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RESEARCH ARTICLE

Greenhouse gas emissions from cassava production influenced by 47 years of diverse fertilizer application practices in Thailand: insights from two years of measurements

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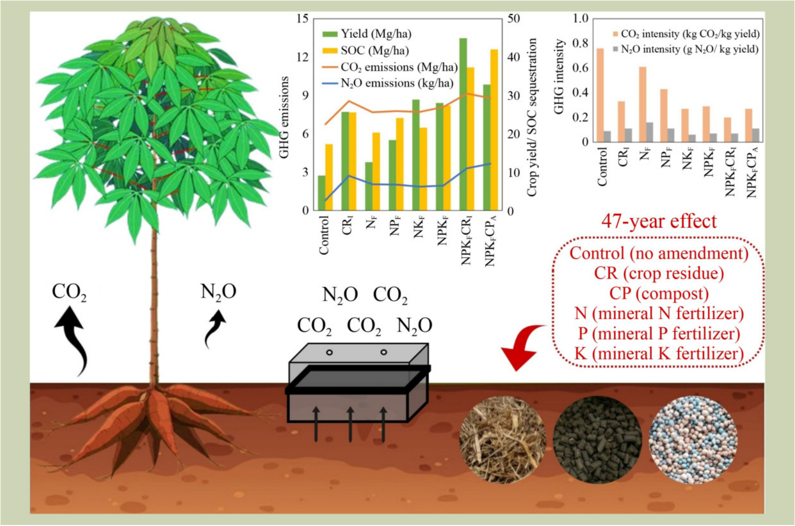
KEYWORDS

Fertilizer management, food crops, greenhouse gas mitigation, soil management, tropical soils

HIGHLIGHTS

- A 47-year field trial on cassava production was evaluated by this study.
- Average direct N_2O emission factor (0.68%) from cassava production under diverse fertilizer application is lower than that of mineral N fertilizer alone (0.75%).
- Mineral fertilizers induced higher N_2O emissions compared to organic amendments.
- *Nitrososphaera* and *Nitrospira* were the predominant genera contributing to N_2O emissions.
- NPK fertilizers combined with crop residues achieved the lowest GHG emissions per yield.

GRAPHICAL ABSTRACT



ABSTRACT

Greenhouse gas (GHG) emissions and their mitigation in food crop production, particularly in tropical regions such as Thailand, remain a knowledge gap in

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advancing sustainable agricultural systems. This study used a 47-year field experiment to assess the effects of diverse fertilizer application practices on GHG emissions, soil properties and cassava yield. The results revealed that carbon inputs from crop residues (CR) and compost (CP) significantly elevated carbon dioxide emissions, primarily due to enhanced soil microbial respiration. Nitrogen applications, whether from mineral or organic sources, significantly stimulated nitrous oxide (N_2O) emissions, with greater N inputs leading to higher N_2O releases. At equivalent N application rates, mineral N fertilizers induced greater N_2O emissions, having a mean emission factor (EF) of 0.75% compared to CR-derived N with an EF of 0.56%. Additionally, mineral fertilizers led to soil acidification and nutrient accumulation. CR and CP inputs increased soil organic carbon stocks by 42.1% and 53.3%, respectively, relative to the control. CP addition also improved soil pH and significantly enhanced phosphorus and potassium availability. Notably, the combined inputs of NPK fertilizers and CR achieved the lowest GHG emissions per unit yield, highlighting the potential of integrated fertilizer application strategies to mitigate GHG emissions while sustaining crop productivity.

1 Introduction

Soil management in food crop production is a key determinant of greenhouse gas (GHG) emissions, particularly in countries with extensive agricultural activity, such as Thailand[1]. Carbon dioxide (CO_2) and nitrous oxide (N_2O) are the predominant GHGs emitted from managed upland agricultural soils, including those used for cassava, maize and sugarcane production[2]. Crop production practices accelerate microbial decomposition of soil organic carbon (SOC), leading to CO_2 emissions[3,4]. In contrast, N_2O emissions primarily result from microbial transformations of organic and inorganic nitrogen via nitrification and denitrification, occurring under aerobic and anaerobic conditions, respectively[5,6]. Notably, methane (CH_4) production is inhibited under the aerobic conditions characteristic of managed upland agricultural soils[2].

Tropical agriculture represents a major source of atmospheric N_2O emissions[1]. In Thailand, emissions from managed soils constitute a significant fraction of the national GHG inventory. In 2019, these emissions exceeded 11,000 Gg CO_2 eq. accounting for 19.6% of total agricultural sector GHG emissions. Consequently, mitigating soil-derived GHG emissions is critical for achieving Thailand's net-zero GHG emissions target[7].

Fertilizer application significantly influences microbial activity, altering soil concentrations of organic carbon (OC), ammonium, nitrite and nitrate. These changes can enhance crop growth and yield[8,9] but may concurrently increase GHG emissions[5,10]. Fertilizer management is therefore a key strategy for mitigating GHG emissions through soil C and N transformations[11–13]. Previous studies have demonstrated divergent effects of fertilizer regimes on GHG fluxes. Zhang et al.[14] reported that manure application significantly increased annual CO_2 emissions in a wheat-maize double-cropping system, with emissions rising by 211% and 37.3% compared to mineral fertilizer and combined mineral-manure treatments, respectively. Similarly, Liyanage et al.[15] observed that mineral N fertilizer substantially increased N_2O emissions in a maize-soybean rotation without significantly affecting CO_2 fluxes, whereas compost application elevated CO_2 emissions but had no significant effect on N_2O emissions. Notably, the combined application of mineral fertilizer and organic amendments resulted in the highest emissions of both CO_2 and N_2O.

Despite the environmental implications of GHG emissions, ensuring food security remains a priority. Thus, fertilizer management must aim to minimize emissions while sustaining or enhancing crop productivity, particularly under long-term implementation[16].

Cassava (*Manihot esculenta*) is a major tropical food crop alongside maize, rice and sugarcane. In 2022, Thailand ranked third in global cassava production, accounting for 4.95% of the total harvested area, following Nigeria and the Democratic Republic of the Congo. However, Thailand remains the leading cassava exporter globally in both volume and economic value. In 2023, cassava production covered 1.68 Mha, comprising 9.82% of the total harvested area for food crops (1.48 Mha) in Thailand[17].

Quantifying and mitigating GHG emissions from cassava production is imperative for both Thailand's domestic supply chains and the sustainability of global food systems. However, despite the significance of Thailand's food crops in international markets, field studies on GHG emissions (particularly N_2O emissions) remain limited, impeding the development of effective mitigation strategies[18].

The Department of Agriculture, Ministry of Agriculture and Cooperatives has maintained a long-term cassava production experiment for 47 years, systematically evaluating diverse fertilizer application treatments under consistent crop management practices. This unique data set presents an opportunity to investigate the long-term impacts of fertilizer management on GHG emissions, crop yield and soil properties. Therefore, this study aimed to assess the effects of different fertilizer application regimes on CO_2 and N_2O emissions, cassava productivity, and associated changes in soil microbial communities and physicochemical properties.

2 Materials and methods

2.1 Experimental site

The long-term experimental cassava field studied was established in 1975 and is located at the Rayong Field Crop Research Center, under the Department of Agriculture, Ministry of Agriculture and Cooperatives, Thailand (12°44′00″ N, 101°08′11″ E) at an elevation of 50 m above mean sea level. This site is situated in the Huaipong Subdistrict of Mueang District, Rayong Province, in the eastern region of Thailand. The soil is classified as Ultisols according to the United States Department of Agriculture soil taxonomy and is referred to as the Huai Pong series in the Thai soil classification system by the Land Development Department. The soil texture is loamy sand, comprising 82% sand, 6% silt and 12% clay. Baseline soil properties at a depth of 20 cm for each treatment (45-year effect) prior to the initiation of this study are presented in Table 1.

Table 1 shows that the mineral fertilizers caused soil acidification and nutrient accumulation, while crop residue (CR) increased SOC. Compost (CP) enhanced soil pH, OC and nutrient concentrations, especially phosphorus and potassium. On average, CR and CP increased SOC sequestration by 50.8% and 86.0%, respectively, compared to unamended soil.

From 2012 to 2021, the study site had an average annual rainfall of 1559 mm, with mean daily minimum and maximum air temperatures of 24.7 and 32.7 °C, respectively.

2.2 Experimental design

The experimental site had a range of fertilizer application treatments as used for cassava production, which continue to this day. The study encompasses eight distinct soil management practices (Table 2): unfertilized control (Control), CR incorporation (CR_I), N fertilizer only (N_F), NP fertilizers (NP_F), NK fertilizers (NK_F), NPK fertilizers (NPK_F), a combination of NPK and CR (NPK_FCR_I), and a combination of NPK fertilizers and CP addition (NPK_FCP_A). CR, consisting of 70% stems and 30% leaves, was applied at a rate of 18.7 $Mg\cdot ha^{-1}$ per season, contributing 8.63 $Mg\cdot ha^{-1}$ C per season, 220 $kg\cdot ha^{-1}$ N per season, 75 $kg\cdot ha^{-1}$ P per season and 188 $kg\cdot ha^{-1}$ K per season. The N content of the stems and leaves was 0.54% and 2.65%, respectively. Municipal CP was applied at a rate of 6.25 $Mg\cdot ha^{-1}$ $season^{-1}$, contributing 1.63 $Mg\cdot ha^{-1}$ C per season, 153 $kg\cdot ha^{-1}$ N per season, 25 $kg\cdot ha^{-1}$ P per season and 175 $kg\cdot ha^{-1}$ K per season. The application rates for mineral fertilizers were 100 $kg\cdot ha^{-1}$ N per season, 22 $kg\cdot ha^{-1}$ P per season and 83 $kg\cdot ha^{-1}$ K per season. The experimental design followed a randomized complete block design with four replicates.

2.3 Crop management

The study focused on the production of cassava cv. Rayong 9, over two growing seasons: 2021–2022 and 2022–2023, referred to as the 2021 and 2022 seasons, respectively. All soils were tilled once prior to planting, about 20–30 days before planting. CR was incorporated into the soil during annual tillage for the CR_I and NPK_FCR_I treatments. Cassava was planted with a spacing of 1 m × 1 m in plots measuring 8 m × 10 m, with planting conducted on 4 August 2021 for the 2021 season and 21 September 2022, for the 2022 season. CP was applied to the NPK_FCP_A treatment 71 and 57 days after planting (DAP) in the 2021 and 2022 seasons, respectively. Mineral fertilizers were applied for the N_F, NP_F, NK_F, NPK_F, NPK_FCR_I, and NPK_FCP_A treatments by hand broadcasting 75 DAP in 2021 and 73 DAP in the 2022 season. All treatments received consistent crop management, including herbicides needed to minimize yield reductions. The cassava was grown with supplementary irrigation conditions and harvested 384 and 387 DAP in the 2021 and 2022 seasons, respectively. Detailed crop management information is provided in Table S1.

Table 1 Basic characteristics of the soil prior to this study and the compost (CP)

Property	Treatment								CP
	Control	CR_I	N_F	NP_F	NK_F	NPK_F	NPK_FCR_I	NPK_FCP_A	
pH [H_2O]	4.70 ± 0.64 b	4.48 ± 0.17 bc	3.63 ± 0.15 d	3.85 ± 0.37 cd	3.88 ± 0.15 bcd	4.03 ± 0.54 bcd	4.25 ± 0.31 bcd	6.05 ± 0.10 a	9.00
EC ($dS \cdot m^{-1}$)	0.05 ± 0.01 a	0.05 ± 0.01 a	0.05 ± 0.01 a	0.05 ± 0.01 a	0.05 ± 0.01 a	0.06 ± 0.01 a	0.06 ± 0.01 a	0.06 ± 0.01 a	10.7
Water content (%)	16.2 ± 2.57 a	15.0 ± 4.35 a	16.2 ± 2.22 a	15.4 ± 3.97 a	15.1 ± 3.92 a	15.6 ± 3.20 a	16.5 ± 4.72 a	14.9 ± 2.39 a	–
WFPS (%)	47.0 ± 14.0 a	44.7 ± 16.9 a	50.0 ± 9.79 a	42.9 ± 9.61 a	41.2 ± 15.1 a	44.4 ± 10.7 a	50.7 ± 18.0 a	43.0 ± 7.75 a	–
OM (%)	0.85 ± 0.14 d	1.29 ± 0.17 c	1.01 ± 0.11 cd	1.17 ± 0.09 cd	1.07 ± 0.21 cd	1.33 ± 0.15 c	1.89 ± 0.22 b	2.45 ± 0.07 a	39.2
OC (%)	0.49 ± 0.08 d	0.75 ± 0.10 c	0.58 ± 0.06 cd	0.68 ± 0.05 cd	0.62 ± 0.12 cd	0.77 ± 0.09 c	1.09 ± 0.13 b	1.42 ± 0.04 a	22.8
Total C (%)	2.45 ± 0.18 de	3.21 ± 0.19 ab	2.23 ± 0.10 e	2.74 ± 0.10 cd	2.61 ± 0.15 cde	2.93 ± 0.09 bc	3.22 ± 0.12 ab	3.41 ± 0.24 a	26.1
Total N (%)	0.15 ± 0.02 c	0.20 ± 0.03 abc	0.18 ± 0.02 bc	0.19 ± 0.03 abc	0.18 ± 0.02 bc	0.22 ± 0.04 abc	0.23 ± 0.04 ab	0.26 ± 0.03 a	2.45
NH_4^+ ($mg \cdot kg^{-1}$)	0.07 ± 0.02 d	0.20 ± 0.05 cd	0.98 ± 0.15 ab	0.99 ± 0.08 ab	0.63 ± 0.32 bc	1.11 ± 0.21 a	0.57 ± 0.05 bc	1.28 ± 0.17 a	480
NO_3^- ($mg \cdot kg^{-1}$)	18.7 ± 4.56 b	28.7 ± 1.47 b	28.4 ± 1.29 b	26.7 ± 5.75 b	35.4 ± 10.0 b	65.2 ± 7.87 a	68.3 ± 14.7 a	72.0 ± 7.80 a	64.0
Available P ($mg \cdot kg^{-1}$)	18.5 ± 10.2 c	21.0 ± 8.76 c	22.5 ± 5.92 c	92.0 ± 24.3 b	20.3 ± 11.8 c	74.5 ± 29.2 bc	84.0 ± 10.7 b	647 ± 53.5 a	180
Exchangeable K ($mg \cdot kg^{-1}$)	14.0 ± 9.66 c	22.5 ± 6.19 bc	13.0 ± 3.46 c	18.0 ± 9.38 bc	17.3 ± 5.38 bc	22.0 ± 8.16 bc	37.0 ± 14.7 b	133 ± 9.45 a	11,150
CEC ($cmol \cdot kg^{-1}$)	3.80 ± 0.14 ef	3.51 ± 0.12 f	4.58 ± 0.21 cd	4.26 ± 0.10 de	3.88 ± 0.23 ef	5.00 ± 0.13 bc	6.25 ± 0.18 a	5.20 ± 0.22 b	50.2
Bulk density ($g \cdot cm^{-3}$)	1.71 ± 0.14 a	1.74 ± 0.08 a	1.78 ± 0.08 a	1.70 ± 0.05 a	1.65 ± 0.12 a	1.71 ± 0.06 a	1.77 ± 0.07 a	1.73 ± 0.02 a	–
SOC stock ($Mg \cdot ha^{-1}$)	16.7 ± 2.23 d	25.9 ± 2.92 c	20.8 ± 2.07 cd	23.1 ± 2.29 cd	20.3 ± 3.33 cd	26.4 ± 3.35 c	38.7 ± 4.74 b	49.1 ± 1.68 a	–

Note: Different letters indicate significant differences ($p < 0.05$) among treatments. Control, no amendments; CR_I, crop residue incorporation; N_F, NP_F, NK_F and NPK_F, refer to N, NP and NK, NPK fertilizer applications, respectively; NPK_FCR_I, combination of NPK_F and CR_I treatments; and NPK_FCP_A, combination of NPK_F and CP addition. EC, electrical conductivity; WFPS, water-filled pore space; OM, organic matter; OC, organic carbon; CEC, cation exchange capacity; SOC, soil organic carbon.

Table 2 Experimental design (unit: $kg \cdot ha^{-1}$ per season)

Treatment	Mineral fertilizer			CR	CP
	N	P	K		
Control	0	0	0	0	0
CR_I	0	0	0	1.88×10^3	0
N_F	100	0	0	0	0
NP_F	100	22	0	0	0
NK_F	100	0	83	0	0
NPK_F	100	22	83	0	0
NPK_FCR_I	100	22	83	1.88×10^3	0
NPK_FCP_A	100	22	83	0	6.25×10^3

2.4 Measurement of CO_2 and N_2O emissions

CO_2 and N_2O emissions were measured using the closed rectangular chamber method, as described by Sriphirom et al.[19]. The chamber, constructed from acrylic, comprised a body and a base. The chamber body dimensions were 30 cm × 30 cm × 10 cm (L × W × H). To mitigate internal temperature fluctuations, the chamber body was covered with thermal insulation sheets. The chamber base, with the same length and width as the body, had a height of 15 cm, with the lower 10 cm embedded in the soil at the center of each plot. The remaining

5 cm protruded above the soil surface and was sealed with water to prevent gas leakage during sampling.

Gas samples were collected biweekly between 9:00 and 11:30 a.m. over a 26-month period (August 2021 to September 2023). Air temperature within the chamber was measured using a digital thermometer (EW-18004-35, Traceable, Webster, TX, USA) inserted through a rubber septum on the chamber port. Four gas samples were collected at 0, 10, 20 and 30 min after chamber closure. The samples were extracted using a 30-mL plastic syringe and transferred into 20-mL evacuated vials[20].

The concentrations of CO_2 and N_2O in the collected air samples were analyzed using a gas chromatograph (7890B GC, Agilent Technologies, Santa Clara, CA, USA) equipped with a flame ionization detector for CO_2 and an electron capture detector for N_2O, both operated at 300 °C. A HaySep Q packed column was used, with nitrogen and helium as carrier gases at a flow rate of 20 $mL\cdot min^{-1}$. Emission fluxes and cumulative emissions were calculated by the methods of Sriphirom et al.[19].

The direct N_2O emission factor (EF) was calculated by determining the difference in cumulative N_2O emissions ($kg\cdot ha^{-1}$ N_2O-N) between fertilized and unfertilized control soils, and dividing by the total N applied ($kg\cdot ha^{-1}$ N), following Liyanage et al.[15]. Yield-scaled GHG emissions were calculated by dividing seasonal GHG emissions by the corresponding seasonal cassava yield.

2.5 Crop yield measurement and soil analysis

Following harvest, the height of cassava plants and root yield were recorded. The harvested biomass was subsequently dried and weighed. Starch content in the roots was quantified using the Riemann scale balance technique. N content in the aboveground biomass was determined using a CHN analyzer (Model CHN 628, LECO Corporation, St. Joseph, MI, USA), which operated at combustion temperatures between 950 and 1050 °C.

Soil samples were collected to a depth of 20 cm both prior to and following the cropping period for soil characterization. The following parameters were analyzed: pH measured in water using a pH/ISE/ORP Benchtop Meter HI5222 (Hanna Instruments, Woonsocket, RI, USA); electrical conductivity measured with an EC TDS Salinity Benchtop Meter HI2003-02 (Hanna Instruments); OC determined by the Walkley and Black method via acid-dichromate digestion and $FeSO_4$ titration; organic matter (OM) calculated by multiplying OC by 1.724; available P determined spectrophotometrically by the Bray II method; available K extracted using NH_4OAc and analyzed by flame spectrophotometry; cation exchange capacity determined via ammonium saturation; and bulk density measured from 100 cm^3 soil cores, oven-dried at 105 °C for 48 h in a forced air convection drying oven (Binder GmbH, Redline RF 53, Tuttlingen, Germany). These methods were performed as Pansu and Gautheyrou[21].

Total N and C contents were quantified using the CHN analyzer, as described above. Ammonium concentrations were analyzed via ion chromatography using a Dionex Integrion HPIC system (Thermo Scientific, Waltham, MA, USA) fitted with a Dionex IonPac CG16 guard column and a CS16 analytical column, using methanesulfonic acid as the eluent and a conductivity detector, following Thomas et al.[22]. Nitrate concentrations were similarly determined by ion chromatography using a Dionex IonPac AG11 guard column and AS11 analytical column with a 21 $mmol\cdot L^{-1}$ NaOH eluent and a conductivity detector as described by Morales et al.[23]. SOC stocks were computed by multiplying SOC concentration by bulk density and soil depth, based on Lee et al.[24].

During gas sampling events, topsoil moisture content was measured using a soil moisture sensor (CS655, Campbell Scientific, Inc., Logan, UT, USA). The percentage of water-filled pore space (%WFPS) was calculated using the soil water content (derived from gravimetric moisture content multiplied by bulk density), bulk density and a particle density value of 2.65 $g\cdot cm^{-3}$[25] as Wang et al.[26].

2.6 Soil microbial abundance and structure analysis

Soil samples were collected from depths of 0–10 cm before, during (5 March 2022 for the 2021 growing season and 4 April 2023 for the 2022 season) and after cassava production using sterilized stainless-steel sampling tubes. Immediately on collection, samples were frozen in the field using a portable freezer and transported to the laboratory for subsequent analysis. DNA was extracted from 1 g of fresh soil using the DNeasy PowerSoil Pro kit (Qiagen, Hilden, Germany) following the manufacturer’s instructions.

The extracted DNA was analyzed by quantitative real-time polymerase chain reaction to determine the abundance of total bacteria (16S rRNA gene), total archaea (16S rRNA gene), ammonia-oxidizing archaea (AOA, *amo*A gene), ammonia-oxidizing bacteria (AOB, *amo*A gene) and denitrifying bacteria (nitrite reductase genes, *nir*K and *nir*S; nitrous oxide reductase gene, *nos*Z). These assays were performed in triplicate on a CFX96 Touch Real-Time PCR Detection System (Bio-Rad, Hercules, CA, USA). Each 20-μL reaction mix contained 10 μL of Luna Universal qPCR Master Mix (New England Biolabs Inc., Ipswich, MA, USA), 0.4 μL of each forward and reverse primer, 1 μL of DNA template (10 ng) and 8.2 μL of PCR-grade water. Primer sequences and thermocycling conditions are detailed in Table S2.

Soil DNA samples from the 2021 season were analyzed for bacterial diversity by amplifying the 16S rRNA V4 region using primers 515F and 806R[27,28]. The sequencing library was prepared according to the Illumina 16S library preparation protocol (Illumina, San Diego, CA, USA). Dual index adapters, necessary for sequencing on the Illumina MiSeq platform, were ligated using the Nextera XT Index kit (Illumina). The library was pooled, diluted and combined to achieve a final concentration of 4 $\text{nmol}\cdot\text{L}^{-1}$, and DNA concentration was measured using a QFX Fluorometer (DeNovix Inc., Wilmington, DE, USA) with the DeNovix dsDNA High Sensitivity assay. The library was sequenced in a 300-bp paired-end run using the MiSeq Reagent Kit v3 (600 cycles), with PhiX Control Kit v3 (Illumina) as a positive control.

Amplicon sequence analysis was performed using the Quantitative Insights Into Microbial Ecology Pipeline version 2022.2[29]. Adapter and primer sequences (23 and 26 base pairs for forward and reverse sequences, respectively) were removed using the q2-cutadapt tool[30]. The resulting sequences were processed for error correction using amplicon sequence variant processing with DADA2[31]. Forward and reverse amplicon sequences were merged into contigs based on overlapping regions. All candidate contigs were denoised and chimeric sequences were excluded. Sequences were resampled to a consistent depth using the QIIME feature-table rarefying function for further analysis. Both alpha and beta diversity indices were computed from the rarefied data set, with the minimum sequencing depth used as the rarefying depth. Taxonomic assignment was performed using the SILVA database (version 138)[32], with classification based on the naive Bayes classifier[33] at 99% identity for the analyzed regions. Heatmap visualizations were generated using the Multiple Experiment Viewer (version 4.9.0) interactive platform[34].

2.7 Statistical analysis

Principal coordinate analysis of microbial community data was performed and visualized using the R package "vegan"[35]. Functional prediction of microbial communities, based on the Phylogenetic Investigation of Communities by Reconstruction of Unobserved States, was conducted via the Majorbio I-Sanger cloud platform. KEGG Orthology data were retrieved and analyzed to assess the abundances of functional enzymes involved in nitrification and denitrification processes, along with key microbial taxa linked to these processes. The relative abundances of genera associated with these processes were visualized and reported.

Experimental data are presented as means ± SE ($n \geqslant 4$). Statistical analyses were performed by one-way analysis of variance followed by Tukey's honest significant difference test with a 95% confidence level ($p < 0.05$) to identify significant differences. Fertilizer treatments were considered fixed factors and environmental parameters were treated as dependent variables. Statistically significant differences among treatments are denoted by distinct letters.

Pearson's correlation analysis was used to examine the relationships between CO_2 and N_2O emissions, cassava yield, soil pH, SOC sequestration, nutrient inputs (Carbon, N, P and K) and microbial groups (including total bacteria, archaea, AOB, AOA and denitrifying bacteria associated with the *nir*K, *nir*S and *nos*Z genes) throughout the study period. Statistical analyses were performed using IBM SPSS Statistics for Windows, version 29.0 (IBM Corp, Armonk, NY, USA).

3 Results

3.1 Weather data and soil water-filled pore space

During the study period, the total annual rainfall was 1,961 mm, with mean daily minimum and maximum temperatures of 24.7 and 32.3 °C, respectively (Fig. 1(a)). The elevated rainfall significantly influenced soil %WFPS (Fig. 1(b)). Soil %WFPS was further modulated by various fertilizer application treatments. Notably, the NPK_FCR_I treatment resulted in the highest %WFPS, while the NK_F treatment consistently maintained the lowest %WFPS throughout the majority of the observation period (Fig. 1(b)).

3.2 CO_2 and N_2O emissions

Fertilizer application practices substantially impacted CO_2 and N_2O emissions during the study period (Fig. 2). The addition of organic C through CR and CP additions enhanced the soil C substrate availability, thereby promoting CO_2 emissions, as

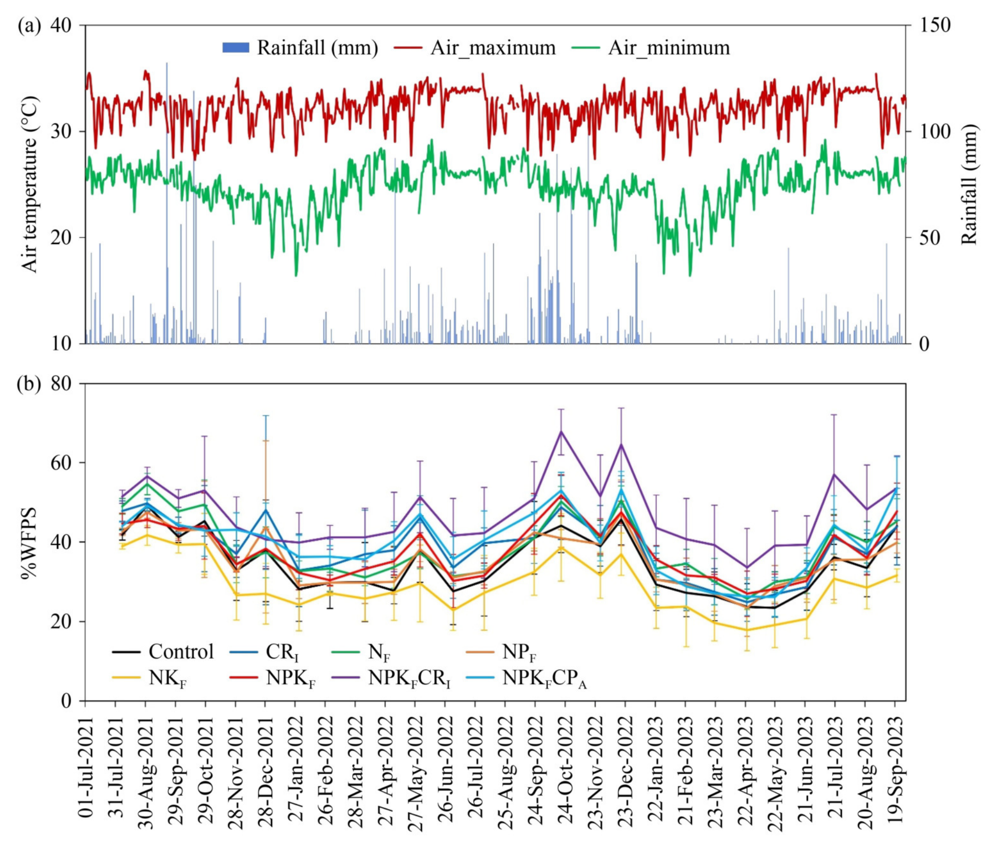

Fig. 1 (a) Air temperature and total rainfall recorded at the study site throughout the study period and (b) soil water-filled pore space (%WFPS) across the observation period. Control, no amendments; CR$_I$, crop residue incorporation; N$_F$, NP$_F$, NK$_F$ and NPK$_F$, refer to N, NP and NK, NPK fertilizer applications, respectively; NPK$_F$CR$_I$, combination of NPK$_F$ and CR$_I$ treatments; and NPK$_F$CP$_A$, combination of NPK$_F$ and CP addition.

evidenced by a linear correlation (Table S3). Increased C input led to elevated CO_2 emissions (Fig. 2(a)). Relative to the control, the treatments CR$_I$, N$_F$, NP$_F$, NK$_F$, NPK$_F$, NPK$_F$CR$_I$ and NPK$_F$CP$_A$ increased annual CO_2 emissions by 36.0%, 13.1%, 14.9%, 19.4%, 23.8%, 41.0% and 33.4%, respectively, in the 2021 season, and by 18.0%, 15.0%, 15.7%, 9.31%, 16.5%, 30.5%, and 27.2%, respectively, in the 2022 season (Table 3).

Similarly, the application of N from organic and inorganic sources significantly influenced N_2O emissions, as evidenced by strong correlations (Table S3). N_2O emissions from mineral fertilizers peaked immediately after application, while emissions from organic N sources were more gradual, occurring throughout the annual cycle (Fig. 2(b)). The treatments CR$_I$, N$_F$, NP$_F$, NK$_F$, NPK$_F$, NPK$_F$CR$_I$ and NPK$_F$CP$_A$ increased N_2O emissions by 229%, 155%, 156%, 132%, 139%, 316% and 359%, respectively, in the 2021 season, and by 250%, 159%, 150%, 136%, 147%, 310% and 364%, respectively, in the 2022 season, relative to the control. Higher N input contributed to increased N_2O emissions, with the combined organic and inorganic treatments (NPK$_F$CR$_I$ and NPK$_F$CP$_A$) releasing the highest amounts of N_2O (Table 3).

The practices with the lowest environmental impact were those involving minimal C and N input; however, these treatments should be evaluated against crop yield potential to ensure food security. The ratio of GHG emissions per unit yield is shown in Table 4. All the crop production practices assessed significantly reduced CO_2 emissions per unit yield in both seasons compared to the control. Similarly, all treatments significantly mitigated N_2O emissions per unit yield in both seasons compared to the N$_F$ treatment. Among the treatments, NPK$_F$CR$_I$ gave the statistically lowest GHG emissions per unit yield. Although NPK$_F$CR$_I$ generated the highest GHG emissions, it had the lowest GHG intensity, indicating its suitability as a balanced approach for achieving sustainability across environmental, economic and social dimensions.

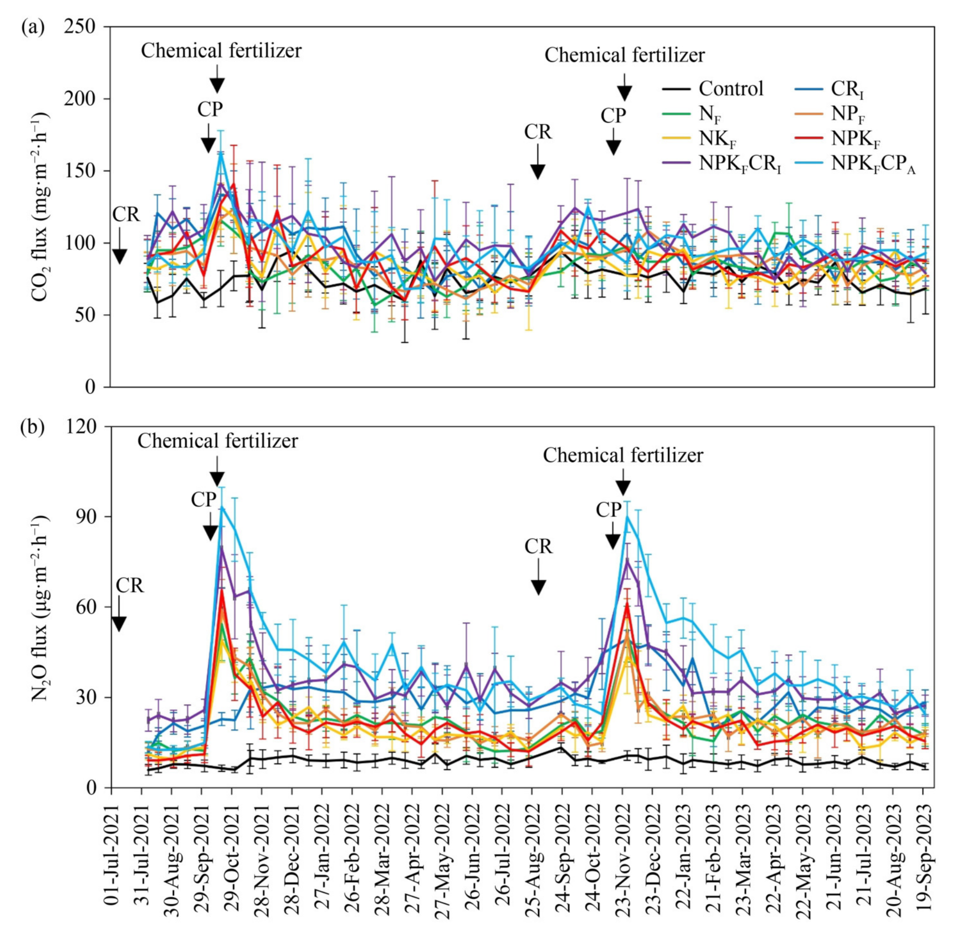

Fig. 2 Temporal fluxes of (a) CO_2 and (b) N_2O throughout the study period. Control, no amendments; CR_I, crop residue incorporation; N_F, NP_F, NK_F and NPK_F, refer to N, NP and NK, NPK fertilizer applications, respectively; NPK_FCR_I, combination of NPK_F and CR_I treatments; and NPK_FCP_A, combination of NPK_F and CP addition.

3.3 N_2O emission factor

N_2O EF varied from 0.50% to 0.80% in the 2021 season and 0.49% to 0.81% in the 2022 season across the production practices assessed (Table 3). The lowest EF values were recorded in the highest N input treatment (NPK_FCR_I) in both seasons. Organic N applications through CR and CP generally resulted in lower N_2O EF compared to mineral fertilizers. Higher N inputs appeared to reduce N_2O EF. The average N_2O EF in this study was 0.67% and 0.69% for the 2021 and 2022 seasons, respectively, both of which were below the Intergovernmental Panel on Climate Change (IPCC) default value of 1% for N_2O EF.

3.4 Soil microbial abundance and structure

Long-term crop production practices influenced microbial abundance and structure (Fig. 3). Organic amendments (CR and CP) generally promoted total bacterial abundance. The combination of organic and inorganic inputs significantly enhanced the abundance of both bacteria and archaea, particularly before and during the 2021 season and after the 2022 season harvest. The application of N from both organic and inorganic inputs increased the abundance of nitrifying and denitrifying microbes (Table S4), with the highest N inputs in CR_I, NPK_FCR_I and NPK_FCP_A soils stimulating the growth of these microbial groups. NPK_FCP_A in particular promoted both nitrifiers and denitrifiers during the 2022 season (Fig. 3(d)).

Changes in microbial community structure were also recorded (Fig. S1). The dominant genera varied according to treatment: *Bacillus* predominated in the control and N_F treated soils, *Nitrososphaera* in organically amended soils (CR_I, NPK_FCR_I and NPK_FCP_A), *Bradyrhizobium* in NP_F and NK_F treated soils, and bacterium Ellin6067 in NPK_F treated soils. These genera are likely key contributors to N_2O production and emission.

Table 3 Cumulative CO_2 and N_2O emissions, along with N_2O emission factors (EF), from cassava production during the 2021–2022 growing seasons

Treatment	Cumulative emission		N_2O EF (%)
	CO_2 ($Mg \cdot ha^{-1}$)	N_2O ($kg \cdot ha^{-1}$)	
2021 season			
Control	6.66 ± 0.21 d	0.80 ± 0.01 f	–
CR_I	9.05 ± 0.36 a	2.64 ± 0.08 c	0.53 ± 0.02 c
N_F	7.52 ± 0.33 c	2.05 ± 0.08 d	0.79 ± 0.06 a
NP_F	7.65 ± 0.43 c	2.06 ± 0.10 d	0.80 ± 0.06 a
NK_F	7.94 ± 0.41 c	1.86 ± 0.04 e	0.67 ± 0.03 b
NPK_F	8.24 ± 0.21 bc	1.92 ± 0.05 de	0.71 ± 0.03 ab
NPK_FCR_I	9.39 ± 0.29 a	3.34 ± 0.11 b	0.50 ± 0.02 c
NPK_FCP_A	8.88 ± 0.41 ab	3.61 ± 0.11 a	0.71 ± 0.02 ab
Average	8.17 ± 0.05	2.28 ± 0.01	0.67 ± 0.02
2022 season			
Control	6.84 ± 0.19 c	0.80 ± 0.06 e	–
CR_I	8.06 ± 0.10 b	2.79 ± 0.17 c	0.58 ± 0.05 c
N_F	7.86 ± 0.37 b	2.07 ± 0.08 d	0.81 ± 0.09 a
NP_F	7.91 ± 0.10 b	2.00 ± 0.07 d	0.76 ± 0.04 ab
NK_F	7.47 ± 0.14 b	1.88 ± 0.08 d	0.69 ± 0.02 b
NPK_F	7.96 ± 0.21 b	1.97 ± 0.08 d	0.75 ± 0.04 ab
NPK_FCR_I	8.92 ± 0.39 a	3.25 ± 0.12 b	0.49 ± 0.01 c
NPK_FCP_A	8.69 ± 0.36 a	3.71 ± 0.04 a	0.73 ± 0.01 ab
Average	7.96 ± 0.10	2.31 ± 0.04	0.69 ± 0.02

Note: Different letters indicate significant differences ($p < 0.05$) among treatments. Control, no amendments; CR_I, crop residue incorporation; N_F, NP_F, NK_F and NPK_F, refer to N, NP and NK, NPK fertilizer applications, respectively; NPK_FCR_I, combination of NPK_F and CR_I treatments; and NPK_FCP_A, combination of NPK_F and CP addition.

Table 4 Cassava yield-scaled GHG emissions from cassava production during the 2021–2022 growing seasons

Treatment	Cassava yield-scaled CO_2 emission ($kg\ CO_2\ kg^{-1}$ yield)		Cassava yield-scaled N_2O emission ($g\ N_2O\ kg^{-1}$ yield)	
	2021 season	2022 season	2021 season	2022 season
Control	0.89 ± 0.03 a	0.64 ± 0.01 a	0.11 ± 0.00 c	0.07 ± 0.01 c
CR_I	0.36 ± 0.02 d	0.31 ± 0.01 d	0.11 ± 0.00 c	0.11 ± 0.01 b
N_F	0.66 ± 0.03 b	0.57 ± 0.03 b	0.18 ± 0.01 a	0.15 ± 0.01 a
NP_F	0.46 ± 0.03 c	0.40 ± 0.01 c	0.12 ± 0.01 b	0.10 ± 0.01 b
NK_F	0.28 ± 0.01 ef	0.25 ± 0.01 e	0.07 ± 0.00 d	0.06 ± 0.01 c
NPK_F	0.31 ± 0.01 e	0.27 ± 0.01 e	0.07 ± 0.00 d	0.07 ± 0.01 c
NPK_FCR_I	0.19 ± 0.01 g	0.22 ± 0.01 f	0.07 ± 0.00 d	0.08 ± 0.01 c
NPK_FCP_A	0.27 ± 0.01 f	0.27 ± 0.01 e	0.11 ± 0.00 c	0.11 ± 0.01 b
Average	0.33 ± 0.01	0.31 ± 0.01	0.09 ± 0.00	0.09 ± 0.01

Note: Different letters indicate significant differences ($p < 0.05$) among treatments. Control, no amendments; CR_I, crop residue incorporation; N_F, NP_F, NK_F and NPK_F, refer to N, NP and NK, NPK fertilizer applications, respectively; NPK_FCR_I, combination of NPK_F and CR_I treatments; and NPK_FCP_A, combination of NPK_F and CP addition.

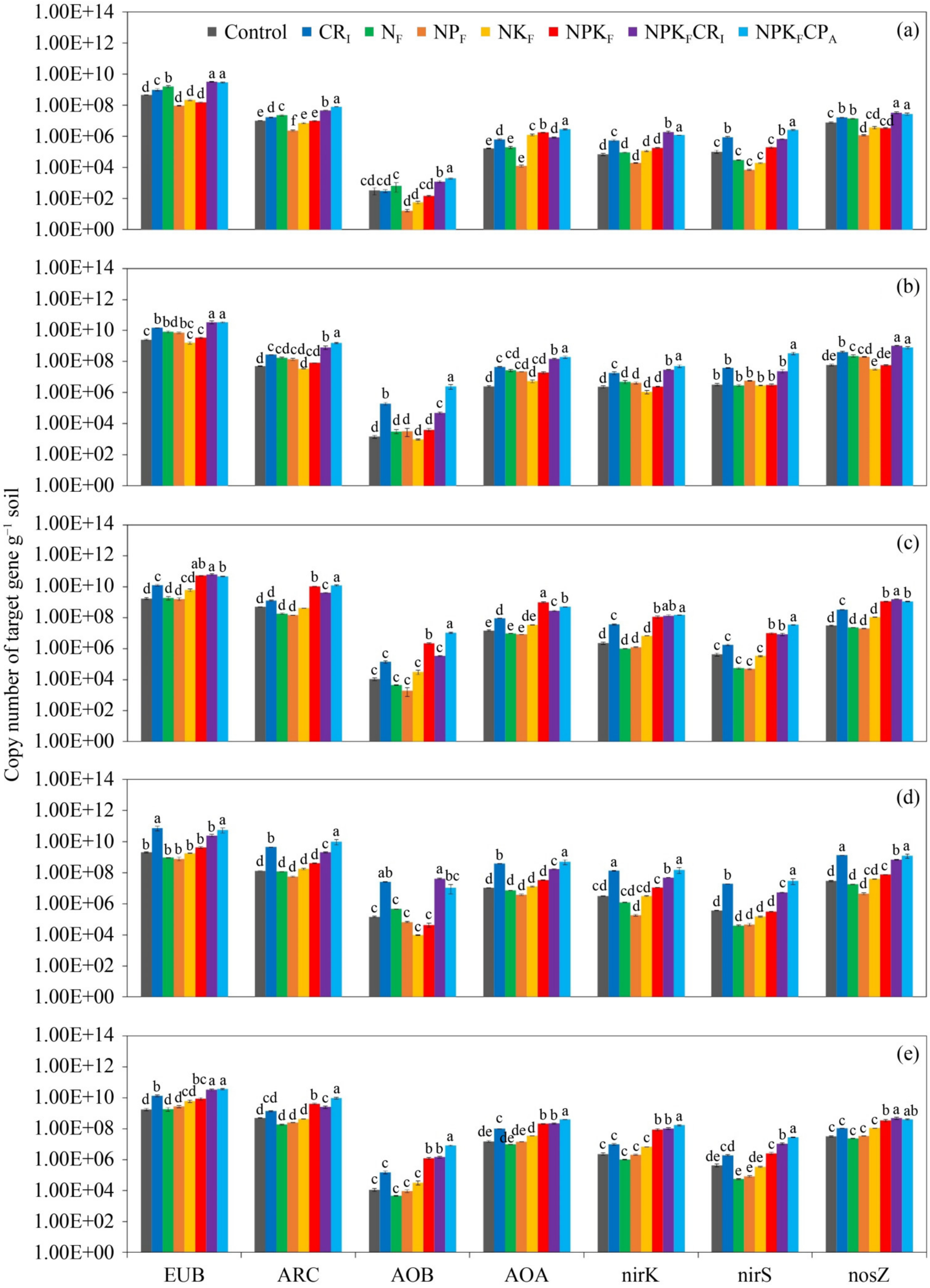

Fig. 3 Abundances of total bacteria (EUB), total archaea (ARC), nitrifiers (AOB and AOA), and denitrifiers (*nir*K, *nir*S and *nos*Z genes) in soil. (a) Prior to cassava production in the 2021 season, (b) during cassava production in the 2021 season, (c) after cassava production in the 2021 season, (d) during cassava production in the 2022 season, and (e) after cassava production in the 2022 season. Different letters indicate significant differences ($p < 0.05$) among treatments. Control, no amendments; CR$_I$, crop residue incorporation; N$_F$, NP$_F$, NK$_F$ and NPK$_F$, refer to N, NP and NK, NPK fertilizer applications, respectively; NPK$_F$CR$_I$, combination of NPK$_F$ and CR$_I$ treatments; and NPK$_F$CP$_A$, combination of NPK$_F$ and CP addition.

3.5 Crop growth and yield

Long-term crop production practices significantly impacted cassava growth and yield. In both the 2021 and 2022 seasons, the tallest cassava plants were observed under combined organic and inorganic inputs (NPK$_F$CR$_I$ and NPK$_F$CP$_A$), while the shortest plants were in the non-fertilized control and the N$_F$

treatment. The combined application of mineral fertilizers and CR (NPK$_F$CR$_I$) resulted in the highest cassava yields, except in the 2022 season where the difference with NPK$_F$CP$_A$ was not significant. The NPK$_F$CR$_I$ treatment produced 79.4%, 42.8%, 72.0%, 59.2%, 35.7%, 37.6% and 26.9% higher yields compared to the control, CR$_I$, N$_F$, NP$_F$, NK$_F$, NPK$_F$ and NPK$_F$CP$_A$, respectively (Table 5). Practices involving N and K addition, whether organic or inorganic, consistently enhanced cassava growth and yield.

The starch content of cassava ranged from 24.0% to 27.1% in the 2021 season and 21.3% to 28.6% in the 2022 season. The incorporation of CR resulted in the highest starch content, with a significant effect observed in the 2022 season. Soils without K and CR additions tended to reduce starch content. However, differences in starch content were less pronounced compared to the variation in cassava yield, indicating that starch yield mirrored cassava yield. The highest starch yield was observed in the NPK$_F$CR$_I$ treatment, with CR$_I$, N$_F$, NP$_F$, NK$_F$, NPK$_F$, NPK$_F$CR$_I$, and NPK$_F$CP$_A$ increasing starch yield by 202%, 28.8%, 87.3%, 218%, 206%, 433%, and 231%, respectively, compared to the control (Table 5).

3.6 Soil properties after the cropping year

Soil properties were significantly influenced by the long-term crop production practices. After the 2022 season harvest, soil properties within the same treatments were similar to those observed before the study began (Table 1). Among treatments, soil pH decreased with mineral fertilizer applications but increased with CP application. The pH changes from the baseline varied as follows: + 0.07 (CR$_I$), −0.66 (N$_F$), −0.55 (NP$_F$), −0.43 (NK$_F$), −0.42 (NPK$_F$), −0.04 (NPK$_F$CR$_I$) and + 1.17 (NPK$_F$CP$_A$) compared to the control. Fertilizer treatments enhanced nutrient accumulation, particularly with CP, which increased P and K contents. Organic amendments, including CR and CP, also had a positive impact on SOC sequestration. After the 2022 season harvest, CR$_I$, NPK$_F$CR$_I$, and NPK$_F$CP$_A$ treatments had increased SOC stock by 48.0%, 116% and 143%, respectively, relative to the control. Compared to NPK$_F$,

Table 5 Growth and yield parameters of cassava during the 2021–2022 growing seasons

Treatment	Plant height (cm)	Cassava yield (Mg·ha^{-1})	Starch (%)	Starch yield (Mg·ha^{-1})
2021 season				
Control	131 ± 10.5 d	7.48 ± 5.19 d	26.0 ± 0.74 abc	2.03 ± 0.91 d
CR$_I$	194 ± 17.2 abc	25.0 ± 6.13 bc	27.1 ± 1.09 a	6.78 ± 1.87 bc
N$_F$	133 ± 14.7 d	11.4 ± 3.23 d	24.8 ± 0.42 cd	2.83 ± 0.86 d
NP$_F$	151 ± 16.3 cd	16.8 ± 4.16 cd	24.0 ± 0.51 d	4.03 ± 1.15 cd
NK$_F$	189 ± 12.5 bc	28.3 ± 3.62 b	26.2 ± 0.59 abc	7.41 ± 1.63 b
NPK$_F$	190 ± 6.75 bc	26.3 ± 6.12 bc	25.7 ± 0.82 abc	6.76 ± 1.71 bc
NPK$_F$CR$_I$	235 ± 10.4 a	48.7 ± 4.32 a	26.6 ± 0.62 ab	13.0 ± 1.45 a
NPK$_F$CP$_A$	222 ± 12.2 ab	33.4 ± 5.12 b	25.4 ± 0.54 bcd	8.48 ± 1.54 b
Average	181 ± 12.8	24.7 ± 4.76	25.7 ± 0.69	6.41 ± 1.41
2022 season				
Control	153 ± 19.5 b	10.7 ± 4.51 d	24.3 ± 0.45 b	2.60 ± 0.52 d
CR$_I$	181 ± 16.4 b	26.4 ± 4.37 b	27.4 ± 0.67 a	7.23 ± 0.67 b
N$_F$	153 ± 18.3 b	13.8 ± 2.06 d	22.8 ± 0.93 bc	3.15 ± 0.37 d
NP$_F$	168 ± 12.9 b	19.9 ± 3.24 c	23.4 ± 0.62 bc	4.66 ± 0.36 c
NK$_F$	178 ± 14.3 b	29.5 ± 5.67 b	24.9 ± 0.25 b	7.35 ± 0.69 b
NPK$_F$	186 ± 12.3 b	29.8 ± 4.67 b	24.9 ± 0.32 b	7.42 ± 0.74 b
NPK$_F$CR$_I$	225 ± 8.45 a	41.2 ± 5.46 a	28.6 ± 1.15 a	11.8 ± 1.03 a
NPK$_F$CP$_A$	227 ± 7.24 a	32.3 ± 6.22 ab	21.3 ± 0.75 c	6.88 ± 0.83 b
Average	184 ± 13.8	25.5 ± 4.63	24.7 ± 0.67	6.38 ± 0.68

Note: Different letters indicate significant differences ($p < 0.05$) among treatments. Control, no amendments; CR$_I$, crop residue incorporation; N$_F$, NP$_F$, NK$_F$ and NPK$_F$, refer to N, NP and NK, NPK fertilizer applications, respectively; NPK$_F$CR$_I$, combination of NPK$_F$ and CR$_I$ treatments; and NPK$_F$CP$_A$, combination of NPK$_F$ and CP addition.

NPK_FCR_I and NPK_FCP_A enhanced SOC stocks by 36.1% and 53.3%, respectively (Table 6). These results highlight the importance of organic amendments for improving soil C status.

4 Discussion

4.1 Variations of diverse long-term fertilizations on CO_2 and N_2O emissions

CO_2 represents the predominant GHG emitted from soils, primarily through microbial respiration, encompassing both autotrophic and heterotrophic processes linked to OM decomposition[36]. Autotrophic respiration contributes about 36% of total soil respiration[37], and its activity is inhibited under acidic soil conditions[38]. Root respiration, including the decomposition of root exudates, can account for up to 50% of soil respiration[39]. CO_2 fluxes typically decline as plants approach physiologic maturity and senescence, coinciding with reduced root activity[40].

In this study, cassava production on acidic soils subjected to diverse fertilizer application treatments resulted in an average CO_2 emission of 8.07 $Mg \cdot ha^{-1}$, with emissions declining slightly as crops matured. Treatments involving CR and CP amendments enhanced SOM and SOC levels, thereby increasing substrates available for microbial decomposition and leading to elevated CO_2 emissions. Specifically, CO_2 emissions increased by 19.9% and 8.47% with CR and CP additions, respectively, with CR contributing more significantly due to the higher quantity of organic material applied. These findings are consistent with Chataut et al.[2], who reported that soil amendments with OC significantly influence CO_2 emissions.

N from both mineral and organic inputs further amplified CO_2 emissions, with a strong positive correlation observed between N input and CO_2 fluxes (Table S3). This observation aligns with Wang et al.[41], who demonstrated that fertilizer application, particularly with organic inputs, enhances CO_2 emissions by altering the soil bacterial community composition. Increased abundance of bacterial groups such as Alphaproteobacteria and Gammaproteobacteria, observed in this study (Fig. S1), likely contributed to these effects. Furthermore, Pareja-Sánchez et al.[42] noted that N fertilizer application enhances the availability of N for decomposers, while Tao et al.[43] established a positive correlation between CO_2 emissions and nitrification rates. Soil moisture also had a linear relationship with CO_2 emissions[42], explaining the higher CO_2 fluxes observed in the NPK_FCR_I, CR_I, and NPK_FCP_A treatments (Fig. 1(b)).

In addition to CO_2, N_2O is a critical GHG emitted from agricultural soils, primarily via nitrification and denitrification processes under specific environmental conditions[6]. This study identified nitrification as the dominant N_2O production pathway, driven by aerobic conditions in cassava soils[44]. Enhanced availability of NH_4^+ from mineral and organic inputs stimulated microbial activity, leading to increased N_2O production. A robust linear correlation between N input and N_2O emissions (Table S3) corroborates findings from Wang et al.[45], who reported that fertilizer application promotes nitrifier abundance and nitrification potential, particularly in the topsoil.

Soils treated with higher N inputs, such as in CR_I, NPK_FCR_I, and NPK_FCP_A, had significantly elevated N_2O emissions (Table 3), attributed to increased abundance and activity of nitrifying bacteria and archaea (Fig. 3, Table S4). Notably, the genera *Nitrososphaera* (AOA) and *Nitrospira* (AOB), which catalyze NH_4^+ oxidation to nitrite via the *amoA* gene[46], were implicated in N_2O production.

Under higher soil moisture conditions (> 50%WFPS), particularly in organically amended soils, denitrification also contributed to N_2O emissions, driven by microorganisms such as *Bradyrhizobium* (Fig. 4)[47–49]. CR and CP amendments further stimulated N_2O production by increasing soil C availability, providing energy sources for microbial activity[50]. Both nitrifiers and denitrifiers use available C for NH_4^+ oxidation and NO_3^- reduction. However, elevated NO_3^- concentrations in CR_I, NPK_FCR_I and NPK_FCP_A treated soils inhibited N_2O reductase activity, limiting the conversion of N_2O to N_2[51].

Soil acidity also influenced N_2O dynamics. Mineral fertilizers exacerbated soil acidification, inhibiting autotrophic nitrification, while CP application mitigated acidity, promoting nitrification[52]. Under acidic conditions (pH < 6), denitrification in organically amended soils predominantly produced N_2O rather than N_2, consistent with findings by Šimek et al.[53].

This study estimated an average direct N_2O EF at 0.68%, lower than the IPCC default value of 1%[54]. EFs for CR_I, mineral fertilizer and combined organic and inorganic treatments were 0.56%, 0.75% and 0.61%, respectively (Table 3), aligning with IPCC disaggregated recommendations except for mineral

Table 6 Basic soil characteristics after cassava harvest in the 2021 and 2022 growing seasons

Property	Control	$\mathrm{CR_I}$	$\mathrm{N_F}$	$\mathrm{NP_F}$	$\mathrm{NK_F}$	$\mathrm{NPK_F}$	$\mathrm{NPK_FCR_I}$	$\mathrm{NPK_FCP_A}$
2021 season								
pH [H_2O]	4.12 ± 0.10 b	4.01 ± 0.16 b	3.51 ± 0.02 d	3.55 ± 0.03 cd	3.94 ± 0.25 bc	3.49 ± 0.10 d	4.26 ± 0.10 b	5.22 ± 0.22 a
EC ($\mathrm{dS \cdot m^{-1}}$)	0.05 ± 0.01 a	0.05 ± 0.01 a	0.06 ± 0.01 a	0.06 ± 0.01 a	0.05 ± 0.01 a	0.06 ± 0.01 a	0.05 ± 0.01 a	0.06 ± 0.01 a
Water content (%)	14.4 ± 2.99 a	15.1 ± 0.65 a	12.9 ± 1.32 a	16.2 ± 1.22 a	13.8 ± 1.28 a	16.1 ± 3.02 a	14.5 ± 2.55 a	16.7 ± 1.76 a
WFPS (%)	41.1 ± 9.46 a	43.4 ± 2.05 a	36.6 ± 4.35 a	46.6 ± 3.45 a	39.5 ± 4.54 a	45.2 ± 7.79 a	42.3 ± 7.47 a	47.4 ± 5.82 a
OM (%)	0.87 ± 0.07 f	1.29 ± 0.11 cd	1.03 ± 0.06 ef	1.23 ± 0.06 de	1.06 ± 0.09 def	1.50 ± 0.08 c	1.75 ± 0.11 b	2.03 ± 0.09 a
OC (%)	0.51 ± 0.04 f	0.75 ± 0.07 cd	0.60 ± 0.04 ef	0.71 ± 0.03 de	0.61 ± 0.05 def	0.87 ± 0.05 c	1.02 ± 0.06 b	1.18 ± 0.05 a
Total C (%)	2.75 ± 0.11 cd	3.45 ± 0.45 ab	2.28 ± 0.10 d	2.85 ± 0.31 bcd	2.67 ± 0.24 cd	3.06 ± 0.05 abc	3.34 ± 0.15 abc	3.72 ± 0.20 a
Total N (%)	0.16 ± 0.01 e	0.22 ± 0.02 bcd	0.19 ± 0.02 cde	0.20 ± 0.02 bcde	0.18 ± 0.02 de	0.25 ± 0.01 ab	0.24 ± 0.03 bc	0.31 ± 0.04 a
NH_4^+ ($\mathrm{mg \cdot kg^{-1}}$)	0.07 ± 0.01 c	1.19 ± 0.05 b	1.03 ± 0.02 b	0.95 ± 0.10 b	0.93 ± 0.07 b	1.03 ± 0.11 b	1.76 ± 0.30 a	1.78 ± 0.33 a
NO_3^- ($\mathrm{mg \cdot kg^{-1}}$)	17.0 ± 2.33 d	36.8 ± 4.39 c	28.4 ± 1.93 c	30.4 ± 0.69 c	33.9 ± 1.43 c	54.0 ± 5.50 b	69.1 ± 5.98 a	77.1 ± 4.11 a
Available P ($\mathrm{mg \cdot kg^{-1}}$)	23.7 ± 2.57 d	60.8 ± 4.51 cd	163 ± 7.10 c	359 ± 26.6 b	26.0 ± 3.25 d	359 ± 53.4 b	368 ± 75.0 b	785 ± 34.4 a
Exchangeable K ($\mathrm{mg \cdot kg^{-1}}$)	7.07 ± 1.33 b	10.8 ± 2.30 b	9.38 ± 3.13 b	10.9 ± 3.04 b	14.1 ± 3.44 b	14.6 ± 4.85 b	15.4 ± 3.76 b	62.5 ± 12.9 a
CEC ($\mathrm{cmol \cdot kg^{-1}}$)	3.69 ± 0.41 cd	3.32 ± 0.14 d	4.32 ± 0.17 c	4.24 ± 0.20 c	3.88 ± 0.21 cd	5.28 ± 0.37 b	6.38 ± 0.03 a	5.04 ± 0.29 b
Bulk density ($\mathrm{g \cdot cm^{-3}}$)	1.72 ± 0.04 a	1.73 ± 0.02 a	1.72 ± 0.02 a	1.73 ± 0.02 a	1.72 ± 0.04 a	1.71 ± 0.03 a	1.74 ± 0.03 a	1.72 ± 0.03 a
SOC stock ($\mathrm{Mg \cdot ha^{-1}}$)	17.4 ± 1.11 f	25.9 ± 2.25 cd	20.6 ± 1.44 ef	24.7 ± 1.05 de	21.1 ± 1.94 def	29.8 ± 1.50 c	35.3 ± 2.07 b	40.5 ± 2.41 a
2022 season								
pH [H_2O]	4.29 ± 0.06 b	4.36 ± 0.10 b	3.63 ± 0.06 c	3.74 ± 0.08 c	3.86 ± 0.07 c	3.87 ± 0.06 c	4.25 ± 0.06 b	5.46 ± 0.20 a
EC ($\mathrm{dS \cdot m^{-1}}$)	0.05 ± 0.01 a	0.05 ± 0.01 a	0.05 ± 0.01 a	0.05 ± 0.01 a	0.05 ± 0.01 a	0.05 ± 0.01 a	0.05 ± 0.01 a	0.06 ± 0.01 a
Water content (%)	15.8 ± 3.19 ab	16.4 ± 2.55 ab	13.6 ± 1.52 ab	14.7 ± 1.12 ab	12.6 ± 0.74 b	17.0 ± 2.92 ab	15.0 ± 1.40 ab	19.5 ± 2.18 a
WFPS (%)	44.2 ± 7.75 ab	47.4 ± 8.58 ab	38.5 ± 4.02 ab	41.4 ± 4.20 ab	35.8 ± 3.18 b	49.0 ± 7.56 ab	42.9 ± 4.33 ab	55.4 ± 6.40 a
OM (%)	0.87 ± 0.06 f	1.28 ± 0.04 c	1.02 ± 0.04 ef	1.21 ± 0.03 cd	1.09 ± 0.07 de	1.37 ± 0.08 c	1.87 ± 0.04 b	2.11 ± 0.08 a
OC (%)	0.51 ± 0.04 f	0.74 ± 0.02 c	0.59 ± 0.02 ef	0.70 ± 0.02 cd	0.63 ± 0.04 de	0.79 ± 0.05 c	1.08 ± 0.02 b	1.22 ± 0.05 a
Total C (%)	2.48 ± 0.03 d	3.15 ± 0.11 ab	2.19 ± 0.06 e	2.72 ± 0.15 cd	2.62 ± 0.12 d	2.94 ± 0.09 bc	3.20 ± 0.07 ab	3.42 ± 0.10 a
Total N (%)	0.15 ± 0.01 c	0.20 ± 0.02 abc	0.19 ± 0.02 bc	0.19 ± 0.03 bc	0.18 ± 0.03 bc	0.21 ± 0.03 abc	0.24 ± 0.02 ab	0.26 ± 0.03 a
NH_4^+ ($\mathrm{mg \cdot kg^{-1}}$)	0.10 ± 0.02 d	0.32 ± 0.09 d	1.06 ± 0.07 bc	1.07 ± 0.08 bc	0.96 ± 0.12 c	1.05 ± 0.09 bc	1.55 ± 0.42 ab	1.94 ± 0.25 a
NO_3^- ($\mathrm{mg \cdot kg^{-1}}$)	11.3 ± 1.02 d	40.0 ± 7.50 b	24.2 ± 3.00 cd	28.9 ± 3.80 bc	23.2 ± 3.17 cd	23.9 ± 3.45 cd	58.7 ± 4.70 a	73.2 ± 10.0 a
Available P ($\mathrm{mg \cdot kg^{-1}}$)	21.5 ± 2.35 d	61.7 ± 3.04 d	38.6 ± 7.02 d	279 ± 32.2 c	31.7 ± 2.42 d	291 ± 40.7 c	415 ± 42.5 b	808 ± 54.7 a
Exchangeable K ($\mathrm{mg \cdot kg^{-1}}$)	6.84 ± 1.47 b	23.1 ± 5.38 b	8.18 ± 1.52 b	9.43 ± 0.92 b	18.9 ± 3.08 b	25.3 ± 6.31 b	30.5 ± 5.57 b	115 ± 26.9 a
CEC ($\mathrm{cmol \cdot kg^{-1}}$)	3.84 ± 0.09 e	3.52 ± 0.08 f	4.60 ± 0.08 c	4.27 ± 0.10 d	3.91 ± 0.05 e	5.15 ± 0.11 b	6.26 ± 0.10 a	5.25 ± 0.08 b
Bulk density ($\mathrm{g \cdot cm^{-3}}$)	1.71 ± 0.03 a	1.73 ± 0.03 a	1.71 ± 0.02 a	1.71 ± 0.03 a	1.71 ± 0.03 a	1.73 ± 0.03 a	1.72 ± 0.03 a	1.72 ± 0.03 a
SOC stock ($\mathrm{Mg \cdot ha^{-1}}$)	17.3 ± 1.03 f	25.6 ± 0.40 c	20.3 ± 0.76 ef	24.1 ± 0.34 cd	21.6 ± 1.09 de	27.4 ± 1.97 c	37.3 ± 1.26 b	42.0 ± 2.01 a

Note: Different letters indicate significant differences ($p < 0.05$) among treatments. Control, no amendments; $\mathrm{CR_I}$, crop residue incorporation; $\mathrm{N_F}$, $\mathrm{NP_F}$, $\mathrm{NK_F}$ and $\mathrm{NPK_F}$, refer to N, NP and NK, NPK fertilizer applications, respectively; $\mathrm{NPK_FCR_I}$, combination of $\mathrm{NPK_F}$ and $\mathrm{CR_I}$ treatments; and $\mathrm{NPK_FCP_A}$, combination of $\mathrm{NPK_F}$ and CP addition. EC, electrical conductivity; WFPS, water-filled pore space; OM, organic matter; OC, organic carbon; CEC, cation exchange capacity; SOC, soil organic carbon.

fertilizers[54]. A review covering tropical and sub-tropical regions across 13 countries found an average annual direct N_2O EF of 1.19%, ranging from 0.70% to 2.10%, with the lowest values observed in Malaysia and Puerto Rico (0.70%)[55]. Similarly, a study on chemical fertilizer application in maize in Thailand reported an average direct N_2O EF of 0.71%[56]. These findings indicate that the average EF observed in the present study is consistent with other studies conducted in similar climate zones. Collectively, these results underscore the necessity of country- or region-specific N_2O EFs, or even

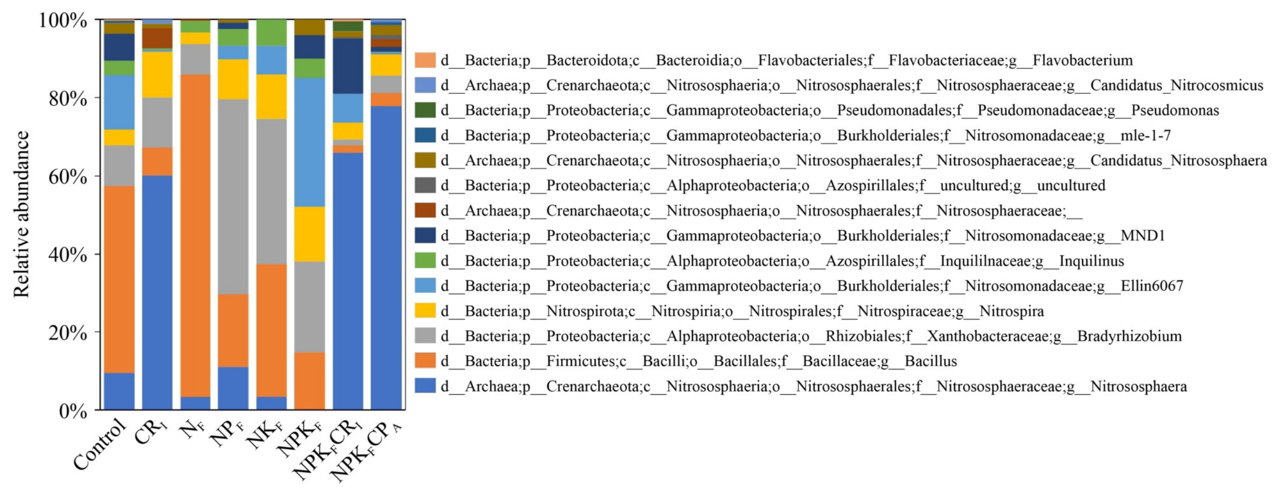

Fig. 4 Genus-level taxonomic profiles of nitrifiers and denitrifiers during cassava production in the 2021 season. Control, no amendments; CR_I, crop residue incorporation; N_F, NP_F, NK_F and NPK_F, refer to N, NP and NK, NPK fertilizer applications, respectively; NPK_FCR_I, combination of NPK_F and CR_I treatments; and NPK_FCP_A, combination of NPK_F and CP addition.

system-specific values, as reliance on IPCC default values may lead to significant inaccuracies in GHG emission estimates[57].

The N_2O emissions intensity per unit yield highlighted the NPK_FCR_I treatment as the most efficient practice in balancing environmental and food security objectives. However, additional mitigation strategies, such as optimized N fertilizer application or integration with nitrification inhibitors, are recommended to minimize excess N inputs and reduce N_2O emissions[58]. Combining nitrification inhibitors with fertilizers can enhance N use efficiency, reduce N losses and lower N_2O emissions without compromising yield or quality[59,60]. This integrated approach offers a sustainable pathway for cassava production, addressing both productivity and environmental concerns.

4.2 Changes in soil properties and crop production by diverse long-term fertilizations

Long-term mineral fertilizer application (47 years) resulted in significant soil acidification (Table 6). N fertilizer-induced nitrification has been identified as a primary mechanism driving soil acidification[61,62]. The proton production associated with nitrification processes contributes to the lowering of soil pH[45,61]. Wang et al.[63] indicated that ammonium nitrate and urea applications lowered soil pH by 0.18–1.7 units, whereas organic N additions caused less acidification due to slower nitrification rates. Similarly, the alkalinity of the compost was found to ameliorate soil acidity in NPK_FCP_A treatment compared to other fertilizer application regimes. Substantial acidification associated with prolonged mineral fertilizer application was identified as a critical factor reducing cassava growth and yield[64]. Although cassava can tolerate acidic soils, its optimal pH range lies between 5.5 and 7.5[65]. Thus, strategies to mitigate soil acidification, such as the application of dolomite[66], lime[65] or biochar[67,68], are recommended. Biochar, in particular, has shown promise in enhancing soil pH and mitigating re-acidification over time[67]. The application of NPK fertilizers resulted in nutrient accumulation in the post-harvest soil, mirroring the nutrient composition of the applied fertilizers. The findings highlighted that the absence of K in fertilizer applications significantly reduced cassava growth and yield (Table 5). For instance, the absence of K in fertilizer applications led to a 60.7% yield reduction in the N_F treatment and a 42.8% reduction in the NP_F treatment. These results underscore the critical roles of balancing N, P, and K for optimal cassava growth, with N and K exerting greater influence than P (Table S3). This aligns with findings by Janket et al.[69], who reported nutrient uptake requirements of 21.1–32.4 g N, 5.1–6.0 g P, and 26.5–31.3 g K per plant for optimal cassava biomass and root production.

The incorporation of CR outperformed CP addition in this study, resulting in a 36.8% higher cassava yield when combined with NPK fertilizers. This outcome is likely to be due to the relatively higher K content in CP, which, at excessive levels, inhibited cassava root development and growth. Xu et al.[70] demonstrated that excessive K supply reduces root-shoot ratio, root activity and NO_3^- ion flow, ultimately impairing photosynthetic efficiency and plant productivity. These findings suggest that CR, which provides balanced nutrient inputs, is more suitable than CP in the study area. Organic amendments also enhanced soil cation exchange capacity, particularly in the NPK_FCR_I treatment. Cooper et al.[71] attributed this effect to the increase in total OC associated with organic amendments.

The organic amendments (CR and CP) significantly enhanced SOC sequestration, consistent with the findings of Menšík et al.[72] and Wang et al.[73]. After the 2022 season (47 years of application), SOC sequestration under the CR_I treatment increased by 48.0% compared to the control, corresponding to the removal of 30.4 $Mg \cdot ha^{-1}$ CO_2 from the atmosphere. Similarly, the NPK_FCR_I and NPK_FCP_A treatments increased SOC by 36.1% (removing 36.3 $Mg \cdot ha^{-1}$ CO_2) and 53.3% (removing 53.5 $Mg \cdot ha^{-1}$ CO_2), respectively, relative to the NPK_F treatment. This improvement is attributed to the mineralization of OC by microbial activity, which releases nutrients that promote plant growth[74]. Enhanced plant growth contributes to SOC storage through increased net primary productivity, root litter, and root exudation[50,75]. Zhao et al.[76] further emphasized that organic amendments enhance SOC storage by sequestering C in stable macroaggregates and microaggregates. Similarly, Mi et al.[77] reported that the combined application of NPK fertilizers with organic amendments improved soil aggregate stability, particularly macroaggregates (> 0.25 mm) and contributed to SOC enrichment.

This long-term study highlights that combining mineral fertilizers with organic amendments, particularly CR, sustains soil quality, enhances SOC sequestration and improves crop yields while mitigating GHG emissions per unit yield. Menšík et al.[72] also observed that organic amendments contribute to long-term stable crop yields and optimal soil quality. Additionally, Munyahali et al.[78] demonstrated that combining mineral and organic amendments resulted in greater cassava growth and yields compared to mineral fertilizer application alone.

To optimize cassava yield while improving soil quality and mitigating GHG emissions, the proportional adjustment of mineral fertilizers and organic amendments, such as increasing the proportion of CR while reducing mineral fertilizer applications, is recommended. Such integrated approaches can enhance soil health, ensure sustainable productivity and reduce the environmental footprint of cassava production systems.

5 Conclusions

This study, based on a 47-year-long fertilizer management experiment in cassava production in Thailand, revealed that organic carbon inputs from CR and CP significantly influenced CO_2 emissions through organic matter decomposition. N inputs from both mineral fertilizers and organic amendments stimulated N_2O emissions primarily via nitrification. For soil properties, specific nutrient additions led to the accumulation of applied nutrients. Mineral fertilizer application intensified soil acidification, whereas organic amendments, including CR and CP, enhanced SOC sequestration. CP addition also improved soil pH and increased P and K levels. Among the evaluated practices, the combined application of NPK fertilizers with CR (NPK_FCR_I treatment) involved the highest C and N inputs, resulting in the highest GHG emissions. However, this practice also achieved the highest cassava yield, leading to the statistically lowest GHG emissions intensity per unit yield. Consequently, the NPK_FCR_I treatment practice is recommended for cassava production systems. To enhance its sustainability, additional soil management strategies should be implemented to mitigate soil acidification and GHG emissions. These may include periodic applications of lime, dolomite or biochar to stabilize soil pH, prevent yield declines associated with soil acidity, and enhance GHG mitigation potential. Additionally, the use of nitrification inhibitors is recommended to suppress N_2O emissions without compromising yield, thereby promoting sustainable cassava production with improved environmental outcomes.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2025641 contains supplementary materials (Fig. S1; Tables S1–S4).

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Compliance with ethics guidelines

Patikorn Sriphirom, Amnat Chidthaisong, Wanlee Amornpon, Kazuyuki Yagi, Wanida Nobuntou, Nimaradee Boonapatcharoen, and Wantanasak Suksong declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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