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Green horizons: Using fodder crops to harness carbon and combat climate change

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Abstract

Climate change, influenced by both natural processes and human activities, has notably transformed Earth's atmospheric composition, primarily due to heightened energy use in industrial and agricultural sectors. To combat this, a study was conducted focusing on soil management strategies, particularly using cumbu napier hybrid grass, to mitigate climate change by enhancing carbon sequestration. The research evaluated the effects of different nutrient sources including inorganic fertilizers, farmyard manure (FYM), poultry manure (PM) and biofertilizers like *Arbuscular mycorrhiza* (AM) and Azophos on greenhouse gas (GHG) emissions, soil carbon pools and soil organic carbon (SOC). The findings revealed that integrating organic manures with biofertilizers, particularly in the treatment involving PM at 75 % nitrogen equivalent combined with AM and Azophos (T_{10}), significantly increased SOC levels (1.04 %) and lowered GHG emissions. This treatment also recorded the highest levels of soil inorganic carbon (0.131 %), passive carbon (7890 mg kg^{-1}), permanent soil carbon stock (14.91 t ha^{-1}year^{-1}), carbon pool index (1.37), carbon management index (201.1) and green fodder yield (370.2 t ha^{-1} year^{-1}). On the other hand, the treatment with FYM alone at 100 % nitrogen equivalent (T_7) resulted in the highest CO_2 emissions (71.4 t ha^{-1}year^{-1}), while the untreated control plot (T_{11}) exhibited the highest global warming potential (GWP). This study underscores the effectiveness of strategic soil management in forage crop systems as a sustainable method to boost soil health, increase carbon sequestration and reduce GHG emissions, thus contributing to climate change mitigation.

Keywords

Biofertilizers; carbon sequestration; carbon pools; fertilizers; manures; soil organic carbon

Introduction

Climate change denotes long-term shifts in atmospheric characteristics resulting from natural phenomena and human actions. In recent decades, the composition of gases in the Earth's atmosphere has altered considerably, mainly due to energy use in the industrial and agricultural sectors. Practices such as deforestation, intensive farming, land use modifications and diverse management strategies have increased the emissions of N_2O, CO_2, CH_4 and other GHGs (1). The yearly increase in atmospheric CO_2 was approximately 0.8 ppm in 1960s whereas it was 2.13 ppm in 2021-2022. This trajectory is expected to have severe and possibly irreversible consequences on the environment and human society, such as higher sea levels, more frequent and intense weather events and shortages of food and water (2). To mitigate climate change, long-term carbon sequestration is a straightforward and effective approach that is achievable in agriculture through soil carbon storage. SOC, the primary component of SOM, is crucial for supplying plant nutrients and maintaining soil health. CO_2 is released from soils when organic residues or soil organic matter (SOM) are oxidized by soil fauna and below-ground roots.

Forage crops, a diverse group of plants used to feed livestock, play a key role in global food systems and livestock production. In addition to providing animal feed, forage crops offer a valuable opportunity for climate change mitigation by sequestering carbon in the soil. Soil, as a dynamic carbon reservoir, can serve as a sink for CO_2 in the atmosphere, thus helping to counterbalance greenhouse gas emissions from human activities. According to a study, grass-type forages, notably fodder grass, play a significant role in carbon sequestration, particularly through long-term storage in roots, which is the below-ground portion (3). This ability makes them effective at rapidly saturating carbon levels, especially where mitigating climate change is essential. Across several fodder crops, the cumbu napier stood out for its high carbon removal both above and below ground.

Enhancing carbon sequestration through strategic nutrient management techniques, particularly in forage crop systems, is a promising strategy for addressing climate change in agriculture. The incorporation of organic manures such as poultry manure and farmyard manure into the soil can increase soil organic matter, potentially leading to reduced greenhouse gas (GHG) emissions (4). When combined with biofertilizers, this approach may further contribute to GHG reduction. Considering these factors, the current study aimed to investigate nutrient management practices, including the application of biofertilizers such as *Arbuscular mycorrhizal* fungi and Azophos. These practices are intended to enhance soil nitrogen levels, thereby reducing the need for nitrogen fertilizers and potentially decreasing GHG emissions while also increasing carbon storage in the soil. This study also evaluated the impact of these practices on soil conditions and productivity of cumbu napier hybrid grass, a crucial aspect of sustainable forage crop management.

Materials and Methods

Experimental site

An investigation was carried out from December, 2022 to, March, 2024 at Tamil Nadu Agricultural University, Coimbatore, to assess carbon sequestration potential and greenhouse gas mitigation under various nutrient sources for cumbu napier fodder crop. The trial site is situated at latitude of 11.01° N and a longitude of 77.10° E in the Coimbatore district, at the foothills of the Western Ghats, with an altitude of 426 m above mean sea level (MSL). The weather and climate at the experimental site included a mean annual rainfall of 746.5 mm distributed over 47 rainy days. The average annual maximum and minimum temperature was 31.8 °C and 21.4 °C respectively.

The experimental initial soil was classified as sandy clay loam, medium (0.64 %) organic carbon (Fig. 1), field capacity of 26.52 %, a permanent wilting point of 13.53 % and a bulk density of 1.30 mg m^{-3}. Initially, the soil had an alkaline pH of 8.09 and an electrical conductivity (EC) of 0.413 d Sm^{-1} and it indicates a relatively low level of soil salinity. However, the initial soil fertility status indicated low available N (173 kg ha^{-1}), medium available P (17.8 kg ha^{-1}) and high available K (503 kg ha^{-1}).

Treatments and experimental setup

The experiment utilized 11 treatments in a randomized block design (RBD) with 3 replications of each treatment. The treatments in the field experiments were as follows: T_1 - recommended fertilizer dose, T_2 - soil test-based recommendation, T_3 - T_2 with added *Arbuscular mycorrhiza*, T_4 - T_2 with added Azophos, T_5 - T_2 with both *Arbuscular mycorrhiza* and Azophos, T_6 - soil test-based recommendation (75 % N + 100 % P_2O_5 +75 % K_2O) with added *Arbuscular mycorrhiza* and Azophos, T_7 - FYM at 100 % N equivalent, T_8 - PM at 100 % N equivalent, T_9 - FYM at 75 % N equivalent with added *Arbuscular mycorrhiza* and Azophos, T_{10} - PM at 75 % N equivalent with added *Arbuscular mycorrhiza* and Azophos and T_{11}- absolute control.

Fertilizer, manure and bio fertilizer application

The prescribed amounts of fertilizers for cumbu napier hybrid CO (5) were 150 kg of nitrogen (N), 50 kg of phosphorus (P_2O_5) and 40 kg of potassium (K_2O)/ha. Initially, 100 % P and K, along with 50 % nitrogen, were applied before planting. The remaining 50 % N was applied 30 days after planting. Additionally, for the treatment with the recommended fertilizer dose (T_1), a basal application of 75 kg of nitrogen per cut was applied.

The soil test-based recommendation treatments (T_2) included full doses of nitrogen (100 %), phosphorus (100 % P_2O_5) and 75 % potassium (K_2O), the treatments receiving bio fertilizers viz., *Arbuscular mycorrhiza* applied at 2000 g ha^{-1} and Azophos applied at 4000 g ha^{-1} during initial stage of the planting. The treatments receiving organic manures such as poultry manure and farmyard manure were applied based on nitrogen equivalent basis.

All recommended intercultural operations were performed accordingly. Cumbu napier green fodder yield was measured initially at 85 days after planting and subsequently at intervals of 45-50 days thereafter. A total of 7 cuts were taken per year to assess the impact of various soil management practices on carbon sequestration, green fodder yield and greenhouse gas mitigation in the cumbu napier field.

Carbon pools

Water-soluble carbon was measured by taking a known volume of soil, mixing it with distilled water, centrifuging the mixture and filtering the supernatant. The filtrate was then reacted with $K_2Cr_2O_7$, H_2SO_4 and H_3PO_4, digested at 150 °C and titrated with ferrous ammonium sulphate (FAS) using diphenylamine as an indicator (5). Labile carbon (LC) was measured by shaking a soil sample with 0.2 M $KMnO_4$ and distilled water at 120 rpm. After allowing the suspension to settle, 0.25 mL was extracted, diluted and analyzed using a spectrophotometer at 550 nm. The amount of remaining $KMnO_4$ was determined from standard values and the portion consumed was used to calculate LC (6).

The modified Walkley and Black method was employed to estimate oxidizable organic carbon (OOC) fractions, as outlined (7) and OOC fractions were obtained using H_2SO_4 solutions of varying concentrations: 12N, 18N and 24N, with ratios of 0.5:1, 1:1 and 2:1 respectively. These ratios facilitated the division of total organic carbon into 4 successive fractions based on their decreasing oxidizability or lability.

Fraction 1 (very labile): Organic carbon oxidizable with 12N H_2SO_4.

Fraction 2 (labile): Difference in oxidizable organic carbon between 18N and 12N H_2SO_4.

Fraction 3 (less labile): Difference in oxidizable organic carbon between 24N and 18N H_2SO_4.

Fraction 4 (recalcitrant): Difference in oxidizable organic carbon after treatment with 24N H_2SO_4.

The initial assessment of SOC was performed with wet digestion method, followed by a reassessment after one year (8). The dry matter carbon content was multiplied to find the carbon below and above ground. The dry combustion method, as outlined (9), was used in the laboratory to assess the dry matter and carbon content of plant biomass. The CO_2 removal was then calculated based on C content, biomass yield and DMP by multiplying carbon content by a factor of 3.67.

Soil carbon stock

The SOC stock was determined (10) and using the total organic carbon (TOC), bulk density (BD) and soil depth (D).

$$\text{C stock (t ha}^{-1}) = \text{TOC} * \text{BD} * \text{D}$$

Carbon management index (CMI)

An indicator of how land management techniques affect soil carbon dynamics is the CMI. It aids in evaluating the sustainability of agricultural practices concerning soil health and carbon sequestration. The CMI is based on 2 main components:

$$\text{Carbon management index (CMI)} = \text{CPI} * \text{LI} * 100$$

$$\text{Carbon pool index (CPI)} = \frac{\text{Sample soil TOC}}{\text{Reference soil TOC}}$$

$$\text{Lability index (LI)} = \frac{\text{Sample soil LC}}{\text{Reference soil LC}}$$

$$\text{Lability of carbon (LC)} = \frac{\text{KMnO4 Oxidized fraction}}{\text{KMnO4 unoxidized C}}$$

Estimation of greenhouse gases

Gas sampling and analysis

Sampling of Gases

During the fodder growing season, gas samples were collected from the soil using the closed chamber method. A syringe was used to gather the gases, which were then stored in glass vacuum vials sealed with airtight butyl rubber stoppers. The chamber was equipped with a motorized fan, powered by batteries to ensure thorough mixing of the gases. Gas samples were collected between 8 a.m. and 10 a.m., at intervals of 0, 15 and 30 min after placing the chamber, using an airtight syringe (11). Additionally, samples were collected 2 days after each green fodder harvest and were analyzed for CO_2 and N_2O concentrations.

The collected samples from experimental plots were examined using gas chromatography. The greenhouse gases in the sample vials were detected using a flame ionization detector (FID) and an electron capture detector (ECD). Samples were introduced into a gas chromatograph by filling a fixed 1.0 mL loop. Calibration of the gas chromatograph was performed prior to sample analysis using a primary standard. The emissions of CO_2 and nitrous oxide were expressed as CO_2 equivalents in kg ha^{-1} $year^{-1}$.

The measured concentrations of CO_2 and N_2O at different times were used to calculate the hourly flux using equations proposed for N_2O (12) and for CO_2 (13). The equations are as follows

$$f \text{ for } N_2O = \frac{V}{A} \times \frac{\Delta C}{\Delta t} \times \rho \times \frac{273}{273 + T}$$

$$f \text{ for } CO_2 = \frac{V}{A} \times \frac{\Delta C}{\Delta t}$$

Where

f	-	Hourly gas flux
V	-	Volume of the chamber (m^3)
A	-	Area of the chamber (m^2)
$\Delta C/\Delta t$	-	Concentration change over time
ρ	-	Gas density at 0 °C (N_2O - 1.977 kg m^{-3})

Conversion of N_2O to CO_2 equivalents

The direct emission factors and overall global warming potential (GWP) values for N_2O were estimated using the IPCC approach, as described (14, 15). CO_2 and N_2O gas fluxes were measured through linear regression and integrated using linear interpolation to calculate the total annual emissions of CO_2 and N_2O. To evaluate the net greenhouse gas (GHG) balance, including the impact of organic matter application on soil carbon sequestration, N_2O emissions were calculated with a global warming potential (GWP) factor of 300 to convert them into CO_2 equivalents.

Statistical analysis

The data obtained from 3 replications of 11 treatments were subjected to statistical analysis via analysis of variance (16). Critical differences were computed for treatments exhibiting significant differences at the 5 % probability level, while treatments lacking significant differences were denoted as NS (non-significant).

Results and Discussions

SOC is vital to maintaining soil fertility and supporting ecosystem functions. It serves as a key energy source for soil microorganisms and plays an integral role in improving water retention, soil structure and nutrient cycling. SOC is also crucial for combating climate change by sequestering atmospheric CO_2 and boosting soil resilience. Due to its importance, examining how different nutrient management practices affect SOC levels is crucial for advancing sustainable agriculture. This study focuses on assessing the effects of various treatments on SOC content, soil carbon pools, carbon balance and CO_2 removal after seven harvests of cumbu napier fodder**.**

Soil organic carbon

SOC content is the main source of energy for microorganisms in terrestrial ecosystems, SOC is essential for these ecosystems to function and is also responsible for controlling soil structure and ecosystem production. At the end of the 7th harvest of green fodder, the soil organic carbon levels varied between 0.53 % and 1.04 % (Fig. 1). Among the treatments, the highest SOC was observed in T_{10} - PM (N equivalent basis - 75 % N) + *Arbuscular mycorrhiza* + Azophos (1.04 %), followed by T_9 - FYM (N equivalent basis - 75 % N) + *Arbuscular mycorrhiza* + Azophos (1.01 %), while the lowest was found in T_{11} absolute control (0.53 %).

The SOC in soil is influenced by various soil properties, including pH, soil nutrient supply and soil microbial biomass (17). The soil microbial load increases the SOC and therefore the increased SOC in T_{10} was due to the increased soil bacterial and fungal populations caused by the application of poultry manure along with biofertilizers. The application of poultry manure in combination with biofertilizers increased the soil temperature, enhanced soil moisture levels and boosted the humus content by addition of organic matter. This could have resulted in an increase in SOC (18). The use of poultry manure in combination with *Arbuscular mycorrhiza* and Azophos significantly boosts SOC by augmenting organic matter, enhancing microbial activity and improving soil structure. This integrated approach not only elevates SOC levels but also enhances overall soil health and fertility, making it a sustainable practice for agricultural systems (19).

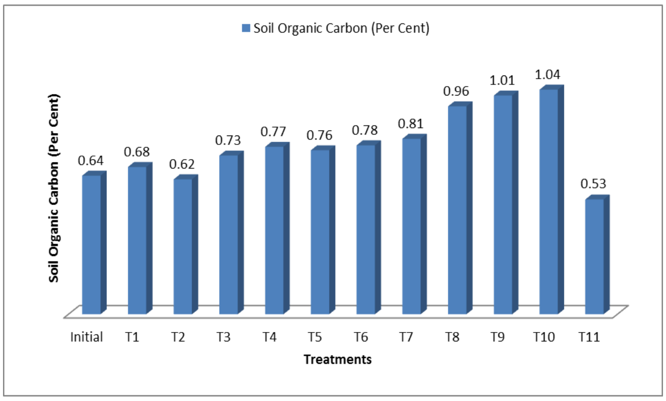

Fig. 1. Impact of inorganics, organics and bio fertilizers on soil organic carbon (per cent) in cumbu napier field.

Soil carbon pools

Soil carbon pools are essential for comprehending the role of soils in carbon dynamics, ecosystem sustainability and efforts to mitigate climate change. These pools include both organic and inorganic carbon stored within the soil, each exhibiting varying degrees of stability and decomposition rates. Soil inorganic carbon (SIC) substantially contributes to terrestrial carbon stocks, particularly in semiarid and arid regions. SIC plays a crucial role in agriculture, carbon dioxide (CO_2) emission and sequestration and climate regulation (20). Assessing soil inorganic carbon levels can offer valuable information regarding carbon storage and efforts toward climate change mitigation. At the end of the 7th cutting, the average soil inorganic carbon (SIC) content ranged from 0.065 to 0.131 %. Out of all the treatments, the one with the greatest SIC value was T_{10} - PM (N equivalent basis - 75 % N) + *Arbuscular mycorrhiza* + Azophos (0.131 %), lowest was found in (T_{11}) absolute control (0.065 %). The application of poultry manure at 75 % N equivalent along with biofertilizers has positive implications for inorganic carbon sequestration in soils, primarily through processes that enhance soil structure, microbial activity, carbonate precipitation and overall soil health. This practice not only aids in mitigating climate change but also supports sustainable agricultural practices (21).

Labile carbon is a component of SOC and functions as a soil quality indicator (22). The labile carbon significantly influences the SOM and serves as an early indicator for assessing soil quality changes due to soil management (23). Labile carbon originates from microbial biomass, roots and root exudates. The labile carbon fraction is directly accessible to microbial activity and serves as the primary energy source for microorganisms in the soil. The mean 7th harvest of the green fodder soil sample carbon pools for very labile, labile and less labile carbon ranged from 0.11 - 0.169 %, 0.125 - 0.183 % and 0.094 - 0.220 % respectively (Table 1). The treatment with highest very labile carbon content was found in T_7 - FYM at 100 % N equivalent basis (0.169 %), while the lowest was the T_2 - soil test value-based recommendation treatment (0.11 %). This fraction is highly reactive, representing the most easily decomposable organic matter in soil. A study demonstrated that organic amendments such as FYM and plant residues can significantly boost the very labile

Table 1. Impact of inorganics, organics and biofertilizers on soil carbon pools in cumbu napier field (per cent).

Treatment Details	Soil Inorganic Carbon	Very labile C	Labile C	Less labile C	Non labile C
T_1 - Recommended dose of fertilizer (RDF)	0.085	0.114	0.130	0.120	0.264
T_2 - Soil Test based recommendation	0.078	0.110	0.125	0.130	0.287
T_3 - T_2 + *Arbuscular mycorrhiza (AM)*	0.093	0.112	0.131	0.130	0.285
T_4 - T_2 + (Azophos)	0.097	0.137	0.130	0.137	0.286
T_5 - T_2 + (*AM* + Azophos)	0.079	0.124	0.159	0.125	0.252
T_6 - (75 % N + 100 % P_2O_5 +100 % K_2O) + (*AM* + Azophos)	0.089	0.143	0.126	0.115	0.254
T_7 - FYM (N equivalent basis - 100 % N)	0.102	0.169	0.135	0.143	0.315
T_8- PM (N equivalent basis-100 % N)	0.121	0.125	0.171	0.211	0.359
T_9 - FYM (N equivalent basis – 75 % N) + (*AM* + Azophos)	0.127	0.108	0.131	0.220	0.330
T_{10} - PM (N equivalent basis - 75 % N) + (*AM* + Azophos)	0.131	0.120	0.183	0.205	0.390
T_{11}- Absolute Control	0.065	0.126	0.129	0.094	0.207
MEAN	**0.097**	**0.126**	**0.141**	**0.148**	**0.294**
SE(d)	**0.005**	**0.026**	**0.023**	**0.014**	**0.02**
CD (P=0.05)	**0.011**	**NS**	**NS**	**0.029**	**0.043**

carbon content in soils (24) and found that organic amendments, especially FYM, enhance microbial activity, leading to more rapid decomposition of organic matter and an increase in the very labile carbon pool.

Labile carbon is an intermediary pool that is crucial for nutrient mineralization and carbon turnover, acting as a link between very labile carbon and more stable forms such as less labile and recalcitrant carbon. At the end of one year (7th cut), the high soil labile carbon was observed in the T_{10} - PM at N equivalent basis - 75 % N + *Arbuscular mycorrhiza* and Azophos treatment (0.183 %) and the lowest labile C content was recorded in the T_2 - soil test value-based recommendation (0.125 %). Labile carbon pools are responsive indicators of soil management practices, with increased levels observed in soils managed with organic inputs and sustainable practices. The incorporation of *Arbuscular mycorrhiza* and biofertilizers, which was evident in treatments with elevated labile carbon levels, has been shown to enhance labile carbon by stimulating root exudation and boosting microbial biomass in the rhizosphere (25).

The less labile carbon was highest in the T_9- FYM at N equivalent basis - 75 % N + *Arbuscular mycorrhiza* and Azophos treatment (0.220 %), lowest was observed in T_{11} - absolute control (0.094 %). Less labile carbon represents more stable organic matter that decomposes at a slower rate, thereby contributing to long-term carbon storage in the soil. Research has demonstrated that its levels increase with the application of organic amendments such as FYM and compost, which contain complex organic compounds that are resistant to rapid decomposition (26). A Study have shown that these organic amendments help accumulate less labile carbon, thereby enhancing the soil's ability to sequester carbon over longer periods (27).

Non labile carbon can withstand microbial decomposition and has remained in the soil for decade to centuries. This long-term carbon storage helps reduce atmospheric CO_2 by sequestering carbon in stable forms. As significant carbon sinks, soils can lower the concentration of carbon dioxide, a major greenhouse gas, in the atmosphere, playing a crucial role in mitigating climate change. The mean soil non-labile carbon ranged from 0.207 % to 0.390 %. The highest non-labile carbon content was observed in T_{10} - PM at N equivalent basis - 75 % N + *Arbuscular mycorrhiza* and Azophos treatment (0.390 %), lowest recorded in T_{11} - absolute control (0.207 %). The application of poultry manure, farmyard manure and biofertilizers has significant potential to enhance soil carbon pools. The role of non-labile carbon in soils under different cropping systems was investigated (28) and the findings revealed that soils receiving regular organic inputs, including poultry manure, compost and biofertilizers had significantly higher non-labile carbon content compared to control treatments. This increase was attributed to the slow decomposition and stabilization of organic matter from these inputs. Each amendment contributes uniquely to SOC dynamics and their combined use can lead to synergistic benefits. Implementing these practices as part of an integrated soil management strategy can improve soil health, enhance carbon sequestration and support sustainable agricultural productivity (29).

Soil carbon balance

Maintaining the carbon balance in soil is essential for preserving soil fertility, structure and health, which are critical for plant growth and agricultural productivity. Storage of carbon and lowering of greenhouse gas emissions also contribute significantly to the alleviation of climate change. Additionally, the soil carbon balance supports water retention, erosion control and sustainable land management practices, which are vital for preserving biodiversity and ecosystem services. Therefore, sustainable management of soil carbon is fundamental to environmental sustainability and agricultural resilience.

The carbon balance, permanent soil carbon stock and added SOC in the passive carbon pool (t $ha^{-1}year^{-1}$) were estimated using water-soluble carbon, Walkley and Black carbon, $KMnO_4$ carbon (active C) and bulk density. The soil carbon balance results are presented in Table 2, showing significant variations across treatments. The greatest amount of water-soluble carbon was noted in T_9 - FYM (N equivalent basis - 75 % N) + *Arbuscular mycorrhiza* and Azophos (1370 mg kg^{-1}), lowest was found in T_{11} - absolute control (590 mg kg^{-1}). This difference is likely due to the application of farmyard manure and biofertilizers, which increase root exudates and consequently, the water-soluble carbon content in the soil. In a study, it was found that water-soluble carbon levels were significantly higher in soils amended with FYM and *Arbuscular mycorrhizae* compared to those that were not treated (30). This increase was attributed to the enhanced microbial activity and decomposition of organic matter driven by these amendments. Similarly, a study noted that organic amendments, such as farmyard manure and biofertilizers, led to a substantial rise in WSC levels (31). Their research indicated that the boost in WSC was due to increased root exudates and microbial activity associated with these treatments.

Similarly, significant differences found in Walkley and Black carbon, $KMnO_4$ oxidizable carbon (active pool carbon) and bulk density, The T_{10} - PM (N equivalent basis - 75 % N) + *Arbuscular mycorrhiza* and Azophos exhibited the highest soil SOC at 10,370 mg kg^{-1}, while T_2 - soil test value-based recommendation showed the lowest at 6230 mg kg^{-1}. The highest $KMnO_4$ oxidizable carbon was found in T_8 - PM (N equivalent basis-100 % N) at 1220 mg kg^{-1}, lowest was documented in T_1 - recommended dose of fertilizer treatment of 840 mg kg^{-1}. Treatment with the highest soil passive carbon content (mg kg^{-1}) was T_{10} - PM (N equivalent basis - 75 % N) + *Arbuscular mycorrhiza* and Azophos, registering at 7890 mg kg^{-1}. Conversely, the lowest passive carbon content was observed in T_1 - recommended dose of fertilizer (4500 mg kg^{-1}).

The research highlighted the influence of different organic amendments on soil carbon pools, noting that treatments with farmyard manure, poultry manure and biofertilizers significantly increased soil organic carbon compared to conventional fertilization methods (32). They observed that such organic amendments improved SOC by enhancing microbial activity and organic matter decomposition. In terms of $KMnO_4$ oxidizable carbon, studies demonstrated that this active carbon pool, which reflects readily decomposable carbon, was notably higher in soils treated with organic inputs like farmyard manure (33). Their findings aligned with previous work, who reported that organic amendments increased $KMnO_4$ oxidizable carbon due to their role in stimulating microbial activity and promoting carbon turnover (34). Regarding soil passive carbon content, research indicated that organic treatments not only enhanced active carbon pools but also contributed to greater passive carbon storage (35). The combined use of poultry manure and biofertilizers has a synergistic effect on soil carbon balance, significantly enhancing both SOC pools. This integrated approach leverages the nutrient richness of poultry manure and the microbial activity stimulated by biofertilizers, resulting in greater microbial activity, better soil structure and greater plant development (36).

Table 2. Impact of inorganics, organics and bio fertilizers on soil carbon balance in cumbu napier field.

Treatment Details	**Water-soluble carbon (mg/kg) (1)**	**Walkley and Black C(mg/kg) (2)**	**$KMnO_4$ carbon (Active C) (mg/kg) (3)**	**Passive carbon (mg/kg) (4) = (2) – (1+3)**	**PSOC (%) (5)**	**Permanent soil carbon stock (t/ha/year) (6) = (5) *(7)* Depth**	**Bulk density (Mg/m^3) (7)**	**Added SOC in passive carbon pool (t/ha/year)(8)**
Initial Soil Sample	**655**	**6400**	**850**	**4895**	**0.49**	**9.10**	**1.24**	
T_1 - Recommended dose of fertilizer (RDF)	820	6800	840	4500	0.45	8.37	1.24	**-0.73**
T_2 - Soil Test based recommendation	750	6230	850	5200	0.52	9.52	1.22	**0.41**
T_3 - T_2 + *Arbuscular mycorrhiza (AM)*	810	7330	780	5740	0.57	10.68	1.24	**1.57**
T_4 - T_2 + (Azophos)	850	7730	1050	5830	0.58	10.76	1.23	**1.65**
T_5 - T_2 + (*AM* + Azophos*)*	780	7570	910	5950	0.59	10.93	1.23	**2.56**
T_6 - (75 % N + 100 % P_2O_5 +100 % K_2O) + (*AM* + Azophos*)*	720	7800	1110	5970	0.59	10.88	1.22	**1.36**
T_7 - FYM (N equivalent basis - 100 % N)	890	8100	950	6260	0.62	12.49	1.33	**1.81**
T_8- PM (N equivalent basis-100 % N)	1310	9600	1220	7070	0.70	14.00	1.32	**3.24**
T_9 - FYM (N equivalent basis - 75 % N) + (*AM* + Azophos*)*	1370	10100	1040	7690	0.76	14.76	1.28	**3.83**
T_{10} - PM (N equivalent basis - 75 % N) + (*AM* + Azophos*)*	1280	10370	1200	7890	0.78	14.91	1.26	**4.03**
T_{11}- Absolute Control	590	6300	950	4760	0.47	8.85	1.24	**-3.63**
MEAN	**924**	**7994**	**991**	**6078**	**0.60**	**11.47**	**1.25**	**1.46**
SE(d)	**22.25**	**170.9**	**21.62**	**101.2**	**0.01**	**0.27**	**0.03**	**0.05**
CD (P=0.05)	**46.75**	**358.9**	**45.42**	**212.6**	**0.03**	**0.56**	**0.06**	**0.11**

Permanent soil carbon stock (t ha^{-1} year^{-1})

The presence of permanent passive soil carbon stock is crucial for ensuring long-term environmental health, agricultural sustainability and effective climate regulation. This stable and enduring carbon sink contributes greatly to reducing climate change, supporting soil health and fertility, promoting biodiversity and facilitating sustainable land management practices. The average soil permanent carbon stock varied between 8.37 and 14.91 t ha^{-1}year^{-1}. The highest permanent soil carbon stock was observed in T_{10} - PM (N equivalent basis - 75 % N) + *Arbuscular mycorrhiza* and Azophos at 14.91 t ha^{-1}year^{-1}, lowest value was noted in T_1 - recommended dose fertilizer at 8.37 t ha^{-1}year^{-1}. In a study, the impact of integrated nutrient management on soil carbon stocks was evaluated (37). The researchers found that combining organic inputs with biofertilizers led to significantly higher permanent soil carbon stocks. Specifically, *Arbuscular mycorrhizae* and Azophas markedly enhanced soil carbon sequestration compared to conventional fertilization methods.

The average added soil organic carbon in the passive pool ranged from -3.63 to 4.03 t ha^{-1}year^{-1}(Fig. 2). T_{10} - PM (N equivalent basis - 75 % N) + *Arbuscular mycorrhiza* and Azophos had the highest value of 4.03 t ha^{-1}year^{-1}, while T_{11} - absolute control had the lowest at -3.63 t ha^{-1}year^{-1}. The combined application of poultry manure along with AM fungi and Azophas had a synergistic effect on the passive soil organic carbon pool. This integrated approach enhances the stabilization of organic matter, promotes soil aggregation and increases microbial activity, leading to improved soil structure and long-term carbon sequestration. By incorporating these practices into an integrated soil management strategy, farmers can optimize carbon sequestration (38).

Carbon Management index (CMI)

The effects of various treatments on levels of Total Organic Carbon (TOC) were illustrated by the CMI. Values that are either below or above 100 signify a favourable or unfavourable impact on TOC content. The Lability Index (LI) and the Carbon Pool Index (CPI), which are both computed using reference values from natural, uncultivated soils are what determine the CMI.

Lability Index (LI) was greater in the T_1-RDF treatment than in the PM, FYM and bio fertilizer treatments. However, the carbon pool index (CPI) increased in the T_{10}treatment, which received PM (N equivalent basis - 75 % N) + *Arbuscular mycorrhiza* and Azophos. According to the results for CPI and LI, the highest CMI value was recorded in T_{10}(201.1), lowest was noted in T_1absolute control (127.9). The TOC content improved as a result of all treatments. The T_{10}, which included PM (N equivalent basis - 75 % N) + *Arbuscular mycorrhiza* and Azophos, exhibited the highest values and performed better in maintaining soil carbon. Research highlighted that treatments with a higher proportion of readily available organic inputs, such as farmyard manure (FYM) and synthetic fertilizers, tend to have higher LI values (39). This is because these treatments enhance microbial activity and accelerate the decomposition of organic matter. In contrast, treatments with more stable organic inputs generally show lower LI values (40).

The ratio between labile and recalcitrant carbon indicated the main type of carbon found in soil (Table 3). A value <1 suggests a high degree of lability in carbon, while a value greater than one indicates that recalcitrant carbon is predominant (41). Although all treatments with inorganic, biofertilizers and organic additions showed values greater than one, indicating a predominance of recalcitrant carbon, the T_{10} treatment (PM - N equivalent basis - 75 % N + *Arbuscular mycorrhiza* and Azophos) contained more carbon content than the rest. This suggests that the combination of organic inputs and biofertilizers effectively enhances the stability and accumulation of recalcitrant carbon in the soil (42).

Soil Carbon Stock

Maintaining and enhancing carbon stocks is crucial for reducing atmospheric CO_2 levels, improving soil fertility and promoting overall ecosystem resilience. Among the different treatments, T_{10} sequestered 19.6 t ha^{-1} of carbon, followed by T_9 with 19.4 t ha^{-1}year^{-1}and T_8 with 19.0 t ha^{-1} year^{-1} showed the highest soil carbon stock (Fig. 3). This could be because these specific treatments include biomass addition and recalcitrant carbon storage. Carbon is associated with micro aggregates, which protect it from degradation and allow for long-term storage (43). Research underscored the positive impact of biofertilizers along with manures on soil carbon stocks (44). They observed that biofertilizers and manures enhance microbial activity, which promotes the stabilization of organic matter and increases carbon sequestration in soils. This likely contributed to the higher carbon stock in T_{10}.

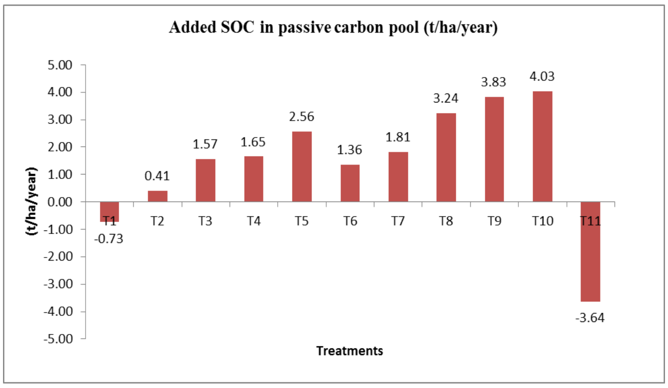

Fig. 2. Impact of inorganics, organics and bio fertilizers on added soil organic carbon in passive pool (t ha^{-1} year^{-1}) of cumbu napier field.

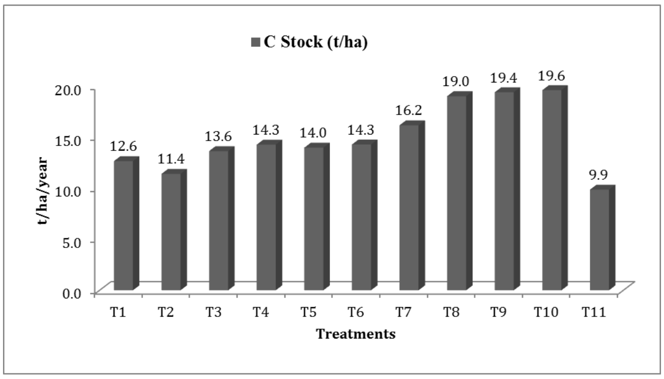

Fig. 3. Impact of inorganics, organics and bio fertilizers on Carbon stock (t ha^{-1} year^{-1}) of cumbu napier field.

Table 3. Impact of inorganics, organics and bio fertilizers on soil carbon management index in cumbu napier field.

Treatment Details	Carbon pool index	labiality index	Lability of carbon	Carbon management index
T_1 - Recommended dose of fertilizer (RDF)	0.94	1.64	0.13	127.9
T_2 - Soil Test based recommendation	0.86	1.50	0.15	129.5
T_3 - T_2 + (*Arbuscular mycorrhiza)*	1.04	1.35	0.13	140.1
T_4 - T_2 + (Azophos)	1.08	1.36	0.13	146.2
T_5 - T_2 + (*Arbuscular mycorrhiza* + Azophos*)*	1.02	1.58	0.16	161.5
T_6 - (75 % N + 100 % P_2O_5 +100 % K_2O) + (*Arbuscular mycorrhiza* + Azophos*)*	1.01	1.46	0.16	166.0
T_7 - FYM (N equivalent basis - 100 % N)	1.08	1.56	0.15	168.5
T_8- PM (N equivalent basis-100 % N)	1.23	1.37	0.13	187.2
T_9 - FYM (N equivalent basis – 75 % N) + (*Arbuscular mycorrhiza* + Azophos*)*	1.33	1.36	0.13	173.9
T_{10} - PM (N equivalent basis - 75 % N) + (*Arbuscular mycorrhiza* + Azophos*)*	1.37	1.30	0.16	201.1
T_{11}- Absolute Control	0.82	1.59	0.16	129.5
Mean	**1.07**	**1.48**	**0.14**	**157.4**
SE(d)	**0.02**	**0.03**	**0.002**	**3.37**
CD (P=0.05)	**0.05**	**0.07**	**0.005**	**7.09**

CO_2 removal from atmosphere by above ground biomass

To assess CO_2 removal, biomass yield was crucial. For every harvest, the above-ground portion's yield of green fodder was recorded. A relatively high biomass of 370.2 t $ha^{-1}year^{-1}$ was detected in PM (N equivalent base - 75 % N). + *Arbuscular mycorrhiza* and Azophos, followed by 362.1 t $ha^{-1}year^{-1}$in plots treated with FYM (N equivalent basis - 75 % N) + *Arbuscular mycorrhiza* and Azophos (Fig. 4).

The biomass yield was translated into dry matter yield in order to compute carbon removal from atmosphere. The highest dry matter production (DMP) was recorded in T_{10} (85.1 t $ha^{-1}year^{-1}$), with the lowest occurring in T_{11} absolute control plot (66.5 t $ha^{-1}year^{-1}$). Fig. 4 indicates that the above-ground carbon removal was greatest in plots treated with PM (N equivalent basis - 75 % N) + *Arbuscular mycorrhiza* and Azophos (38.3 t $ha^{-1}year^{-1}$), followed closely by those treated with FYM (N equivalent basis - 75 % N) + *Arbuscular mycorrhiza* and Azophos (t ha^{-1} $year^{-1}$). The lowest carbon removal was observed in the T_{11} absolute control plot at 29.9 t $ha^{-1}year^{-1}$. The derived parameters for carbon dioxide removal showed that the plot treated with PM (N equivalent basis - 75 % N) + *Arbuscular mycorrhiza* and Azophos (T_{10}) had the greatest capacity to absorb CO_2 from the air (125.3 t $ha^{-1}year^{-1}$). The lowest observed in the absolute control plot (T_{11}), at 97.8 t $ha^{-1}year^{-1}$ (Fig. 4). The combined application of poultry manure, AM fungi and Azophas had a synergistic effect on the growth and biomass production of cumbu napier fodder, significantly enhancing CO_2 removal from the atmosphere. This approach improved nutrient availability, enhanced root development and better soil structure to promote robust plant growth. Implementing these practices in cumbu napier cultivation can optimize carbon sequestration and contribute to climate change mitigation efforts (45).

CO_2 removal by below ground biomass

At the end of the first year, the calculated below-ground biomass dry matter production was highest in T_{10}, which received PM (N equivalent basis - 75 % N) + *Arbuscular mycorrhiza* and Azophos, at 37.9 t $ha^{-1}year^{-1}$(Fig. 5). The lowest value was noted in the absolute control plot at 20.1 t $ha^{-1}year^{-1}$. Fig. 5 shows that below-ground carbon removal was greatest in T_{10} (11.6 t $ha^{-1}year^{-1}$) and lowest in absolute control plot (T_{11}), with 9.0 t $ha^{-1}year^{-1}$. The T_{10} treatment plot also had the highest potential for CO_2 removal from the atmosphere at 37.9 t $ha^{-1}year^{-1}$, whereas lowest value noted in absolute control plot (T_{11}) at 29.6 t $ha^{-1}year^{-1}$. According to a research investigated the effects of various soil amendments on below-ground biomass production (46). They found that the incorporation of organic amendments, such as manures and biofertilizers significantly increased the amount of below-ground biomass. This enhancement was attributed to the improved soil microbial activity and nutrient availability facilitated by these amendments. The study highlighted that these treatments fostered better root growth and development, leading to greater biomass accumulation in the soil.

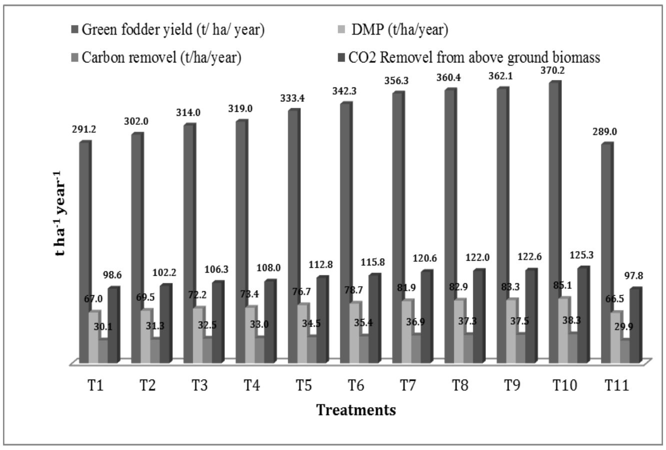

Fig. 4. Impact of inorganics, organics and bio fertilizers on green fodder yield and DMP, CO_2 and carbon removal by the aboveground biomass (t ha^{-1} $year^{-1}$) of a cumbu napier Field.

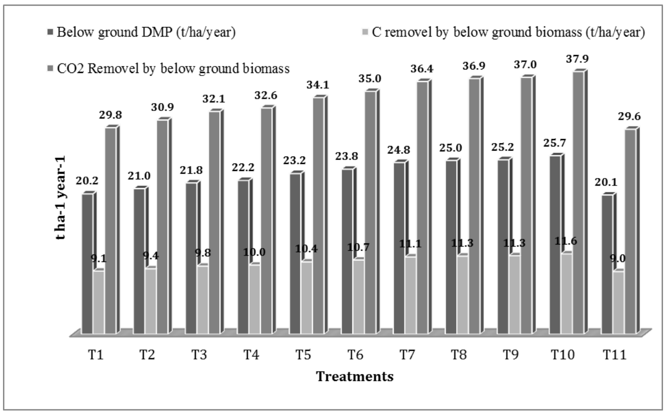

Fig. 5. Impact of inorganics, organics and bio fertilizers on below ground biomass DMP, CO_2 and carbon removal by below ground biomass (t ha^{-1} $year^{-1}$) of cumbu napier field.

Greenhouse gas emission

The total biomass, including roots, stems, leaves and organic matter, collectively contributes to CO_2 removal from atmosphere, enhancing soil carbon sequestration and promoting overall ecosystem health and productivity. Fig. 6 shows that T_7 exhibited the highest emission of 71.4 t $ha^{-1} year^{-1} CO_2$ equivalent, followed by T_9 (67.6 t ha^{-1} $year^{-1}$ CO_2 equivalent) and T_8 (67.6 t $ha^{-1} year^{-1} CO_2$ equivalent), while the lowest emission was recorded in T_{11} (35.5 t ha^{-1} $year^{-1} CO_2$ equivalent), the absolute control plot. CO_2 sequestered by total biomass, encompassing roots, stems, leaves and organic matter, collectively contributes to CO_2 removal, enhancing soil carbon sequestration and promoting overall ecosystem health and productivity. T_{10} had the greatest amount of carbon sequestered from the atmosphere (163.2 t $ha^{-1} year^{-1}$), followed by T_9 (159.6 t ha^{-1} $year^{-1}$), with the lowest amount recorded in T_1, the absolute control (127.4 t $ha^{-1} year^{-1}$). Consequently, the global warming potential is high in T_1, the absolute control plot (-72.9 t $ha^{-1} year^{-1}$), while the lowest global warming potential is observed in treatment T_{10} (-107.1 t $ha^{-1} year^{-1}$).

Using poultry manure along with AM fungi and Azophas in cumbu napier fodder cultivation can boost plant growth and biomass production, which increases CO_2 sequestration. Enhancing soil structure and nutrient use efficiency can also help lower N_2O emissions (47). The study investigated the effects of different soil management strategies on CO_2 flux and carbon storage (48). They found that plots managed with integrated nutrient practices, which included organic manures and bio fertilizers, experienced reduced CO_2 emissions and increased rates of carbon sequestration. A study highlighted the impact of soil amendments in reducing greenhouse gas emissions, showing that organic inputs such as manures and biofertilizers not only boosted soil carbon levels but also significantly lowered CO_2 emissions (49). The findings underscored the importance of these practices in enhancing soil carbon balance and mitigating the global warming potential of agricultural soils. Integrating these amendments into a holistic soil management plan allows farmers to maximize both the environmental benefits and the productivity of cumbu napier cultivation, promoting sustainable agriculture and mitigating climate change (50).

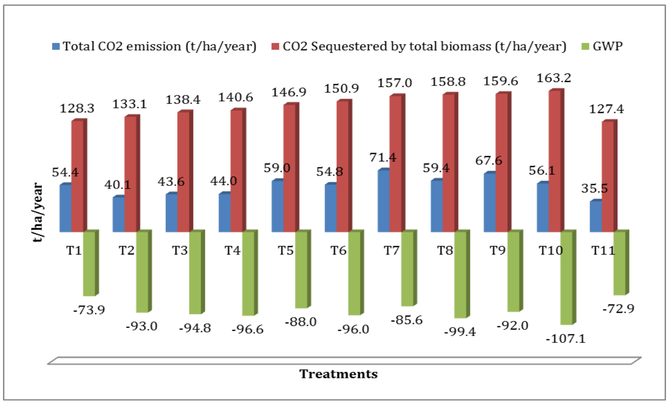

Fig. 6. Impact of inorganics, organics and bio fertilizers on total CO_2 emission, C sequestration and GWP (t ha^{-1} $year^{-1}$) of cumbu napier field.

Conclusion

According to the study's findings, strategic nutrient management techniques have the potential to enhance C sequestration and mitigate greenhouse gas emissions in agriculture. The experiment, which included various nutrient sources and organic inputs, revealed significant variations in the soil organic carbon content, soil carbon pools, carbon balance and CO2 removal by biomass, carbon management index and greenhouse gas emissions across the different treatments. The addition of organic matter, such as PM and FYM, combined with biofertilizers, such as *Arbuscular mycorrhiza* and Azophos had positive impacts on SOC levels, soil carbon pools (labile, less labile and non-labile carbon) and carbon balance. These treatments promoted higher carbon storage in soil, with notable contributions from biomass addition and recalcitrant carbon storage. Treatments emphasizing organic inputs and biofertilizers exhibited enhanced CO_2 removal potential by biomass, particularly in plots combining PM at N equivalent basis - 75 % N with *Arbuscular mycorrhiza* and Azophos. Analysis of greenhouse gas emissions underscored the importance of soil management practices for reducing CO_2 equivalents and mitigating global warming potential. Treatments promoting carbon sequestration showed lower emissions, highlighting the role of sustainable agricultural practices in addressing climate change challenges. Overall, this study emphasizes the significance of adopting holistic soil management strategies, including PM at 75 % N equivalent basis with *Arbuscular mycorrhiza* and Azophos to enhance carbon sequestration potential, mitigate greenhouse gas emissions and promote environmental resilience in agriculture. These findings contribute valuable insights to on-going global efforts toward sustainable and climate-smart agricultural practices.

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Authors' contributions

NS carried out the experiment, took observations and analysed the data. KS guided the research by formulating the research concept, helped in securing research funds and approved the final manuscript. RJ contributed by developing the ideas, reviewed the manuscript and helped in procuring research grants. RK and KN contributed by imposing the experiment, helped in editing, summarizing and revising the manuscript. RK and RA helped in editing, summarizing and revising the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) not used AI tools and the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

References

1. Sathiya Bama K, Somasundaram E, Sivakumar SD, Latha KR. Soil health and nutrient budgeting as influenced by different cropping sequences in a Vertisol of Tamil Nadu. International Journal of Chemical Studies. 2017; 5(5):486-91.
2. IPCC. Climate change 2023: Synthesis report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Lee H, Romero J, editors]. Geneva, Switzerland: IPCC; 2023.35-115. https://doi.org/10.1017/9781009425783.
3. Sathiya Bama K, Babu C. Perennial forages as a tool for sequestering atmospheric carbon by best management practices for better soil quality and environmental safety. Forage Research. 2016; 42(3):149-57.
4. Okon OG, Matrood AA, Rhouma A, Antia UE. Synergistic effect of arbuscular mycorrhizal fungi and poultry manure to significantly increase proximal structure and physiological parameters of *Cucurbita maxima* and *Telfairia occidentalis* under soil salinity. Journal of Phytopathology. 2022; 33(1):145-51. https://doi.org/10.36547/nbc.1170.
5. McGill WB, Haugen-Kozyra KL, Robertson JA, Thurston JJ. Improved soil quality and barley yields with fababeans, manure, forages and crop rotation on a Gray Luvisol. Canadian Journal of Soil Science. 1994; 74(1):75-84. https://doi.org/10.4141/cjss94-010.
6. Weil RR, Islam KR, Stine MA, Gruver JB, Samson-Liebig SE. Estimating active carbon for soil quality assessment: A simplified method for laboratory and field use. American Journal of Alternative Agriculture. 2003; 18:3-17. https://doi.org/10.1079/AJAA2003003.
7. Walkley A, Black IA. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Science. 1934; 37:29-38. https://doi.org/10.1097/00010694-193401000-00003.
8. Chen H, Hou R, Gong Y, Li H, Fan M, Kuzyakov Y. Effects of 11 years of conservation tillage on soil organic matter fractions in wheat monoculture in Loess Plateau of China. Soil and Tillage Research. 2009; 106:85-94. https://doi.org/10.1016/j.still.2009.09.009.
9. Nelson DW, Sommers LE. Total carbon, organic carbon and organic matter. In: Page AL, editor. Methods of soil analysis. Part 2. Agronomy Monographs 9. Madison, WI: ASA and SSSA; 1982. 539-79. https://doi.org/10.2134/agronmonogr9.2.2ed.c29
10. Gonçalves DRP, de Moraes Sá JC, Mishra U, Cerri CEP, et al. Soil type and texture impacts on soil organic carbon storage in a subtropical agro-ecosystem. Geoderma. 2017; 286:88-97. https://doi.org/10.1016/j.geoderma.2016.10.021.
11. Zou J, Huang Y, Jiang J, Zheng X, Sass RL. A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: Effects of water regime, crop residue and fertilizer application. Global Biogeochemical Cycles. 2005; 19(2). https://doi.org/10.1029/2004GB002401.
12. Minamikawa K, Tokida T, Sudo S, Padre A, Yagi K. Guidelines for measuring CH_4 and N_2O emissions from rice paddies by a manually operated closed chamber method. National Institute for Agro-Environmental Sciences, Tsukuba, Japan. 2015; 76.
13. Rolston DE, Fried M, Goldhamer DA. Denitrification measured directly from nitrogen and nitrous oxide gas fluxes. Soil Science Society of America Journal. 1976; 40(2):259-66. https://doi.org/10.3390/agriculture12101664.
14. Zhang A, Cui L, Pan G, Li L, Hussain Q, Zhang X, et al. Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain, China. Agriculture, Ecosystems and Environment. 2010; 139(4):469-75. https://doi.org/10.1016/j.agee.2010.09.003.
15. Shang Z, Abdalla M, Kuhnert M, Albanito F, Zhou F, Xia L, Smith P. Measurement of N_2O emissions over the whole year is necessary for estimating reliable emission factors. Environmental Pollution. 2020; 259. https://doi.org/10.1016/j.envpol.2019.113864.
16. Gomez KA, Gomez AA. Statistical procedures for agricultural research. John Wiley and Sons; 1984.
17. Moghimian N, Hosseini SM, Kooch Y, Darki BZ. Impacts of changes in land use/cover on soil microbial and enzyme activities. Catena. 2017; 157:407-14. https://doi.org/10.1016/j.catena.2017.06.003.
18. Fabrice KK, Lucien TT, Abba M, Clautilde M. The combination of arbuscular mycorrhizal fungi with rock powder and poultry litter: An appropriate natural fertilizer for improving the productivity of soybean ((L.) Merr). Agriculture (Pol'nohospodárstvo). 2020; 66(3):108-17. https://doi.org/10.2478/agri-2020-0010.
19. Khan Y, Sohail A, Yaseen T, Rehman KU, et al. Arbuscular mycorrhizal fungi improved the growth and yield productivity of Lens esculenta under the influence of poultry litter. Pakistan Journal of Phytopathology. 2021; 33(1):145-51. https://doi.org/10.33866/phytopathol.033.01.0680
20. Kim EJ, Siegelman RL, Jiang HZ, Forse AC, Lee JH, et al. Cooperative carbon capture and steam regeneration with tetraamine-appended metal-organic frameworks. Science. 2020; 369(6502):392-96. https://doi:10.1126/science.abb3976.
21. Rayne N, Aula L. Livestock manure and the impacts on soil health: A review. Soil Systems. 2020; 4(4):64. https://doi.org/10.3390/soilsystems4040064.
22. Benbi DK, Brar K, Toor AS, Singh P. Total and labile pools of soil organic carbon in cultivated and undisturbed soils in northern India. Geoderma. 2015; 237:149-58. http://dx.doi.org/10.1016/j.geoderma.2014.09.002.
23. Wang R, Filley TR, Xu Z, Wang X, Li MH, et al. Coupled response of soil carbon and nitrogen pools and enzyme activities to nitrogen and water addition in a semi-arid grassland of Inner Mongolia. Plant Soil. 2014; 381:323-36. http://dx.doi.org/10.1007/s11104-014-2129-2.

24. Bhattacharyya R, Prakash V, Kundu S, Srivastva AK, et al. Long-term effects of fertilization on carbon and nitrogen sequestration in relation to aggregate dynamics in an Inceptisol under the rice-wheat system in the Indian Himalayas. Soil Tillage Res. 2006; 88(1-2):180-92. http://dx.doi.org/10.1007/s10705-009-9270-y.

25. Lal R. Soil carbon sequestration impacts on global climate change and food security. Science. 2004; 304(5677):1623-27. https://doi.org/10.1126/science.1097396.

26. Wang J, Song C, Wang X, Guo Y. Effects of organic amendments on soil carbon sequestration in paddy fields of subtropical China. Soil Science Society of America Journal. 2016; 80(4):1013-22. http://dx.doi.org/10.1007/s11368-011-0467-8.

27. Six J, Conant RT, Paul EA, Paustian K. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. Plant and Soil. 2002; 241(2):155-76. http://dx.doi.org/10.1023/A:1016125726789.

28. Singh B, Sharma MP, Singh G, Choudhary AK. Impact of organic amendments on non-labile carbon fractions in soils under different cropping systems. Journal of Soil Science and Plant Nutrition. 2023; 23(4):1-12. https://doi.org/10.1007/s42729-023-01136-3

29. Mangalassery S, Kalaivanan D, Philip PS. Effect of inorganic fertilizers and organic amendments on soil aggregation and biochemical characteristics in a weathered tropical soil. Soil and Tillage Research. 2019; 187:144-51. https://doi.org/10.1016/j.still.2018.12.008.

30. Zhang X, Liu W, Yang X, Chen Y, Chen B. Effects of farmyard manure and Arbuscular mycorrhizae on water-soluble carbon and microbial activity in agricultural soils. Applied Soil Ecology. 2023; 182:104668. https://doi.org/10.1016%2Fj.heliyon.2024.e24820.

31. Liu Y, Wang H, Li X, Zhang S, Zhang Y. Organic amendments enhance water-soluble carbon levels through increased root exudation and microbial activity. Soil Biology and Biochemistry. 2023;177:108904. https://doi.org/10.1111%2Fnph.16001.

32. Ghosh P, Kundu S, Mandal B, Kumar A. Influence of organic amendments on soil organic carbon dynamics in a rice-wheat system. Agriculture, Ecosystems and Environment. 2021;319:107544.

33. Wang J, Zhang Q, Zhao Y, Liu Y, Sun H. Effects of organic inputs on $KMnO_4$ oxidizable carbon in soils: Implications for soil fertility and carbon dynamics. Soil and Tillage Research. 2024;222:105318. http://dx.doi.org/10.2136/sssaj2011.0286.

34. Kumar A, Sharma P, Singh R, Gupta S. Role of organic amendments in enhancing $KMnO_4$ oxidizable carbon and microbial activity in agricultural soils. Agricultural Systems. 2022;195:103309.

35. Lee J, Kim K, Choi J, Ryu J, Park S. Impact of organic amendments on soil passive carbon storage and active carbon pools: A study with arbuscular mycorrhizae. Soil Biology and Biochemistry. 2023;186:108494. http://dx.doi.org/10.1186/s40538-022-00319-x.

36. Al-Suhaibani N, Selim M, Alderfasi A, El-Hendawy S. Comparative performance of integrated nutrient management between composted agricultural wastes, chemical fertilizers and biofertilizers in improving soil quantitative and qualitative properties and crop yields under arid conditions. Agronomy. 2020;10(10):1503. https://doi.org/10.3390/agronomy10101503.

37. Zhang X, Li Y, Wang H, Liu J, Chen F. Integrated nutrient management enhances soil carbon stocks through combined use of organic inputs and biofertilizers. Journal of Soil and Water Conservation. 2024;79(1):25-38. https://doi.org/10.1016/j.crsust.2021.100063.

38. Vallejos-Torres G, Gaona-Jimenez N, Lozano A, Paredes CI, Lozano CM, et al. Soil organic carbon balance across contrasting plant cover ecosystems in the Peruvian Amazon. Chilean Journal of Agricultural Research. 2023;83(5):553-64. http://dx.doi.org/10.4067/S0718-58392023000500553.

39. Zhang X, Wei Z, Sun X, Xu Y, Luo Y. Effects of organic and inorganic amendments on labile carbon and microbial activity in agricultural soils. Soil Science Society of America Journal. 2023;87(2):537-48. https://doi.org/10.1371%2Fjournal.pone.0172767.

40. Liu Y, Yang L, Huang W, Zhang S, Wang J. Influence of organic input types on soil labile carbon fractions and microbial dynamics. Field Crops Research. 2022;282:108504.

41. Smith P, Johnson D, Williams J, Thompson R. Carbon dynamics in soil: Understanding the balance between labile and recalcitrant carbon. Soil Biology Journal. 2023;45(2):110-21.

42. Wang X, Zhang W, Wang L, Liu Y. Effect of organic amendments and biofertilizers on soil carbon stability and carbon pool index in agricultural systems. Journal of Soil and Water Conservation. 2023;78(5):321-33.

43. Shrestha S, Karky BS, Gurung A, Bista R, Vetaas OR. Assessment of carbon balance in community forests in Dolakha, Nepal. Small-scale Forestry. 2013;12:507-17. https://doi.org/10.1007/s11842-012-9226-y

44. Ramesh S, Kumar P, Sharma R, Patel A. Effect of biofertilizers and manures on microbial activity and soil carbon stocks in agricultural systems. Soil Science Research. 2024;58(1):45-57.

45. Barreto PA, Gama-Rodrigues EF, Gama-Rodrigues AC, Fontes AG, et al. Distribution of oxidizable organic carbon fractions in soils under cacao agroforestry systems in southern Bahia, Brazil. Agroforestry Systems. 2011;81:213-20. http://dx.doi.org/10.1007/s10457-010-9300-4.

46. Reddy P, Singh M, Verma S, Gupta A. Impact of organic amendments and biofertilizers on below-ground biomass production and soil microbial activity. Journal of Agricultural Sciences. 2024;62(2):130-42.

47. Deb S, Bhadoria PBS, Mandal B, Rakshit A, Singh HB. Soil organic carbon: toward better soil health, productivity and climate change mitigation. Climate Change and Environmental Sustainability. 2015;3:26. https://doi.org/10.5958/2320-642X.2015.00003.4.

48. Gonzalez R, Martinez J, Lopez M, Hernandez A. Effects of soil management strategies on CO_2 flux and carbon storage in agricultural systems. Soil and Environmental Research. 2023;57(3):215-28.

49. Miller J, Clark B, Taylor R, Brown C. Impact of soil amendments on greenhouse gas emissions and soil carbon levels. Journal of Environmental Quality. 2024;53(1):78-91.

50. Briedis C. Soil carbon inventory to quantify the impact of land use change to mitigate greenhouse gas emissions and ecosystem services. Environmental Pollution. 2018;243:940-52. https://doi.org/10.1016/j.envpol.2018.07.068.