOC = SOC_{scenario} - SOC_{S19}$$

where SOC_{S19} is the final SOC stock of the reference treatment (19.5 t C ha^{-1}).

A negative ΔSOC indicates that the treatment accumulated more carbon than the reference treatment (higher final SOC stock), while a positive ΔSOC indicates a lower final SOC stock relative to the reference.

The corresponding CO_2-equivalents were then calculated using a molecular weight conversion factor of 44/12 (3.67) (Equation 7).

Equation 7 $$CO2 - eq_{\Delta SOC} = \Delta SOC \times 3.67 \times 1000$$

Negative ΔSOC values indicate a higher final SOC stock relative to the reference treatment (estimated net carbon accumulation relative to the reference), while positive values indicate a lower final SOC stock.

Net global warming potential (GWP_{net}) was calculated by incorporating changes in SOC stocks (ΔSOC) into the GWP_{field} as equation 8.

Equation 8 $$GWP_{net} = GWP_{field} + GWP_{Seq}$$

ΔSOC were converted to CO_2-equivalents using a molecular conversion factor of 44/12 and added to GWP_{field} to obtain GWP_{net}. Negative ΔSOC values indicate estimated net carbon accumulation and reduce GWP_{net}, whereas positive values represent net carbon losses and increase the overall warming potential.

To evaluate GHG emissions relative to agricultural productivity, the carbon footprint of wheat grain was calculated by normalizing net GWP by grain yield as equation 9:

Equation 9 $$GWP_{Yield-scaled} = \frac{GWP_{net}}{Grain\ yield\ (kg\ ha^{-1})}$$

This indicator is particularly useful for evaluating the short- to medium-term climate impacts of fertilizer management, tillage intensity, and crop rotation at the field scale (Linquist et al., 2012).

Statistical analysis

Statistical analyses were performed using R software (version 4.3.1). A linear mixed-effects model was fitted using the `lme4` package to account for the split-split plot structure, with tillage, crop rotation, biochar rate, and their interactions as fixed effects and block and the corresponding experimental strata as random effects. Because GWPnet is a derived index (calculated from emission-factor estimates and final SOC stocks) and strongly violated normality assumptions (Shapiro–Wilk test, $p < 0.05$), differences among levels of the main factors were evaluated using the non-parametric Kruskal–Wallis test followed by Dunn's post-hoc test with Bonferroni correction. A full factorial non-parametric analysis that fully respects the split-split plot structure was not feasible with the available sample size; therefore only main-effect results are reported for GWP_{net}. The complete linear mixed-effects model (including all interactions and appropriate error strata) was applied to the directly measured variables (SOC stock, mineral nitrogen and grain yield).

To evaluate the robustness of the results to the choice of emission factors, sensitivity analyses were performed using the default IPCC Tier 1 emission factor (EF = 0.01 kg N_2O-N kg^{-1} N) without management adjustments, and ±30% variation around the management-adjusted EFs.

RESULTS

SOC and mineral N

The interaction of tillage system, crop rotation, and biochar application rate significantly affected SOC stock and mineral nitrogen. Across all tillage systems, SOC stock generally increased with increasing biochar rate. Under no-tillage, SOC interval was 23.25 to 28.70 t C ha^{-1} across rotations, 21.21–27.22 and 19.50–25.20 t C ha^{-1} under reduced tillage and conventional tillage, respectively (Table 3).

Table 3. SOC stock, mineral nitrogen, and grain yield in year 3 of the experiment across tillage system × crop rotation × biochar.

Tillage systems	Crop rotation	Biochar t ha^{-1}	SOC stock t C ha^{-1}	Mineral N (kg ha^{-1})	Grain yield (t ha^{-1})
No Tillage	Wheat- Wheat-Wheat	0	23.31	46.6	0.776
		5	26.16	32.5	0.74
		10	28.7	27.8	0.733
	Wheat- Fallow-Wheat	0	23.25	46.5	1.21
		5	26.7	31.8	1.25
		10	28.6	27.5	1.24
	Wheat – Grass pea- Wheat	0	23.43	46.9	1.33
		5	26.8	32.1	1.33
		10	28.63	28.2	1.35
Reduced Tillage	Wheat- Wheat-Wheat	0	21.78	43.6	0.7
		5	24.7	29.5	0.716
		10	26.57	26.1	0.74
	Wheat- Fallow-Wheat	0	21.22	42.5	1.8
		5	23.4	30.2	1.83
		10	27.22	26.8	1.87
	Wheat – Grass pea- Wheat	0	21.21	42.4	1.67
		5	23.2	29.8	1.68
		10	26.81	26.4	1.94
Conventional Tillage	Wheat- Wheat-Wheat	0	19.5	39.0	0.67
		5	22.7	25.8	0.6
		10	23.4	23.9	0.7
	Wheat- Fallow-Wheat	0	19.55	39.1	1.56
		5	24.1	27.5	1.58
		10	25.2	24.5	1.6
	Wheat – Grass pea- Wheat	0	19.65	39.3	1.4
		5	22.84	26.9	1.44
		10	24.81	24.2	1.61
	LSD		1.45	3.5	0.15

In contrast, mineral N consistently declined with biochar application across all tillage systems and crop rotations. Mineral N was generally lower in biochar-amended treatments than in the corresponding controls, with the greatest reductions observed at 10 t ha^{-1} biochar. These results indicate that biochar application reduced soil mineral N availability while increasing SOC stocks across management combinations.

Wheat seed yield

Across all tillage systems, continuous wheat monoculture produced the lowest grain yield. Also, the highest grain yield was obtained from reduced-tillage management, followed by conventional tillage. Increasing the biochar rate and adopting fallow or grass pea cultivation instead of successive wheat cultivation across all three tillage systems was associated with higher yields (Table 3).

GWP_{N_2O}, GWP_{field}, and Soil carbon stock changes

GWP_{N_2O} constituted a major component of field-scale emissions. Estimated GWP_{N_2O} (148 to 343 kg CO_2-eq ha^{-1}), with the lowest values generally observed under no-tillage systems with biochar application and the highest under conventional tillage, particularly in diversified rotations (Table 4). Identical GWP_{N_2O} values at 5 and 10 t ha^{-1} biochar within the same tillage × rotation combinations resulted from the application of the same adjusted EF at both rates. GWP_{field} (188.6 to 517.2 kg CO_2-eq ha^{-1}) in conservation-oriented systems (NT and RT with biochar) showed substantially lower GWP_{field} than conventional tillage without biochar. Across tillage systems, GWP_{field} decreased with declining soil disturbance (Table 4). Soil carbon stocks ranged from 19.5 to 28.7 t C ha^{-1}. Changes in SOC (ΔSOC) were 0 to -9.2 t C ha^{-1}, corresponding to CO_2-equivalents of up to approximately -11255 kg CO_2-eq ha^{-1}.

Net global warming potential (GWP_{net})

GWP_{net} ranged from -11053 to +466 kg CO_2-eq ha^{-1}. Most treatments (23 of 27) exhibited negative GWP_{net} values, indicating that estimated net carbon accumulation outweighed field emissions. The highest value (+466 kg CO_2-eq ha^{-1}) occurred under conventional tillage with continuous wheat and no biochar, whereas the lowest value (-11053 kg CO_2-eq ha^{-1}) was observed under no-tillage with continuous wheat and 10 t ha^{-1} biochar.

Table 4. GWPs (kg CO_2-eq ha^{-1}) and Yield-scaled GWP (kg CO_2-eq t^{-1} grain) across Tillage × Crop rotation × Biochar

Tillage systems	Crop rotation	Biochar t ha^{-1}	$GWP_{(N2O)}$	GWP_{field}	CO_2-eq ΔSOC	GWP_{net}	$GWP_{(Yield-scaled)}$
No Tillage	Wheat-Wheat-Wheat	0	218	272	-4661	-4389	-5.66
		5	148	202	-8147	-7945	-10.74
		10	148	202	-11255	-11053	-15.08
	Wheat-Fallow-Wheat	0	246	300	-4588	-4288	-3.54
		5	150	204	-8808	-8604	-6.88
		10	150	204	-11132	-10928	-8.81
	Wheat – Grass pea-Wheat	0	263	317	-4808	-4491	-3.38
		5	169	223	-8930	-8707	-6.55
		10	169	223	-11169	-10946	-8.11
Reduced Tillage	Wheat-Wheat-Wheat	0	245	352	-2789	-2437	-3.48
		5	150	257	-6361	-6104	-8.53
		10	150	257	-8649	-8392	-11.34
	Wheat-Fallow-Wheat	0	264	371	-2104	-1733	-0.96
		5	169	276	-4771	-4495	-2.46
		10	169	276	-9444	-9168	-4.90
	Wheat – Grass pea-Wheat	0	277	384	-2092	-1708	-1.02
		5	183	290	-4526	-4236	-2.52
		10	183	290	-8943	-8653	-4.46
Conventional Tillage	Wheat-Wheat-Wheat	0	292	466	0	466	0.70
		5	169	343	-3915	-3572	-5.95
		10	169	343	-4771	-4428	-6.33
	Wheat-Fallow-Wheat	0	336	510	-61	449	0.29
		5	195	369	-5627	-5258	-3.33
		10	195	369	-6973	-6604	-4.13
	Wheat-Grass pea-Wheat	0	343	517	-183	334	0.24
		5	225	399	-4086	-3687	-2.56
		10	225	299	-6496	-6197	-3.85

According to Table 5, GWP_{net} decreased significantly with decreasing tillage intensity ($p < 0.001$), while crop rotation ($p < 0.01$) and biochar application ($p < 0.001$) also significantly affected GWP_{net}. The 10 t ha^{-1} biochar rate produced the lowest net emissions through reduced N_2O emissions and increased ΔSOC.

Table 5. Median and interquartile range (IQR) of GWPs (**kg CO_2-eq ha^{-1}**) for different tillage systems, biochar rate (t ha^{-1}) across 27 managements.

Managements	GWPs									
	$GWP_{(N_2O)}$		GWP_{field}		CO_2-eq-ΔSOC		GWP_{net}		Yield scaled GWP	
Tillage system	Median	IQR	Median	IQR	Median	IQR	Median	IQR	Median	IQR
No-tillage	165	98b	220	105b	-9930	3850c	-8710	3920c	-6.52	5.3**a**
Reduced tillage	180	112b	287	128b	-4771	4320b	-4498	4680b	-3.45	4.2**b**
Conventional tillage	222	145a	396	162a	-4086	4150a	-3690	4880a	-3.30	3.85**c**
Biochar rate t ha^{-1}										
0	260	138a	368	155a	-2104	2780a	-1740	2980a	-1.00	2.90c
5	167	45b	274	68b	-5627	3650b	-5265	3810b	-3.82	3.75b
10	167	42b	274	72b	-8943	3950c	-8670	4150c	-6.30	5.55a
Crop rotation										
Wheat- Wheat- Wheat	167	98b	257	135b	-6361	4850b	-6104	5720b	-6.95	7.25a
Wheat- Fallow- Wheat	195	105ab	319	148a	-5627	4680a	-5258	5410a	-3.54	4.35**b**
Wheat- Grass pea- Wheat	225	132a	343	165a	-4808	4920a	-4491	5890a	-3.38	4.1**b**

Different letters within each management factor indicate significant differences according to the Kruskal–Wallis test followed by Dunn's post-hoc test ($p < 0.05$).
Kruskal–Wallis p-values: Tillage system ($p < 0.001$), Biochar rate ($p < 0.001$), Crop rotation ($p < 0.01$).

Uncertainty and sensitivity analysis

As shown in Table 6, the absolute values of GWP_{net} varied across scenarios, but the overall ranking of treatments remained consistent. No-tillage combined with 10 t ha⁻¹ biochar consistently produced the most negative GWP_{net} values across all scenarios. This confirms the robustness of the main conclusions.

Table 6. Sensitivity analysis of net global warming potential (GWP_{net}, kg CO_2-eq ha^{-1}) under different emission factor scenarios for all 27 treatments.

Tillage System	Crop Rotation	Biochar (t ha^{-1})	GWP_{net} (EF = 0.01)	GWP_{net} (EF -30%)	GWP_{net} (EF +30%)
No-tillage	Wheat-Wheat-Wheat	0	−4389	−4454	−4324
		5	−7945	−7989	−7901
		10	−11053	−11097	−11009
	Wheat-Fallow-Wheat	0	−4288	−4362	−4214
		5	−8604	−8649	−8559
		10	−10928	−10973	−10883
	Wheat – Grass pea-Wheat	0	−4491	−4570	−4412
		5	−8707	−8758	−8656
		10	−10946	−10997	−10895
Reduced tillage	Wheat-Wheat-Wheat	0	−2437	−2510	−2364
		5	−6104	−6149	−6059
		10	−8392	−8437	−8347
	Wheat-Fallow-Wheat	0	−1733	−1812	−1654
		5	−4495	−4546	−4444
		10	−9168	−9219	−9117
	Wheat – Grass pea-Wheat	0	−1708	−1791	−1625
		5	−4236	−4291	−4181
		10	−8653	−8708	−8598
Conventional tillage	Wheat-Wheat-Wheat	0	**+466**	**+378**	**+554**
		5	−3572	−3623	−3521
		10	−4428	−4479	−4377
	Wheat-Fallow-Wheat	0	**+449**	**+348**	**+550**
		5	−5258	−5317	−5199
		10	−6604	−6663	−6545
	Wheat – Grass pea-Wheat	0	**+334**	**+231**	**+437**
		5	−3687	−3755	−3619
		10	−6197	−6265	−6129

DISCUSSION

SOC and mineral N

Our observations on SOC and nitrogen stock changes by management are consistent with meta-analytical evidence indicating substantial SOC and nitrogen losses under long-term conventional management in semi-arid agroecosystems (de Souza Medeiros et al., 2023). The observed increase in SOC under no-tillage compared with conventional tillage aligns with evidence that reduced soil disturbance enhances carbon stabilization by minimizing aggregate disruption and oxidation losses (Six et al., 2004; Lal, 2004). Conservation tillage promotes physical protection of organic matter within aggregates, thereby improving carbon change. However, given the relatively short experimental duration (three growing seasons), the SOC stock differences should be interpreted as short-term responses rather than confirmed long-term change.

The significant reduction in mineral N following biochar application across all tillage and rotation treatments is consistent with biochar's high C ratio. Biochars typically contain highly aromatic carbon with limited nitrogen content, stimulating microbial immobilization of inorganic nitrogen and temporarily reducing soil ammonium and nitrate concentrations (Clough and Condron, 2010). This effect has been widely reported in meta-analyses, particularly during the initial stages after application (Jeffery et al., 2011; Nguyen et al., 2017). In addition, adsorption of ammonium (NH_4^+) onto biochar surfaces and retention within pore structures may further reduce extractable mineral N pools (Lehmann and Joseph, 2024).

The consistency of mineral N reduction across tillage systems suggests that biochar exerted a stronger influence than tillage on short-term nitrogen dynamics. Reduced mineral N availability may also partially explain the relatively minor contribution of N_2O-derived GWP, since lower substrate availability limits nitrification and denitrification processes (Bashmakov et al., 2022). Overall, these findings demonstrate that biochar acts as a carbon-enriching but nitrogen-immobilizing amendment across contrasting tillage intensities and crop rotations.

Grain yield response

The higher grain yield generally observed under reduced tillage compared with no-tillage may reflect a balance between soil disturbance and soil water conservation. While no-tillage reduced soil disturbance and improved soil carbon status, the absence of soil loosening may have limited early-season soil warming, root-zone aeration, and nutrient availability under the semi-arid conditions of the study. Reduced tillage may therefore have provided a more favorable balance between soil moisture conservation and root-zone conditions, resulting in higher grain yield. The response to biochar also varied among crop rotations. Under no-tillage with continuous wheat, biochar application slightly reduced grain yield, whereas under reduced tillage with W–G–W, the 10 t ha^{-1} rate increased yield substantially. This contrasting response may reflect differences in residue quality, nitrogen availability, and soil–plant interactions associated with crop rotation. In the continuous wheat system, the relatively high C:N ratio of biochar may have temporarily increased microbial N immobilization and limited mineral N availability, potentially constraining crop growth. In contrast, the inclusion of grass pea may have improved N availability and residue quality, allowing the soil-conditioning effects of biochar to translate into greater crop productivity under reduced tillage. These results indicate that the productivity response to biochar was strongly dependent on the interaction between tillage system and crop rotation rather than being consistent across management systems.

GWP_{N_2O}, GWP_{field} and Soil carbon stock changes

Estimated N_2O emissions contributed between 135 and 343 kg CO_2-eq ha^{-1} to GWP_{field}. These values fall within the range reported for rainfed cereal systems using IPCC Tier 1 methodology with management adjustments (IPCC, 2006; Shcherbak et al., 2014). Conservation tillage and biochar application reduced N_2O-derived GWP, whereas legume-inclusive rotations slightly increased it through enhanced nitrogen cycling. However, these increases were small relative to the carbon accumulation benefits, emphasizing the importance of evaluating mitigation on a net basis rather than by individual gas components.

The reduction in GWP_{field} agrees with findings of Cayuela et al. (2014), who reported average N_2O emission reductions of 30–50% following biochar application. Likewise, lower GHG emissions under conservation tillage than conventional tillage have been widely documented (Zhang et al., 2016). Reduced tillage likely limited soil disturbance and mineralization, while biochar effects were associated with improved aeration, altered microbial activity, and increased nitrogen immobilization. The pine-needle biochar used in this study had a slightly acidic pH (6.74), in contrast to the alkaline biochars commonly reported in the literature. Given the initial soil pH of 7.5, this biochar was unlikely to have substantially increased soil pH. Therefore, the observed reduction in estimated N_2O emissions under biochar treatments was more likely attributable to nitrogen immobilization (high C:N ratio), improved aeration, and sorption of inorganic N, rather than a liming effect (Cayuela et al., 2014).

The magnitude of CO_2-eq from SOC changes exceeded GWP_{field} in most treatments, indicating that soil carbon accumulation dominated the GHG balance. According to IPCC (2021), annual estimated net carbon accumulation rates of 0.3–1.0 t C ha^{-1} are common in conservation systems, and the SOC gains observed here fall within the upper reported range for semi-arid cereal systems. As estimated by Smith et al. (2008), accumulation of 1 t C ha^{-1} offsets approximately 3.67 t CO_2, highlighting the climate significance of SOC accumulation.

SOC accumulation under conservation tillage and diversified rotations was likely driven by greater residue retention, reduced oxidation of organic matter, and improved aggregate stability. Biochar further enhanced SOC storage through the addition of recalcitrant carbon and promotion of organo-mineral stabilization processes.

It should be noted that the largest relative differences in final SOC stock (up to 9.2 t C ha^{-1}) were observed in treatments receiving 10 t ha^{-1} biochar. Given that the pine-needle biochar contained 78% C, this application rate introduced approximately 7.8 t C ha^{-1} of exogenous carbon. Therefore, the majority of the observed increase in final SOC stock under high biochar rates is attributable to the direct addition of biochar-C. The residual difference may reflect reduced mineralization and greater residue retention under reduced and no-tillage systems; however, longer-term measurements would be required to confirm the permanence of these differences.

The identical estimated GWP_{N_2O} values observed at 5 and 10 t ha^{-1} biochar reflect the stabilization threshold applied in the emission factor adjustment rather than the absence of biochar effects at the higher rate. Biochar can reduce N_2O production by promoting microbial immobilization of mineral N through its high C:N ratio, reducing the availability of mineral N for nitrification and denitrification. In addition, mineral N adsorption and changes in soil microbial processes may contribute to reduced N_2O emissions. However, these effects may not increase proportionally with increasing biochar rates; therefore, the present estimation framework assumed no additional reduction in the adjusted EF beyond 5 t ha^{-1} biochar.

Methane (CH_4) was considered negligible in the present study because the rainfed wheat system was non-flooded and predominantly aerobic, conditions that generally limit methanogenesis. However, well-aerated upland soils can act as net CH_4 sinks through oxidation by methanotrophic microorganisms, and this uptake may be enhanced under no-tillage through changes in soil structure and microbial activity. Nevertheless, global evidence indicates that the effect of no-tillage on CH_4 fluxes in dryland agroecosystems is generally small or inconsistent (Maucieri et al., 2021). Therefore, CH_4 uptake was not included as a separate component of the estimated GHG balance, consistent with the non-flooded conditions of the present rainfed system.

Net global warming potential *(*GWP_{net}*)*

The lowest estimated GWP_{net} occurred under no-tillage with 10 t ha^{-1} biochar, whereas the highest value was observed under conventional tillage with continuous wheat and no biochar.

These findings demonstrate that integrated conservation practices can substantially improve the estimated GHG balance of rainfed wheat systems.

The shift in estimated GWP_{net} from +466 to -11053 kg CO_2-eq ha^{-1} indicates a transition from a calculated net GHG source to a calculated net sink. Similar mitigation effects of biochar and conservation tillage have been reported by Cayuela et al. (2014) and Zhang et al. (2016). The magnitude of mitigation observed here suggests strong complementary effects between reduced soil disturbance and stable carbon additions.

Negative GWP_{net} values were primarily driven by SOC accumulation. Consistent with Powlson et al. (2011, 2014) and Houghton (2014), the results indicate that excluding SOC changes would substantially overestimate the climate impact of agricultural systems. Reduced soil disturbance promotes aggregate stability, protects organic matter from oxidation, and enhances carbon retention, causing the SOC contribution to outweigh differences in estimated N_2O emissions.

Yield-scaled estimated GWP further confirmed the climate benefits of conservation management. Negative values indicate that grain production was associated with a calculated net atmospheric CO_2 removal. Although reduced tillage generally produced the highest yields, no-tillage combined with biochar achieved the lowest carbon footprint per unit grain. These findings support previous studies showing that yield-scaled metrics provide a more comprehensive assessment of mitigation efficiency than yield or emissions alone (Burney et al., 2010).

Biochar emerged as a major contributor to climate mitigation by simultaneously increasing stable soil carbon and reducing emission intensity. Consistent with Jeffery et al. (2011) and Woolf et al. (2010), the combined effects of carbon accumulation and lower field emissions produced substantial reductions in GWP_{net}. Overall, the results demonstrate that under rainfed wheat systems, the mitigation benefit of conservation management is driven predominantly by enhanced soil carbon changes rather than large reductions in direct N_2O emissions.

The observed reductions in GWP_{net} under no-tillage and biochar application are consistent with meta-analyses reporting mitigation benefits from conservation agriculture and biochar (Cayuela et al., 2014; Sainju, 2016; Amirahmadi et al., 2025). However, the magnitude of mitigation in the present study is more conservative than some earlier reports, primarily because management-specific emission factors were adjusted based on field-relevant meta-analyses rather than maximum reported reductions. Therefore, the estimated GWP_{net} values should be interpreted as comparative indicators of the relative climate performance of the management systems rather than as direct measurements of field greenhouse gas fluxes. The emission-factor-based approach introduces uncertainty related to the emission factors and their management-specific adjustments, and direct field measurements would be required to validate the absolute magnitude of the estimated emissions.

Study limitations

Several limitations should be considered when interpreting the results of this study. First, greenhouse gas emissions were estimated using management-adjusted IPCC emission factors rather than direct field measurements, which introduces a degree of uncertainty. Second, the experiment was conducted over only three growing seasons at a single location, limiting the extrapolation of findings to longer-term and multi-site conditions. Third, the analysis was restricted to field-scale impacts and did not include emissions associated with biochar production and transport. Finally, although substantial increases in soil organic carbon stocks were observed, their long-term stability remains to be verified. Given the relatively short experimental period, the observed increases in SOC should be interpreted as short- to medium-term carbon accumulation rather than confirmed long-term sequestration. Longer-term monitoring is therefore required to confirm the permanence of these changes.

CONCLUSIONS

Tillage system, crop rotation, and biochar application significantly influenced soil carbon status and the estimated GHG balance of rainfed wheat systems. Differences in soil carbon accounted for most of the variation in GWP_{net} among treatments. Conservation-based practices, particularly reduced soil disturbance and biochar application, generally improved environmental performance while maintaining grain productivity. These findings suggest that integrating soil carbon assessments with GHG balance estimates can support the evaluation of sustainable management strategies in semi-arid rainfed agroecosystems.

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اثرات تلفیقی خاک‌ورزی، تناوب زراعی و بیوچار بر پتانسیل گرمایش جهانی خالص برآوردشده دربوم نظام گندم دیم

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چکیده

عملیات مدیریتی مبتنی بر حفاظت از منابع، از جمله کاهش به‌هم‌خوردگی خاک، تنوع‌بخشی به تناوب‌های زراعی و کاربرد بیوچار، به‌عنوان رویکردهای بالقوه برای کاهش اثرات زیست‌محیطی نظام‌های تولید غلات به‌طور فزاینده‌ای مورد توجه قرار گرفته‌اند. در این پژوهش اثرات سیستم خاک‌ورزی، تناوب زراعی و کاربرد بیوچار بر کربن خاک و بیلان گازهای گلخانه‌ای برآوردی در یک بوم‌نظام گندم دیم در خسروشهر، شمال‌غرب ایران ارزیابی شد. آزمایش به‌صورت اسپلیت‌اسپلیت‌پلات طی یک دوره سه‌ساله زراعی (۱399–۱402) با سه سیستم خاک‌ورزی، شامل خاک‌ورزی مرسوم، خاک‌ورزی کاهش‌یافته و بدون خاک‌ورزی، سه تناوب زراعی (کشت پیاپی گندم، گندم–آیش–گندم و گندم–خلر–گندم) و سه سطح بیوچار (۰، ۵ و ۱۰ تن در هکتار) انجام شد. اثرات اقلیمی با استفاده از ضرایب انتشار سطح ۱ IPCC همراه با تعدیل‌های مدیریتی محاسبه گردید. عملیات مدیریتی تأثیر معنی‌داری بر کربن آلی خاک، عملکرد دانه و بیلان گازهای گلخانه‌ای برآوردی داشت. کربن آلی خاک از 19/5 تا 28/7 تن کربن در هکتار متغیر بود، در حالی که پتانسیل گرمایش جهانی خالص برآوردی (GWP_{net}) از ۱۱۰۵۳- تا ۴۶۶+ کیلوگرم معادل CO_2 در هکتار در بین تیمارها تغییر کرد. سیستم‌های مبتنی بر حفاظت، به‌ویژه ترکیب بدون خاک‌ورزی و خاک‌ورزی کاهش‌یافته با کاربرد بیوچار، عموماً مقادیر منفی‌تری از *GWPnet* برآوردی نسبت به سیستم‌های خاک‌ورزی مرسوم ایجاد کردند.