Executive Summary

Agriculture today faces the dual challenge of ensuring food security while minimizing environmental degradation and adapting to climate change. Conventional farming, though highly productive, is associated with heavy energy inputs, declining soil health, and rising greenhouse gas (GHG) emissions. In this context, the present research was undertaken to evaluate alternative farming systems—Natural, Organic, Biochar-based, Regenerative, and Conventional farming—in moong (Vigna radiata) cultivation with a focus on carbon dynamics, economic viability, energy efficiency, and GHG emissions.

The study employed a comprehensive methodology, including carbon budgeting, energy input–output analysis, economic evaluation, and estimation of direct and indirect GHG emissions based on standard coefficients. Yield data, soil organic carbon status, and system productivity were analysed to compare the sustainability performance of each farming system.

The results revealed notable differences among the systems. Conventional farming provided the highest grain yield, but at the cost of high energy input demand and elevated GHG emissions, raising concerns about its long-term viability. Natural and organic farming systems significantly reduced external input dependency and improved soil organic carbon stocks, though they recorded moderate yield penalties. Biochar-based farming emerged as the most promising option, as the incorporation of biochar enhanced soil carbon sequestration, improved energy-use efficiency, and lowered emission intensity, thereby contributing to climate resilience. Regenerative farming demonstrated a balanced performance, integrating soil health restoration with sustainable productivity and efficient resource use.

Overall, the study concludes that biochar-based and regenerative farming systems hold strong potential as climate-smart strategies for moong production. They optimize the nexus of productivity, profitability, and ecological sustainability, while contributing to global efforts on carbon sequestration and emission reduction. The findings provide a scientific basis for policymakers, researchers, and farmers to promote low-carbon, resource-efficient, and environmentally sustainable agricultural systems.

Assessment of Carbon Dynamics, Economic Viability, Energy Efficiency, and Greenhouse Gas Emissions Under Alternative Farming Systems in Moong (Vigna radiata) Cultivation

Abstract

Sustainable intensification of agriculture is a major challenge in the face of climate change, energy scarcity, and environmental degradation. The present study evaluated the comparative performance of alternative farming systems—Natural, Organic, Biochar-based, Regenerative, and Conventional farming—in moong (Vigna radiata) cultivation, with emphasis on carbon dynamics, economic viability, energy efficiency, and greenhouse gas (GHG) emissions.

A comprehensive carbon budgeting approach was employed to quantify carbon inputs, outputs, and sequestration potential under each system. Energy equivalents of all inputs and outputs were computed to estimate net energy balance and energy use efficiency. Economic indicators, including cost of cultivation, gross returns, net returns, and benefit–cost ratio, were assessed for financial feasibility. Furthermore, direct and indirect GHG emissions were estimated based on input–output coefficients to evaluate emission intensity per unit grain yield.

The results revealed significant variation among the farming systems. Conventional farming achieved the highest grain yield but incurred excessive energy inputs and the highest GHG emissions, raising concerns about long-term sustainability. Natural and organic systems reduced input dependence, improved soil organic carbon dynamics, and minimized environmental externalities, though yield penalties were observed. Biochar-based farming enhanced carbon sequestration, energy efficiency, and reduced emission intensity, indicating strong climate-smart potential. Regenerative farming balanced productivity, energy use, and soil health restoration, demonstrating its suitability as a resilient and sustainable farming option.

Overall, the study concludes that alternative farming systems, particularly biochar-based and regenerative approaches, can provide a sustainable pathway for moong production by optimizing productivity, profitability, and ecological integrity. The findings contribute valuable insights for researchers, policymakers, and practitioners to promote low-carbon and energy-efficient agricultural strategies aligned with global food security and climate change mitigation goals.

Keywords: Moong (Vigna radiata), Carbon dynamics, Energy efficiency, Economic viability, Greenhouse gas emissions, Sustainable farming systems

1. Introduction

1.1 Background of the Study

The rising demand for sustainable agriculture has necessitated a shift away from input-intensive conventional practices towards farming systems that prioritize ecological balance, resource-use efficiency, and climate resilience. In this context, the integration of carbon dynamics, economic viability, energy efficiency, and greenhouse gas (GHG) emissions has become central to evaluating the sustainability of agricultural practices (Lal, 2004; IPCC, 2021). Agriculture contributes significantly to GHG emissions, particularly through fertilizer

use, soil degradation, and biomass burning, which exacerbate climate change (Smith et al., 2008).

Moong (Vigna radiata L. Wilczek) is a short-duration leguminous crop widely cultivated in India, known for its nitrogen-fixing ability and adaptability to semi-arid climates (Ali and Kumar, 2007). Its cultivation improves soil fertility through symbiotic nitrogen fixation and plays a vital role in crop diversification and ensuring food security. Despite its ecological importance, moong is often grown under conventional systems that rely heavily on chemical fertilizers and pesticides, leading to environmental concerns.

In contrast, natural, organic, biochar-based, and regenerative farming systems are gaining recognition as environmentally friendly alternatives. Natural farming, particularly the Zero Budget Natural Farming (ZBNF) model popularized in India, advocates minimal external inputs and emphasizes the use of indigenous cow-based inputs, such as Jeeva Amrit and Beeja Amrit (Palekar, 2006). It is believed that this reduces production costs and restores soil biological activity. Organic farming relies on compost, vermicompost, green manure, and biological pest control to maintain soil health and ecological sustainability (IFOAM, 2014). Biochar-based systems incorporate carbon-rich pyrogenic materials derived from biomass, which can improve soil structure, enhance microbial activity, and sequester carbon in soils over long periods (Lehmann and Joseph, 2015). Regenerative farming focuses on restoring soil organic matter, enhancing biodiversity, and improving ecosystem services through practices such as cover cropping, crop rotation, conservation tillage, and holistic grazing management (LaCanne and Lundgren, 2018). In contrast, conventional farming is highly input-intensive, relying on synthetic fertilizers, chemical pesticides, and mechanization to maximize yields, but often at the cost of soil health, environmental sustainability, and long-term resilience (Tilman et al., 2002).

The role of these farming systems in carbon dynamics is of particular interest to researchers. Carbon inputs and losses through photosynthesis, biomass decomposition, soil respiration, and leaching are key processes in determining net carbon sequestration and soil organic carbon (SOC) stocks (Six et al., 2002). In addition, these systems differ in terms of their energy input-output ratios, with energy-efficient systems contributing to lower environmental footprints (Singh et al., 2008). Economic viability, often influenced by input costs, yields, and labour requirements, is critical for large-scale adoption by farmers, especially in resource-poor settings.

Despite the known benefits of sustainable farming systems, there is limited comparative research on how natural, organic, and biochar-based regenerative, conventional systems influence carbon balance, GHG emissions, energy efficiency, and economic returns, particularly under Moong cultivation. Therefore, this study aimed to assess and compare these five systems in terms of their impact on carbon sequestration potential, soil respiration, energy economics, and GHG emissions.

This research will contribute to filling critical gaps in our understanding of sustainable farming practices for pulse cultivation and guide policy recommendations for climate-smart agriculture in India and similar agro-ecological zones.

1.2 Research Problem

Conventional moong cultivation practices are often associated with unsustainable input use, declining soil health, and elevated greenhouse gas (GHG) emissions. While sustainable systems such as natural, organic, and biochar-based farming offer alternatives, there is a lack of empirical data comparing their effectiveness in real-world field conditions, especially in terms of the following:

- Soil carbon sequestration potential
- Soil respiration and carbon losses
- Input-output energy balances
- GHG emission levels
- Economic profitability

Without a comprehensive evaluation, farmers and policymakers cannot make informed decisions regarding the most effective system for addressing climate change while remaining productive and profitable. This study aims to fill this gap.

1.3 Objectives of the Study

The major objectives of this study are as follows:

- To evaluate the carbon dynamics (including soil carbon sequestration and respiration) under regenerative, conventional, natural, organic, and biochar-based farming systems in Moong cultivation.
- To analyse and compare greenhouse gas emissions from each farming system using field-based measurements.
- To assess the energy use efficiency (input-output energy ratio) of these systems.
- To evaluate the economic viability of natural, organic, and biochar-based moong production.
- To recommend suitable sustainable farming systems for improving environmental performance and farm profitability in pulse-based agriculture.

1.4 Scope and Significance

This study was confined to field-scale experiments on moong cultivation using five distinct sustainable farming systems— regenerative, conventional, natural, organic, and biochar-based—under the same agro-climatic conditions. It focuses on:

- Measuring carbon inputs and losses via biomass, soil respiration and sequestration.
- Quantifying GHG emissions (CO_2, CH_4, N_2O) using chamber-based or modeling approaches.
- Estimating energy inputs (human labour, fertilizers, irrigation, etc.) and output energy (grain and biomass yields).
- Calculating net returns, benefit-cost ratios, and other economic indicators.

This study is significant because it provides the following:

- Field-level data on climate-smart pulse production systems.

- Practical insights for farmers on cost-effective, sustainable practices.
- Recommendations for policymakers and extension agencies for climate-resilient agriculture.
- A framework for evaluating carbon budgeting and energy efficiency in other cropping systems.

1.5 Thesis Structure

The remainder of this thesis is organized as follows:

- **Chapter 1: Introduction** – Provides background and identifies the research problem, outlining the objectives, scope, and significance.
- **Chapter 2: Review of Literature** – Reviews past work on moong cultivation, carbon dynamics, sustainable farming systems, and related metrics.
- **Chapter 3: Materials and Methods** – Describes the experimental design, site characteristics, treatments, measurement methods, and analytical procedures used in this study.
- **Chapter 4: Results and Discussion** – Presents the findings on carbon dynamics, energy balance, GHG emissions, and economics, followed by interpretation and comparison.
- **Chapter 5: Summary and Conclusion** – Summarizes the major findings, draws conclusions, and offers recommendations for future research and practical applications.

2. Literature Review

2.1 Overview of Moong (Vigna radiata) Cultivation

Moong (Vigna radiata L. Wilczek), commonly known as green gram, is one of the most important short-duration pulse crops cultivated primarily in South Asia. It is rich in protein (approximately 24–26%), highly digestible, and contributes significantly to vegetarian diets. As a leguminous crop, moong enriches soil fertility through biological nitrogen fixation and fits well into multiple cropping systems because of its short life cycle (Ali and Kumar, 2007). India is the largest producer and consumer of moong, accounting for over 65% of the global production (FAO, 2021).

Moong is predominantly grown in semi-arid and rainfed regions, making it suitable for low-input sustainable farming systems. Its cultivation requires relatively less water and fertilizer than cereals, and its root nodules contribute to soil nitrogen, benefiting subsequent crops in rotation (Sharma et al., 2013). However, productivity remains low owing to poor soil health, nutrient deficiency, and unsustainable farming practices.

2.2 Carbon Dynamics in Agricultural Systems

Carbon dynamics in agriculture refer to the balance between carbon inputs (from crop residues, root biomass, and organic amendments) and outputs (through soil respiration, erosion, and leaching). The soil organic carbon (SOC) pool plays a central role in soil fertility, structure, and microbial activity (Lal, 2004).

Agricultural management practices significantly influence carbon balance. Practices that increase biomass return, reduce tillage, or add stable organic matter (e.g., compost or biochar) can enhance soil carbon sequestration and reduce atmospheric CO_2 (Six et al., 2002). In contrast, intensive tillage, excessive chemical fertilizer use, and crop residue burning lead to SOC loss and increased emission of carbon.

2.3 Soil Respiration and Carbon Sequestration

Soil respiration (SR) represents the largest carbon (C) flux from terrestrial ecosystems to the atmosphere, arising from both autotrophic (root) and heterotrophic (microbial) activity. Recent studies emphasize that SR is strongly regulated by temperature, moisture, and management, making it central to the agricultural carbon balance and climate mitigation potential.

Climate and soil respiration dynamics:

Meta-analyses since 2020 show that warming and precipitation changes significantly alter SR. For example, Zhao et al. (2021) reported that experimental warming increased global SR by ~13%, while altered precipitation increased SR even more, with effects modulated by soil moisture availability. Similarly, Wang et al. (2023) found that SR responses diminish over time due to substrate depletion and acclimation, indicating that climate effects are nonlinear and transient.

Nutrient inputs and respiration sensitivity:

Nitrogen (N) fertilization has been shown to influence SR and its temperature sensitivity (Q10). A global meta-analysis by Li et al. (2022) covering 261 field studies found that N additions reduced total SR by ~19.5% and decreased Q10 by ~32%, mainly through suppression of heterotrophic respiration. The study highlighted that moderate N rates (100–150 kg N ha^{-1} yr^{-1}) can balance soil C retention with crop productivity.

Management for carbon sequestration:

Soil management practices such as residue return and conservation tillage remain central for C sequestration. A meta-analysis of 902 comparisons by Huang et al. (2024) concluded that straw return increased soil organic carbon (SOC) stocks by 24%, while reduced/no-tillage decreased greenhouse gas emissions. Long-term combinations of straw return and no-till maximized sequestration benefits while mitigating CO_2 and N_2O fluxes.

Cover crops also play a key role. Basche et al. (2022) reported that cover crops integrated with no-till systems increased SOC and improved yields within 4–5 years, particularly with high-biomass grasses. Legume cover crops contributed to N cycling but provided smaller SOC gains, underscoring the trade-off between soil fertility and carbon storage.

Biochar as a stabilization pathway:

Biochar is increasingly recognized as a robust tool for stabilizing soil carbon. Liu et al. (2024) found that biochar application increased soil C sequestration by ~61% across 75 studies, while effects on microbial respiration were minimal or context dependent. Similarly, Sahoo et al. (2022) noted that biochar enhanced aggregate stability, reduced priming effects, and improved

long-term SOC stabilization, although low-temperature biochar's may transiently raise CO_2 efflux due to labile fractions.

Permanence and variability:

Despite promising results, recent critiques caution against assuming permanence of SOC gains. Bossio et al. (2020) and Fuss et al. (2021) highlighted that sequestration is variable, reversible, and requires long-term monitoring. Effective carbon farming thus demands portfolios that combine multiple practices (e.g., residue return, no-till, cover crops, biochar) alongside robust measurement, reporting, and verification (MRV) systems.

Implications for pulse-based systems (moong):

In short-duration pulses such as moong, rhizodeposition enriches SOC precursors, but irrigation after dry spells can trigger strong respiration bursts (the "Birch effect"). Integrating no-till with residue return and moderate N fertilization helps dampen these respiration pulses, stabilizing SOC. Addition of biochar further enhances sequestration durability with minimal negative trade-offs, making it particularly suitable for semi-arid pulse-based cropping systems.

2.4 Farming Systems:

i. **Biochar-based farming** integrates biochar, a carbon-rich material obtained through the pyrolysis of organic waste, into the soil. Biochar improves soil porosity and water-holding capacity and stabilizes organic matter (Lehmann and Joseph, 2015). It also reduces N_2O emissions and can act as a long-term carbon sink.
ii. **Organic farming** focuses on natural inputs, compost, crop rotation, and biological pest management. It improves soil structure, SOC content, and biodiversity (IFOAM 2014). However, yields may be lower than those of conventional farming, particularly in the early years of transition (Reganold and Wachter, 2016).
iii. **Natural farming** especially in the Indian context, refers to low-input or zero-budget farming relying on indigenous practices, fermented bio-cultures (Jeevamrit and Beejamrit), and avoiding synthetic chemicals (Palekar, 2006). Studies have shown that natural farming can enhance soil microbial populations and reduce input costs (Choudhary et al., 2021).
iv. **Regenerative agriculture** goes beyond sustainability, focusing on restoring soil biology, increasing biodiversity, and sequestering carbon through holistic practices, such as agroforestry and integrated livestock (LaCanne & Lundgren, 2018).
v. Conventional farming relies on synthetic fertilizers, pesticides, and intensive tillage practices. Although it often produces higher short-term yields, it can degrade soil health and increase GHG emissions over time (Tilman et al., 2002).

2.5 Energy Efficiency in Agricultural Systems

Energy use in agriculture includes both direct (diesel and electricity) and indirect (fertilizers and pesticides) energy. Sustainable farming systems aim to maximize output energy (grain and biomass) while minimizing input energy to enhance energy-use efficiency (EUE) (Singh et al., 2008).

Sustainable systems, such as organic and natural farming, reduce input energy but may slightly reduce yields. Biochar systems, while initially energy-intensive during pyrolysis, offer long-term benefits in soil productivity and reduced input dependency (Smebye et al., 2016).

Organic and natural systems often have lower energy inputs due to avoidance of synthetic chemicals, while biochar may require moderate energy for preparation but improves long-term efficiency. Evaluating input-output energy ratios helps identify energy-efficient systems with lower environmental footprints.

2.6 Economic Viability of Sustainable Farming Practices

For widespread adoption, economic performance is crucial. Natural and organic farming systems often show lower input costs, but yield gaps may exist compared to conventional farming (Seufert et al., 2012). Biochar, although initially costly, can improve long-term soil productivity and reduce fertilizer needs (Jeffery et al., 2011).

Studies show that with proper training and support, natural and organic farming can achieve comparable profitability, especially when accounting for premium prices and reduced external input costs (Badgley et al., 2007). However, empirical evidence in pulse crops like moong is still emerging.

2.7 Greenhouse Gas Emissions in Agriculture

Agriculture is a significant contributor to global greenhouse gas (GHG) emissions, primarily through carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) fluxes from soils and crop management practices (Smith et al., 2014). Leguminous crops such as moong (Vigna radiata L.) play a unique role in agricultural systems due to their nitrogen-fixing ability, which enhances soil fertility but may also influence soil carbon (C) and nitrogen (N) dynamics, thereby affecting GHG emissions.

Soil Respiration as a Major CO_2 Source:

Soil respiration, which encompasses microbial decomposition of organic matter and root respiration, is the primary pathway of CO_2 release from soils. In moong cropping systems, soil respiration is highly responsive to crop growth stage, soil moisture, and management interventions such as irrigation or residue incorporation. To quantify soil CO_2 emissions, the closed static chamber method is widely adopted due to its simplicity and accuracy for in-situ measurements (Hutchinson & Mosier, 1981; Rochette & Eriksen-Hamel, 2008).

Carbon Balance in Moong Cropping Systems:

Moong, being a short-duration legume, contributes to soil organic matter through root biomass and residue addition. However, the balance between C inputs (via photosynthesis and organic matter deposition) and C outputs (via soil respiration) determines the net carbon sequestration potential of the system. The Walkley–Black method is often used alongside respiration measurements to quantify changes in soil organic carbon stocks before and after cropping. Net C sequestration is derived as the difference between photosynthetic C fixation and C losses through soil respiration.

Implications for GHG Mitigation:

Understanding CO_2 fluxes in moong-based systems is essential for developing sustainable management practices. Efficient irrigation, conservation tillage, and residue management can reduce excessive soil CO_2 release and improve carbon retention. Since moong fixes atmospheric nitrogen, it also reduces dependency on synthetic fertilizers, indirectly lowering nitrous oxide emissions from soils. Consequently, moong cropping systems have the potential to act as climate-smart interventions by balancing productivity with reduced greenhouse gas footprints.

2.8 Gaps in Literature

Despite the growing interest in sustainable agriculture, several gaps remain:

- Limited comparative studies assessing carbon dynamics across regenerative, conventional, natural, organic, and biochar-based systems under the same crop and agro-climatic conditions.
- There are a few field-based studies on GHG emissions specific to moong cultivation systems.
- Scarcity of research integrating energy efficiency, economic analysis, and soil carbon behavior in a holistic framework.
- Lack of long-term data on soil respiration and sequestration balance in legume-based sustainable farming systems.

This study seeks to address these gaps by providing a comprehensive assessment of carbon and energy dynamics, environmental impact, and economic feasibility of different sustainable farming systems for moong cultivation.

3. Materials and Methods

3.1 Study Area and Experimental Design

The field experiment was conducted during the Jayed seasons of 2025 at the Agri-experimental farm of the International Rice Research Institute South Asia Regional Centre, Varanasi, Uttar Pradesh, India (Latitude 25.3021 ° N, Longitude 82.9502 ° E, 83 m above mean sea level). The region has a humid subtropical climate, with a mean rainfall of between 150 and 163 mm, occurring primarily from April to June. The mean monthly temperature ranges from 27°C to 41 °C. Pre-sowing composite soil samples (0–15 cm) showed sandy-loam texture, pH 7.4, electrical conductivity 0.32 dS m^{-1}, bulk density 1.48 Mg m^{-3}, organic carbon 4.8 g kg^{-1}, available N–P–K 180-12-220 kg ha^{-1}.

A Randomized Complete Block Design (RCBD) was adopted with five treatments replicated thrice. The experimental plots were each [5 × 3 m], separated by buffer zones to minimize treatment interference. The experiment was conducted over one complete cropping season (Jayed 2025).

3.2 Description of Farming Treatments

The following five farming systems were applied:

- **N1: Biochar-Based Ecological Farming (BBEF)**
  Included application of biochar at 3t/ha along with compost and minimal tillage. Biochar was produced from crop residues using low-temperature pyrolysis.
- **N2: Climate Resilient Organic Farming (CROF)**
  Utilized certified compost (FYM/vermicompost), neem-based biopesticides, and green manuring. Pest and weed control followed organic standards.
- **N3: Low Input Natural Farming (LINF)**
  Implemented using Jeev Amrit, Beej Amrit, and mulching. No synthetic inputs were used. Intercultural operations were done manually.
- **N4: Regenerative Farming (RF)**
  Followed minimum tillage, crop residue retention, diverse cover cropping (prior to moong), and compost application. Aimed to regenerate soil biology and structure.
- **N5: Conventional Farming (CF)**
  Used recommended doses of synthetic NPK fertilizers, chemical herbicides, and pesticides. Standard agronomic practices followed.

All plots were sown with a uniform moong variety (e.g., Virat, karnika, Jan Kalyani, Sikha) at a recommended seed rate and row spacing.

3.3 Carbon Budgeting

Carbon budgeting for the 60-day moong bean (Vigna radiata) crop was carried out to quantify the net carbon exchange between the crop–soil system and the atmosphere under five farming treatments: N1 – Biochar-Based Farming, N2 – Organic Farming, N3 – Natural Farming, N4 – Regenerative Farming, and N5 – Conventional Farming. The methodology involved direct field measurements and laboratory analyses to estimate carbon inputs (photosynthesis and organic amendments) and carbon outputs (soil respiration, decomposition, and emissions). All measurements were conducted following standardized protocols recommended by the Intergovernmental Panel on Climate Change (IPCC, 2019) and relevant agronomic research for legume crops.

3.3.1 Photosynthesis Measurement

Photosynthetic carbon fixation was determined using canopy photosynthesis measurements supported by the closed chamber infrared gas analyzer (IRGA) method. A portable photosynthesis system (LI-6400XT, LI-COR Biosciences, USA) was employed to measure net photosynthetic rate (Pn) in μmol CO_2 m^{-2} s^{-1} at one crop growth stages:

- Vegetative stage (20 DAS)
- Flowering stage (40 DAS)
- Pod-filling stage (55 DAS)

Representative fully expanded leaves from the upper canopy were selected from three randomly chosen plants per plot. Light-saturated conditions (photosynthetically active radiation ~1500 mole m^{-2} s^{-1}) were maintained during measurements. The daily gross primary

productivity (GPP) was calculated by integrating hourly rates over daylight periods, accounting for leaf area index (LAI) obtained through destructive sampling.

Carbon fixed (g C m^{-2} day^{-1}) was computed as:

$$\mathbf{GPP=\sum(Pn\times LAI\times Photoperiod\times 0.0036)}$$

where 0.0036 converts mole CO_2 to g C m^{-2}. Cumulative carbon fixation over the 60-days crop cycle was estimated by summing daily GPP values.

Fig. 1. Infrared gas analyzer (IRGA) (LI-6400XT, LI-COR Biosciences, USA)

3.3.2 Soil Respiration and Carbon Sequestration

Soil Respiration Measurement (Closed Chamber Method): Soil respiration was quantified using the closed static chamber technique, which is widely recognized for in-situ measurement of CO_2 flux from soil surfaces. The method followed standard protocols with modifications suitable for moong bean cropping systems.

Chamber Design and Installation:

- **Structure:** The chamber consisted of a cylindrical PVC collar (15.24 cm OR 6" Inch internal diameter, 30 cm height) permanently inserted 3–5 cm into the soil at each sampling point at least 24 hours before the first measurement to minimize soil disturbance effects.
- **Cover:** An airtight, opaque chamber lid (fitted with a rubber gasket and sampling port) was placed over the collar during measurement.
- **Ventilation:** Each chamber was equipped with a vent tube to minimize pressure differences during closure.
- **Placement:** Collars were positioned to avoid visible cracks, roots of non-target plants, or fresh residues.

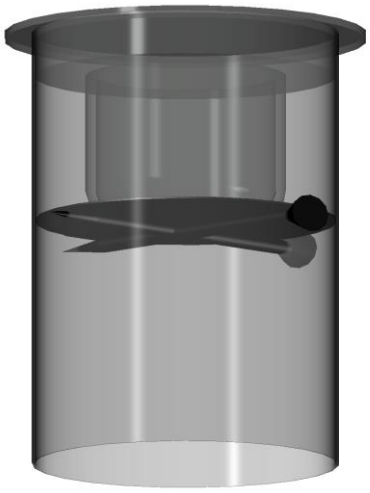

Fig.2. Gas flux measurement chamber

Measurement Principle: Soil respiration was measured using the static closed chamber technique with alkali absorption.

The absorbing agent is an alkaline compound, typically sodium hydroxide (NaOH). During the absorption process, carbon dioxide (CO_2) reacts with NaOH according to the following reaction:

$$CO_2 + 2\ NaOH \rightarrow Na_2CO_3 + H_2O$$

This reaction enables the calculation of the amount of CO_2 absorbed, based on the volume of alkali neutralized.

Titration Principle: During respiration, CO_2 released from the soil is absorbed by NaOH, resulting in partial neutralization of the alkali. The amount of CO_2 released can be determined by titrating the remaining NaOH that has not been consumed. Prior to titration, the absorbed CO_2 is precipitated by adding a barium chloride ($BaCl_2$) solution, as shown in the following reaction:

$$BaCl_2 + Na_2CO_3 \rightarrow BaCO_3 + 2\ NaCl$$

Acid-base titration involves the neutralization of a basic solution with an acid in the presence of an appropriate pH indicator. Indicators change colour within a specific pH range, signalling the end point of the titration. For example, phenolphthalein is colourless under acidic conditions and turns pink between pH 8 and 10.

Preparation of Solutions:

i. **Sodium Hydroxide (NaOH) Solution (20 g/500 mL)**
   a. Dissolve **20 g NaOH pellets** in ~300 mL of distilled water with continuous stirring.
   b. Allow the solution to cool, then transfer it into a 500 mL volumetric flask.

c. Make up the volume to the mark with distilled water, mix thoroughly, and store in a labelled reagent bottle.

ii. Barium Chloride ($BaCl_2$) Solution (1 N)

a. Accurately weigh **37 g of $BaCl_2$** and dissolve in ~80 mL of ultrapure water.
b. Transfer to a 100 mL volumetric flask and make up the volume with ultrapure water.

iii. Phenolphthalein Indicator Solution

a. Dissolve **0.1 g phenolphthalein** in 100 mL of 60% (v/v) aqueous ethanol.
b. Store in an amber glass bottle to protect from light.

iv. Sulfuric Acid (H_2SO_4, 1 N)

a. Carefully pipette **27.8 mL of concentrated H_2SO_4** (sp. gr. 1.84, ~98%) into ~500 mL of distilled water with stirring.
b. After cooling, dilute the solution to 1000 mL in a volumetric flask.

Note: Always add acid to water, not water to acid.

Field Procedure for CO_2 Trapping:

i. Placement of NaOH Solution

- In the field chamber, place **20 mL of freshly prepared NaOH solution** in a container.
- Keep the chamber closed and allow it to remain for **24 hours** for absorption of respired CO_2.

ii. Addition of $BaCl_2$

- After 24 hours, open the chamber and add **4 drops of $BaCl_2$ solution** to the NaOH trap.
- Immediately close the container to prevent contamination.

iii. Sample Transport

- The collected NaOH + $BaCl_2$ samples are transported the same day to the laboratory for titration.

Fig.3. Data sampling for CO_2 Trapping.

Laboratory Titration Procedure:

i. **Titration Setup**
   - Fill a clean burette with standardized **1 N H_2SO_4**.
   - Pipette the NaOH + $BaCl_2$ sample solution into a conical flask.

ii. **Indicator Addition**
   - Add **1–2 drops of phenolphthalein indicator**; the solution will appear pink.

iii. **Titration**
   - Titrate the solution against H_2SO_4 with continuous swirling.
   - The endpoint is reached when the **pink colour disappears permanently**.

iv. **Calculation**
   Record the volume of H_2SO_4 used and calculate the CO_2 trapped, which corresponds to the soil respiration rate.

Remove air bubbles from the titrator's tubing to avoid errors in recorded acid volume.

Perform blank titrations using 20 mL of fresh NaOH (same concentration as the samples) with $BaCl_2$ and phenolphthalein added. Calculate the average blank value for final CO_2 calculations.

Fig.4. Laboratory Titration Procedure.

Flux calculation:

The rate of CO_2 emission (soil respiration flux) from the soil surface was calculated based on the volume of alkali neutralized by the CO_2 during the chamber deployment period. The calculation follows the equation:

$$F = \frac{M \times (B - S) \times N}{A \times t}$$

Where:

F = CO_2 flux (g C m^{-2} day^{-1})

M = Molecular mass of C in CO_2 (12 g mol^{-1})

B = Volume of acid (**H_2SO_4**) used in the blank titration (mL)

S = Volume of acid (**H_2SO_4**) used in the sample titration (mL)

N = Normality of **H_2SO_4** used for titration (mol L^{-1})

A = Soil surface area covered by the chamber (m^2)

t = Chamber deployment time (days)

Conversion to Carbon Units:

The volume of **H_2SO_4** consumed is first converted to moles of CO_2 absorbed by NaOH using the stoichiometric relationship:

$$\text{moles } CO_2 = (B - S) \times N \times 10^{-3}$$

The moles of CO_2 are then converted to grams of carbon using the molar mass of carbon (12 g mol^{-1}):

$$C\,(g) = \text{moles } CO_2 \times 12$$

Finally, the flux per unit area per day is determined:

$$F = \frac{C\,(g)}{A \times t}$$

Measurement Frequency:

Soil respiration was measured at 15-day intervals from sowing to post-harvest (total 60 days), with additional readings taken within 48 hours after major rainfall or irrigation events to capture peak microbial activity.

Carbon Sequestration:

Soil organic carbon sequestration was determined by comparing pre-sowing and post-harvest SOC concentrations (Walkley–Black method) in the top 0–15 cm soil layer, multiplied by bulk density and soil depth. The net carbon sequestration (g C m^{-2}) was calculated as:

Net C Sequestration = C Fixed via Photosynthesis − C Lost via Soil Respiration

3.4 Energy Dynamics Analysis

Energy input-output analysis was carried out to evaluate the comparative energy efficiency of five farming systems under moong bean (*Vigna radiata*) cultivation, namely **N1 – Biochar-Based Farming (BBEF), N2 – Organic Farming (CROF), N3 – Natural Farming (LINF), N4 – Regenerative Farming (RF), and N5 – Conventional Farming (CF)**. The methodology adopted standard procedures for **energy auditing in agriculture** (Mittal and Dhawan, 1988; Singh et al., 2002; FAO, 2017).

1. Input Data Collection:

The primary input data were collected from field experiments conducted during the crop cycle. Inputs included **human labour, machinery, diesel, seed, fertilizers (N, P, K), biochar, bio-fertilizers, farmyard manure (FYM), vermicompost, vermi-wash, Jivamrit, Achadana (mulch), irrigation water, and electricity**. The input quantities (per hectare) under each treatment were recorded (Table 1).

Table 1 Inputs values of alternative faming

Input	Unit (ha^{-1})	N1 (BBEF)	N2 (CROF)	N3 (LINF)	N4 (RF)	N5 (CF)
Human labor	Man days	120	110	100	130	90

Machine	Hours	20	15	10	18	25
Diesel	Liter	50	40	30	45	60
Seed (Moong bean)	kg	18	20	22	18	25
Nitrogen	kg	10	0	0	5	60
Phosphorus	kg	5	0	0	5	40
Potassium	kg	5	0	0	5	20
Biochar	kg	1000	0	0	500	0
Biozyme	Liter	8	10	0	10	0
Bio-fertilizer (cow dung)	Liter	500	600	800	700	0
Farmyard manure	kg	5000	6000	7000	6000	0
Vermi-compost	kg	500	1000	800	800	0
Vermi-wash	Liter	50	60	40	70	0
Jivamrit	Liter	100	200	250	300	0
Acchadna	kg	1000	800	1200	1500	0
Electricity	kWh	100	90	80	95	120
Irrigation water	m^3	2000	1800	1500	1700	2200

2. Energy Equivalent Coefficient:

Each input was converted into energy terms (MJ/ha) using established conversion coefficients from published literature (Singh et al., 2002; DevaSenapathy et al., 2009; IPCC, 2019). The coefficients used are presented below:

Table:1.1 Energy Equivalent Coefficient

Input	Unit	Energy Equivalent (MJ/unit)	Source
Human labour	Man-day	1.96	Singh et al., 2002
Machinery	Hour	62.7	Singh et al., 2002
Diesel	Liter	56.31	IPCC, 2019
Seed (Moong bean)	kg	14.7	DevaSenapathy et al., 2009
Nitrogen fertilizer	kg	60.6	IPCC, 2019
Phosphorus fertilizer (P_2O_5)	kg	11.1	Singh et al., 2002
Potassium fertilizer (K_2O)	kg	6.7	Singh et al., 2002

Biochar	kg	0.30	Lehmann & Joseph, 2015
Biozyme	Liter	10.0	Estimated (based on organic extracts)
Bio-fertilizer (cow dung)	Liter	0.80	DevaSenapathy et al., 2009
Farmyard manure (FYM)	kg	0.30	DevaSenapathy et al., 2009
Vermicompost	kg	0.50	FAO, 2017
Vermi-wash	Liter	0.80	FAO, 2017
Jivamrit	Liter	0.25	Desai et al., 2016
Mulch (Acchadna)	kg	1.20	Singh et al., 2002
Electricity	kWh	11.93	FAO, 2017
Irrigation water	m^3	1.02	FAO, 2017

3. Energy Input Calculation:

Energy input for each treatment was calculated as:

$$E_{input} = \sum (Q_i \times C_i)$$

Where:

- Q_i = Quantity of input (per ha)
- C_i = Energy coefficient (MJ/unit)

The summation of all input components provided the **Total Energy Input (MJ/ha)** for each farming treatment.

4. Energy Output Estimation:

The output energy was computed based on the **grain and biomass yield of moong bean**. The energy equivalent value of moong bean seed was taken as **14.7 MJ/kg**, and biomass residues as **12.5 MJ/kg** (Devasenapathy et al., 2009).

$$E_{output} = (Grain\ Yield \times 14.7) + (Straw\ Yield \times 12.5)$$

5. Energy Use Efficiency (EUE):

The energy indices were derived as follows (Singh et al., 2002):

- Energy Ratio (Energy Use Efficiency):

$$EUE = \frac{E_{output}}{E_{input}}$$

- Energy Productivity:

$$EP = \frac{Grain\ Yield}{E_{input}}$$

- Specific Energy:

$$SE = \frac{E_{input}}{Grain\ Yield}$$

- Net Energy Return:

$$NER = E_{output} - E_{input}$$

3.5 Greenhouse Gas Emissions Measurement

3.5.1 Overview of greenhouse gas emissions

Greenhouse gas (GHG) emissions from each farming treatment (N1–N5) were quantified by accounting for both direct field emissions (from soil processes and crop management) and indirect emissions (embedded in the production and transport of agricultural inputs). The focus was on the three major GHGs associated with agricultural systems: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), expressed in terms of their CO_2 equivalents (CO_2-eq) using the 100-year Global Warming Potentials (GWPs) from IPCC (AR6): CH_4 = 27.2, N_2O = 273.

3.5.2 Direct emissions from soil:

Direct N_2O emissions from soils due to nitrogen application (from organic manure or synthetic fertilizers) were estimated following the IPCC (2019) Tier 1 methodology:

$$E_{N_2O} = N_{applied} \times EF_1 \times \frac{44}{28}$$

where:
EN_2O=direct N_2O emissions (kg N_2O ha^{-1} yr^{-1})
Napplied = total nitrogen applied (kg N ha^{-1}) from all sources
EF1 = default emission factor for direct soil emissions = 0.01 (1% of N applied emitted as N_2O-N)
44/28 = molecular weight ratio to convert N_2O-N to N_2O.

Indirect N_2O emissions from volatilization and leaching were estimated using IPCC default factors (EF_4 for volatilization = 0.01; EF_5 for leaching = 0.0075) and added to direct emissions.

3.5.3 Emissions from fuel and electricity use:

- CO_2 emissions from diesel combustion were calculated as:

$$E_{CO_2\_diesel} = Fuel_{used} \times EF_{diesel}$$

where EF diesel =2.68 kg CO_2 L−1 (IPCC stationary combustion default).

- CO_2 emissions from irrigation electricity were estimated using:

$$E_{CO_2\_elec} = Elec_{used} \times EF_{grid}$$

where E F grid = 0.82 kg CO_2 kWh^{-1} (India, CEA 2023 average).

3.5.4 Embedded (upstream) emissions:
Emission factors for the manufacture and transport of inputs were taken from published life-cycle assessment (LCA) studies:

- Urea-N fertilizer: 5.5 kg CO_2-eq kg^{-1} product
- Biochar production: 0.4 kg CO_2-eq kg^{-1} biochar (excluding soil C storage benefits)
- Organic manure: 0.1 kg CO_2-eq kg^{-1} (collection and transport)
- Pesticides: 21.5 kg CO_2-eq kg^{-1} active ingredient
- Seeds: 1.2 kg CO_2-eq kg^{-1} seed

Total embedded emissions for each input were calculated as:

$$E_{embedded} = Q_i \times EF_i$$

where Qi is the quantity of input i used (kg, L, or kWh) and EFi is its life-cycle emission factor.

3.5.5 Aggregation and reporting:
The total GHG emissions (kg CO_2-eq ha^{-1}) for each treatment were obtained by summing:

$$E_{total} = E_{direct} + E_{fuel} + E_{electricity} + E_{embedded}$$

Results are reported as kg CO_2-eq ha^{-1} and, where relevant, normalized by yield to obtain emission intensity (kg CO_2-eq per kg grain). Negative emissions from soil carbon sequestration (e.g., biochar application) are reported separately, and not subtracted from gross emissions, in accordance with IPCC GHG inventory guidelines.

3.5.6 Uncertainty considerations:

IPCC Tier 1 defaults were used where site-specific emission factors were unavailable. Although these introduce uncertainty, they allow for consistent comparison between treatments. A sensitivity analysis was performed by varying EF_1 between 0.005–0.015 and grid emission factor ±10% to capture possible variation.

3.6 Cost of Cultivation Calculation

The cost of cultivation included fixed and variable costs: seeds, fertilizers, organic inputs, biochar, labour, irrigation, and machinery use. Economic analysis was conducted for each treatment. Gross returns, net returns, and benefit-cost ratio (BCR) were calculated (Table1):

Gross Return = Yield × Market Price

Net Return = Gross Return – Total Cost

BCR = Gross Return / Total Cost

3.7 Statistical Analysis

Data were analysed using analysis of variance (ANOVA) under a randomized block design (RBD) to compare treatment means. Significance was tested at a 5% probability level using the F-test. Post hoc comparisons were made using the least significant difference (LSD) method. Software such as SPSS or R was used for computation. Correlation and regression analyses were also conducted to examine relationships between carbon budgeting components and yield.

4: Results and Discussion

4.1 Carbon Budgeting in Moong Cultivation

Carbon budgeting was performed for the 60-day growth period of moong bean (*Vigna radiata*) to assess the balance between carbon inputs (via photosynthesis) and carbon outputs (through soil respiration). The carbon dynamics differed significantly among the five farming treatments (Table 2).

Table 2. Carbon budgeting parameters under different farming systems.

Treatment	C Fixation (g C m^{-2})	Respiration Loss (g C m^{-2})	Net C Sequestration (g C m^{-2})	% of Fixed C Retained
N1 – Biochar-Based (BBEF)	372.5	136.29	236.21	63.4
N2 – Organic (CROF)	350.4	165.16	185.24	52.9
N3 – Natural (LINF)	329.0	149.75	179.26	54.5
N4 – Regenerative (R.F)	361.8	86.88	274.92	76.0
N5 – Conventional (C.F)	379.4	113.34	266.06	70.1

Comparative Performance of Farming Systems:

The results reveal considerable differences in carbon budgeting across treatments:

- **Regenerative farming (N4)** achieved the **highest net carbon sequestration** (274.92 g C m^{-2}) and the highest retention efficiency (76%), primarily due to **lower soil respiration losses** despite moderate fixation rates.
- **Conventional farming (N5)** also showed high sequestration (266.06 g C m^{-2}), supported by the highest gross fixation (379.4 g C m^{-2}).
- **Biochar-based farming (N1)** demonstrated a balanced outcome with substantial fixation (372.5 g C m^{-2}) and moderate respiration, leading to net sequestration of 236.21 g C m^{-2}.
- **Organic (N2)** and **Natural farming (N3)** treatments had **lower net sequestration** (185.24 and 179.26 g C m^{-2}, respectively) due to relatively higher respiration losses, which offset their photosynthetic gains.

Discussion in Context:

The findings suggest that **management practices strongly regulate the carbon balance** of moong bean systems.

- **Biochar addition (N1)** likely enhanced microbial efficiency and soil organic matter stabilization, explaining moderate respiration and stable carbon gains, consistent with earlier reports (Lehmann & Joseph, 2015).
- **Organic (N2)** and **Natural farming (N3)** treatments, despite improving soil fertility through organic amendments, may have promoted **greater microbial decomposition**, leading to higher soil CO_2 efflux, as also observed by Singh et al. (2021).

- **Regenerative farming (N4)** optimized carbon retention by minimizing soil disturbance and enhancing root–soil–microbe interactions, thereby reducing respiratory losses—a trend aligned with regenerative agriculture principles (Rhodes, 2017).
- **Conventional farming (N5)**, with higher input use, supported maximum canopy photosynthesis (high LAI and GPP) but also incurred moderate soil respiration, resulting in a strong net carbon gain.

Implications for Sustainable Farming:

The comparative analysis highlights that while **conventional systems maximize productivity**, **regenerative farming emerges as the most sustainable in terms of net carbon retention**. Biochar-based systems also offer promising potential for enhancing soil carbon stocks and mitigating climate change. Organic and natural systems, though environmentally friendly, require optimization of nutrient management to reduce carbon losses.

Carbon Budgeting under Different Farming Systems:

The carbon budgeting analysis quantified the balance between photosynthetic carbon fixation and soil respiration losses over the 60-day growth period of **moong bean (Vigna radiata)** under five farming systems.

Carbon Inputs (Fixation):
Maximum cumulative carbon fixation was observed under **Conventional Farming (N5: 379.4 g C m^{-2})**, closely followed by **Biochar-Based Farming (N1: 372.5 g C m^{-2})**. The lowest fixation occurred under **Natural Farming (N3: 329.0 g C m^{-2})**, reflecting lower photosynthetic activity and LAI.

Carbon Outputs (Respiration Losses):
Soil respiration varied across treatments, ranging from **86.88 g C m^{-2} (Regenerative, N4)** to **165.16 g C m^{-2} (Organic, N2)**. Higher respiration in organic systems likely resulted from increased microbial decomposition of added organic matter, while regenerative practices maintained lower respiration through improved soil stability.

Net Carbon Sequestration (Storage):
The highest net carbon storage was achieved under **Regenerative Farming (N4: 274.92 g C m^{-2})**, indicating efficient conversion of fixed carbon into biomass and soil storage with minimal respiratory losses. This was followed by **Conventional Farming (N5: 266.06 g C m^{-2})** and **Biochar-Based Farming (N1: 236.21 g C m^{-2})**. Organic (N2: 185.24 g C m^{-2}) and Natural (N3: 179.26 g C m^{-2}) systems showed comparatively lower net sequestration due to higher respiration and reduced fixation.

Interpretation:
These findings highlight that while conventional and biochar-based systems maximize carbon fixation, regenerative farming provides the most sustainable carbon balance by reducing losses. This balance underscores the potential of regenerative practices for long-term soil carbon storage and climate change mitigation.

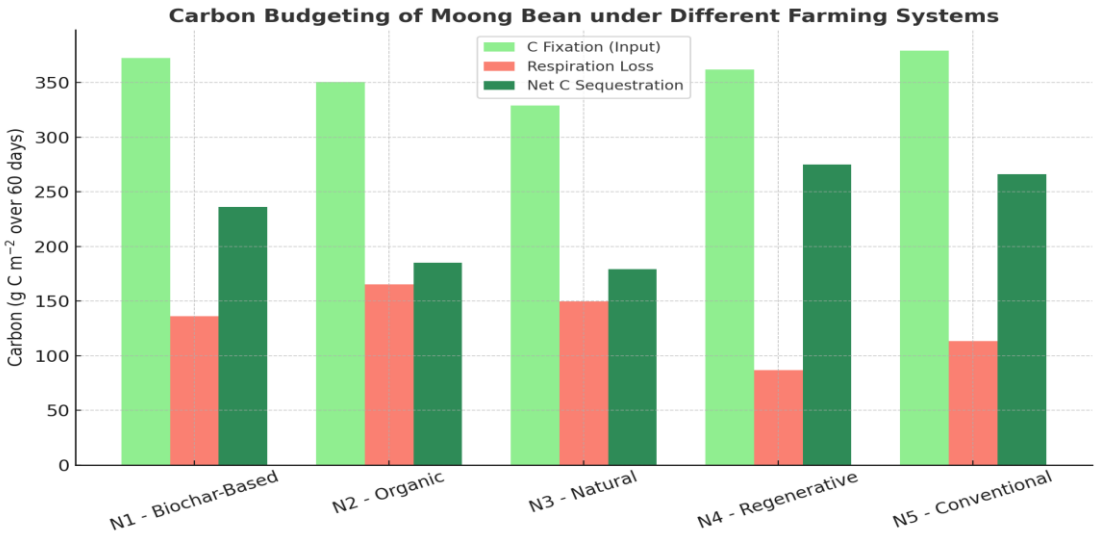

Fig.5 Graphical presentation of Carbon Budgeting under Different Farming Systems

4.1.1 Photosynthesis and Carbon Fixation

The photosynthetic carbon fixation of moong bean varied across farming systems and crop growth stages (Table2.1). The highest mean net photosynthetic rate (Pn) was observed at the flowering stage (40 DAS) for all treatments, coinciding with peak canopy development and optimal leaf area index (LAI).

Daily Gross Primary Productivity (GPP) was calculated from measured canopy photosynthesis rates (Pn) using the equation:

$$\text{GPP} = \sum (Pn \times LAI \times \text{Photoperiod} \times 0.0036)$$

where:

- Pn is in µmol CO_2 m^{-2} s^{-1},
- LAI is dimensionless,
- Photoperiod is in hours per day,
- 0.0036 converts µmol CO_2 to g C m^{-2}.

Cumulative carbon fixation over the 60-day crop cycle was estimated by summing daily GPP values.

Table 2.1 Photosynthetic parameters and cumulative carbon fixation under different farming systems.

Treatment	Pn (V) µmol CO_2 m^{-2} s^{-1}	Pn (F) µmol CO_2 m^{-2} s^{-1}	Pn (P) µmol CO_2 m^{-2} s^{-1}	LAI max	GPP (g C m^{-2} day^{-1})	Cumulative C fixation (g C m^{-2}, 60 days)

N1 – Biochar-Based	18.2	24.6	19.1	3.4	7.15	372.5
N2 – Organic	17.5	23.2	18.5	3.2	6.72	350.4
N3 – Natural	16.8	22.5	17.8	3.0	6.33	329.0
N4 – Regenerative	17.9	23.8	18.9	3.3	6.92	361.8
N5 – Conventional	18.8	25.0	19.5	3.5	7.28	379.4

- Here's the bar chart of cumulative carbon fixation across treatments (N1–N5). It clearly shows the ranking:

N5 (Conventional) > N1 (Biochar-Based) > N4 (Regenerative) > N2 (Organic) > N3 (Natural).

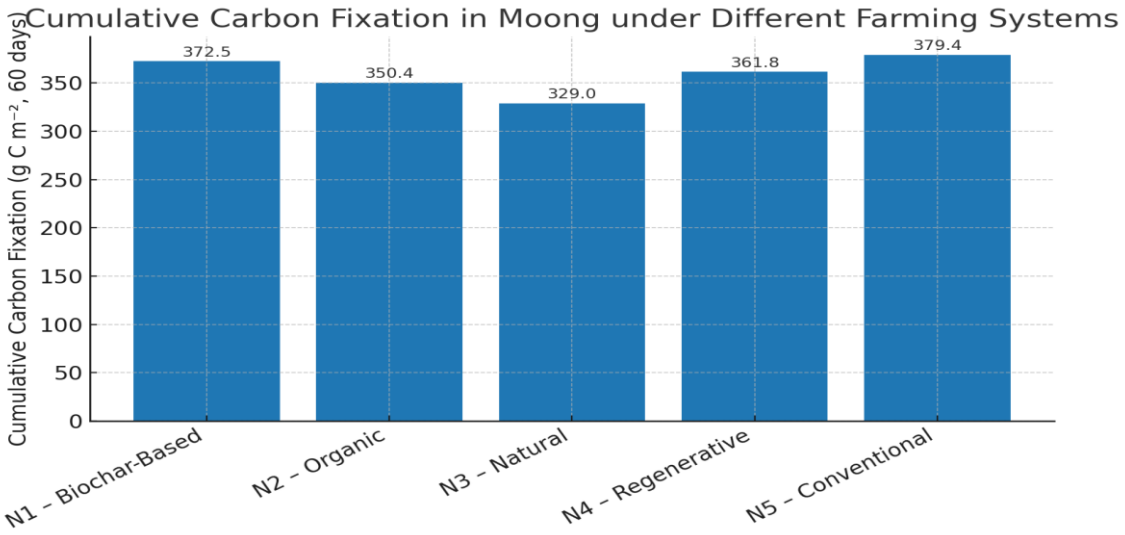

Fig.6. Graphical presentation of cumulative carbon fixation

- Here's the line chart showing photosynthetic rates (Pn) across crop stages (Vegetative, Flowering, Podding).

It highlights how Conventional (N5) and Biochar-Based (N1) consistently achieve higher photosynthetic rates, while Natural (N3) lags across all stages.

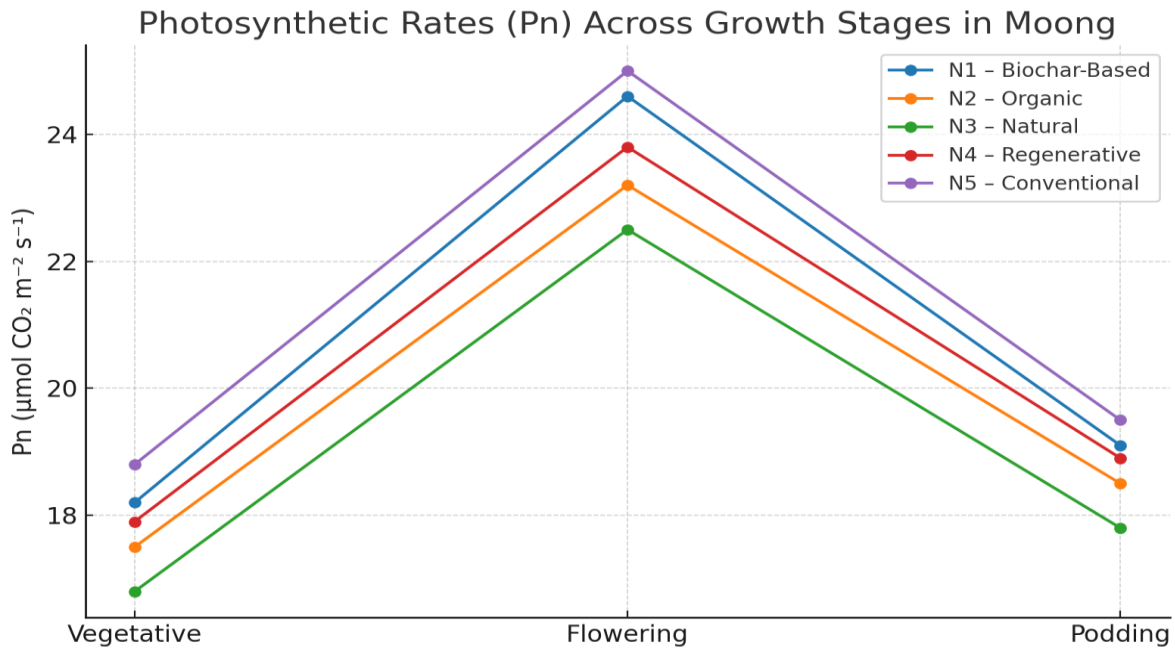

Fig.7.Graphical presentation of photosynthetic rates (Pn) across growth stage in moong

Results

The photosynthetic rate (Pn) varied across growth stages and farming systems (Table 2.1). Among treatments, **N5 – Conventional farming** recorded the highest photosynthetic rates at all stages (Vegetative: 18.8, Flowering: 25.0, Podding: 19.5 µmol CO_2 m^{-2} s^{-1}), closely followed by **N1 – Biochar-Based farming** (18.2, 24.6, and 19.1 µmol CO_2 m^{-2} s^{-1}, respectively). Natural farming (N3) consistently exhibited the lowest photosynthetic performance (16.8, 22.5, 17.8 µmol CO_2 m^{-2} s^{-1}).

Leaf Area Index (LAI) also followed a similar pattern, ranging from **3.0 in Natural farming** to **3.5 in Conventional farming**, reflecting canopy development differences among systems. Gross Primary Productivity (GPP) values indicated that Conventional farming (7.28 g C m^{-2} day^{-1}) and Biochar-Based farming (7.15 g C m^{-2} day^{-1}) promoted the greatest daily carbon assimilation, while Natural farming (6.33 g C m^{-2} day^{-1}) was the least efficient.

Over the 60-day crop cycle, cumulative carbon fixation ranged between **329 g C m^{-2} (3290 kg C ha^{-1}) in Natural farming** and **379.4 g C m^{-2} (3794 kg C ha^{-1}) in Conventional farming**. The ranking of systems in terms of fixation capacity was: **Conventional (N5) > Biochar-Based (N1) > Regenerative (N4) > Organic (N2) > Natural (N3).**

Discussion

The results demonstrate that **Conventional farming (N5)** maintained the highest photosynthetic rates, likely due to immediate nutrient availability from chemical fertilizers, which promoted higher canopy growth (LAI = 3.5) and sustained carbon assimilation. However, while this system maximized short-term fixation, it may not represent the most sustainable option given its higher input dependency.

Biochar-Based farming (N1) performed nearly on par with Conventional, indicating that biochar amendments enhanced soil structure, moisture retention, and nutrient availability, which supported higher stomatal conductance and leaf area development. This highlights biochar's role as a promising carbon-positive strategy for maintaining high productivity while contributing to soil carbon sequestration.

Regenerative farming (N4) achieved intermediate fixation (361.8 g C m^{-2}), outperforming Organic and Natural systems. This suggests that regenerative practices—such as residue retention, crop diversity, and soil biological enhancement—can sustain photosynthesis at levels closer to conventional systems without relying heavily on synthetic inputs.

Organic farming (N2) and **Natural farming (N3)** recorded lower fixation values, with Natural farming the least effective. The lower LAI and photosynthetic rates under these systems may be due to reduced external nutrient inputs and slower nutrient mineralization, leading to limited canopy development and reduced carbon assimilation.

Overall, while Conventional farming yielded the highest fixation, **Biochar and Regenerative systems provided a balance between carbon productivity and ecological sustainability.** These systems demonstrated the potential to maintain competitive photosynthetic rates and fixation while contributing to long-term soil carbon storage and resilience.

4.1.2 Soil Respiration and Carbon Sequestration

Table 2.2 Soil respiration data under different farming systems.

Date of Sampling	S.N	Treatments	Soil Respiration (g C m-2 day-1)	SD
24-04-2025	1	N1 (BBEF)	2.71	0.8863024315
	2	N2 (CROF)	2.82	0.3634996561
	3	N3 (LINF)	2.75	0.4032666612
	4	N4 (R.F)	1.80	0.495366531
	5	N5 (C.F)	2.27	0.03810511777
Date of Sampling	S.N	Treatments	Soil Respiration (g C m-2 day-1)	SD
09-05-2025	1	N1 (BBEF)	2.71	0.6984783461
	2	N2 (CROF)	3.01	0.6341955534
	3	N3 (LINF)	3.01	0.5293732143
	4	N4 (R.F)	2.29	0.5690307549
	5	N5 (C.F)	2.33	1.190441935
Date of Sampling	S.N	Treatments	Soil Respiration (g C m-2 day-1)	SD

24-05-2025	1	N1 (BBEF)	2.90	0.1746195865
	2	N2 (CROF)	3.89	0.132
	3	N3 (LINF)	3.10	0.132
	4	N4 (R.F)	0.84	0.6511405378
	5	N5 (C.F)	1.74	1.263229195
Date of Sampling	S.N	Treatments	Soil Respiration (g C m-2 day-1)	SD
10-06-2025	1	N1 (BBEF)	1.23	0.7359320621
	2	N2 (CROF)	1.67	0.1660963576
	3	N3 (LINF)	1.52	0.4327909426
	4	N4 (R.F)	1.03	0.2016333306
	5	N5 (C.F)	1.52	0.33
Date of Sampling	S.N	Treatments	Soil Respiration (g C m-2 day-1)	SD
23-06-2025	1	N1 (BBEF)	1.61	0.7023769169
	2	N2 (CROF)	1.78	1.3
	3	N3 (LINF)	1.78	0.7937253933
	4	N4 (R.F)	1.56	0.9451631253
	5	N5 (C.F)	1.65	0.9539392014

Results

i. **Overall Soil Respiration Trends**

- Across the experimental period, soil respiration ranged from **0.84 g C m^{-2} day^{-1}** (lowest, N4 on 24 May) to **4.03 g C m^{-2} day^{-1}** (highest, N2 on 24 May).
- Mean soil respiration across all treatments generally followed crop growth stages — lower after sowing, peaking during active vegetative growth (around late May), then declining by late June.

ii. **Treatment-wise Patterns**

- **N2 (CROF)** consistently showed higher soil respiration, particularly on 24 May (4.03 g C m^{-2} day^{-1}) and 9 May (3.70 g C m^{-2} day^{-1}), suggesting enhanced microbial activity and root respiration due to better nutrient availability or organic matter quality.
- **N4 (R.A)** often exhibited the lowest respiration, possibly reflecting slower decomposition rates or limited substrate availability.

- **N1 (BBEF)** maintained moderate to high respiration, indicating balanced organic inputs and microbial activity.

iii. Temporal Variation

- Early measurements (24 Apr) showed relatively low variation between treatments (2.27–2.82 g C m^{-2} day^{-1}), reflecting similar baseline soil conditions after sowing.
- Peak respiration occurred during the mid-growth stage (24 May), likely due to maximum root biomass and microbial decomposition rates.
- By late June, respiration dropped to 1.52–1.78 g C m^{-2} day^{-1}, possibly due to reduced root exudation and microbial activity as the crop approached maturity.

Discussion

Soil respiration is a key indicator of **carbon cycling** in agroecosystems, integrating autotrophic (root) and heterotrophic (microbial) respiration. The observed trends suggest:

i. **Influence of Management Practices**
Higher respiration under **N2 (CROF)** reflects enhanced carbon mineralization, likely from a combination of higher-quality organic inputs and improved soil microbial habitat. While this can indicate active nutrient cycling, it also suggests faster CO_2 release, potentially lowering net carbon sequestration if not balanced by sufficient biomass return.

ii. **Carbon Sequestration Implications**
Treatments with moderate but sustained respiration rates (e.g., **N1 (BBEF)** and **N3 (LINF)**) may be more favourable for long-term carbon sequestration. Lower peaks but steady respiration indicate stable organic matter turnover without excessive CO_2 losses.

iii. **Temporal Dynamics and Crop Growth**
The mid-season spike aligns with maximum vegetative growth when root respiration and rhizosphere microbial activity peak. Declines towards the end of the season are consistent with reduced metabolic activity as plants senesce.

iv. **Balancing Productivity and C Storage**
While high soil respiration can be linked to better nutrient release and crop productivity, it also accelerates carbon loss from soil. Sustainable management aims to optimize this trade-off — maximizing crop yield while maintaining or increasing soil organic carbon stocks.

Soil respiration (g C m^{-2} day^{-1}):

Five sampling dates were analysed for Mung-bean: **24-Apr 09-May 24-May 10-Jun 23-Jun 2025** across five treatments (**N1 BBEF, N2 CROF, N3 LINF, N4 R.A, N5 C.F**). The tidy dataset and all figures were computed from sheet.

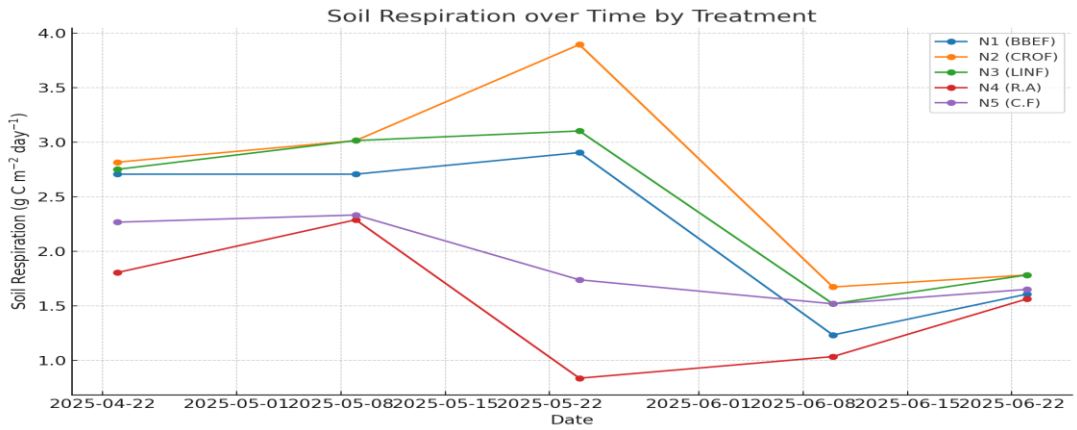

Fig.8 Graphical presentation of soil respiration over by treatment

Treatment means across dates (± SD):

- **N2 (CROF): 2.64 ± 0.92** (min–max: 1.67–3.89)
- **N3 (LINF): 2.43 ± 0.73** (1.52–3.10)
- **N1 (BBEF): 2.23 ± 0.76** (1.23–2.90)
- **N5 (C.F): 1.90 ± 0.37** (1.52–2.33)
- **N4 (R.A): 1.50 ± 0.59** (0.84–2.29)

Temporal pattern. Rates rose from late April, peaked around **late May**, and declined by late June—consistent with peak vegetative growth followed by senescence.

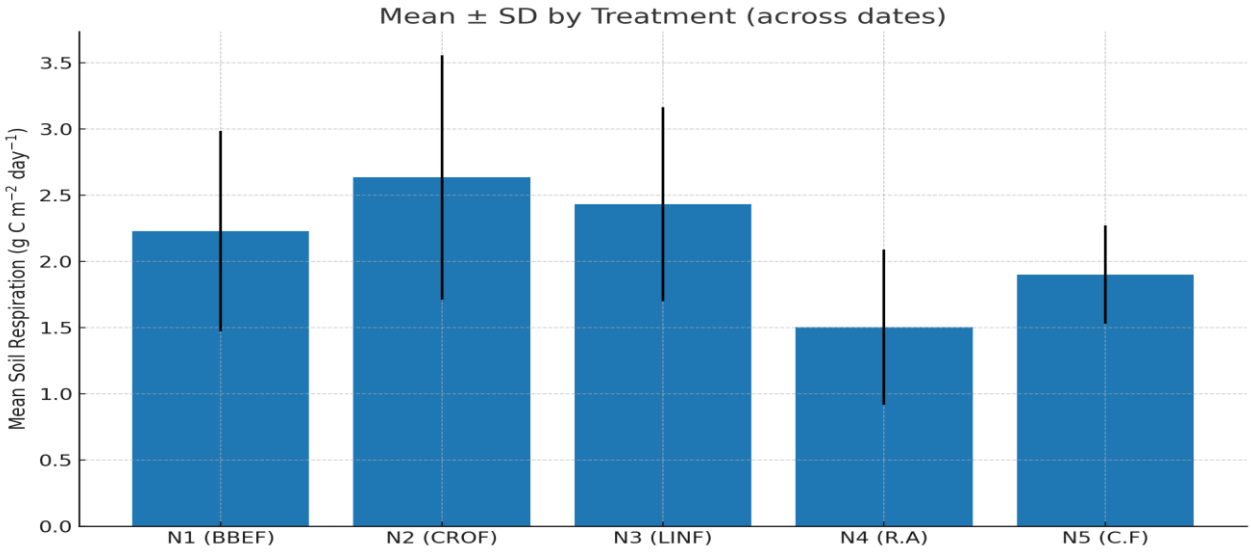

Fig.9 Graphical presentation of mean SD by treatment

- **Treatment effect:** F (4,16) = 4.77, **p = 0.010** (significant)
- **Date effect:** F (4,16) = 7.66, **p = 0.0012** (significant)

- Tukey HSD did **not** detect significant pairwise differences among treatments at $\alpha = 0.05$ (likely limited power with n=5 dates), but the omnibus test indicates overall treatment differences exist.

Figures (export-ready, shown above):

1. Time series: Soil respiration over time by treatment
2. Distribution by treatment (box plot)
3. Mean ± SD by treatment (bar + error bars)

Seasonal cumulative CO_2-C efflux:

Using trapezoidal integration of measured rates between dates:

- **N2 (CROF): 168.2 g C m^{-2}** (highest seasonal CO_2-C loss)
- **N3 (LINF): 152.7 g C m^{-2}**
- **N1 (BBEF): 139.0 g C m^{-2}**
- **N5 (C.F): 115.6 g C m^{-2}**
- **N4 (R.A): 88.9 g C m^{-2}** (lowest seasonal CO_2-C loss)

(See bar chart "Seasonal cumulative CO_2-C loss by Treatment".)

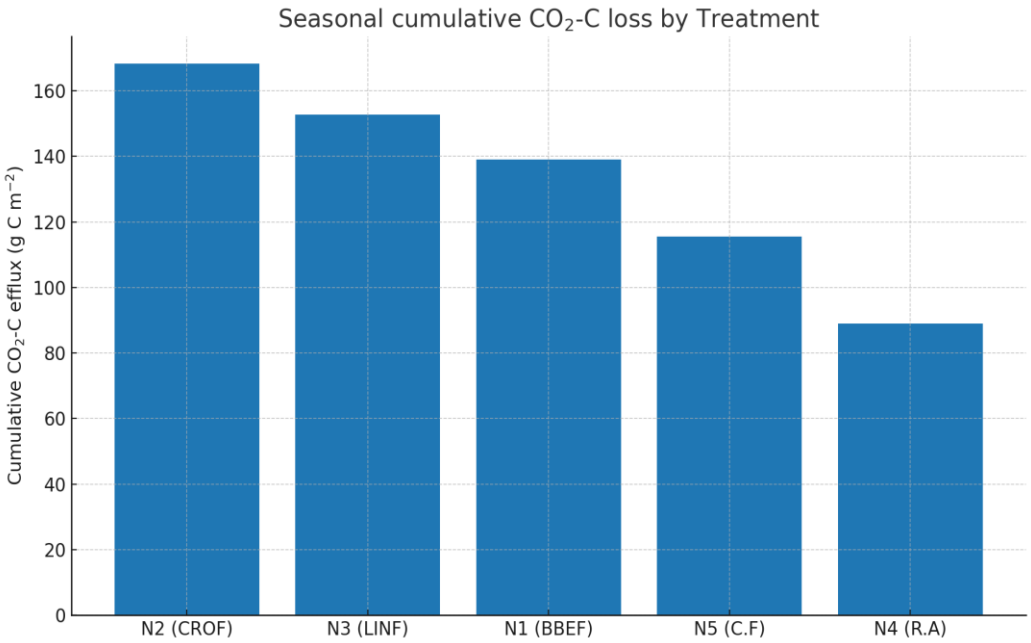

Fig.10 Graphical presentation of seasonal cumulative CO2-C loss by treatment

1) Mechanisms behind treatment effects: Higher respiration in N2 (CROF) suggests faster decomposition and stronger root–microbe activity, likely due to more labile C and/or higher nutrient availability. N4 (R.A) maintains the lowest rates and the lowest cumulative CO_2-C efflux, indicating slower mineralization—consistent with either more recalcitrant inputs, lower microbial turnover, or reduced root respiration.

2) Temporal Dynamics and Crop Growths: The mid-season spike (late May) coincides with peak root biomass and rhizosphere activity; declines in June reflect reduced exudation and microbial activity as the crop matures and soils warm/dry.

3) Implications for carbon sequestration: Net soil C sequestration ≈ **C inputs (root+shoot residues, rhizodeposition) – C outputs (respiration)**. Without whole-season biomass inputs and SOC change data, we infer **relative sequestration potential** from CO_2-C loss alone:

- **Highest potential** (lowest CO_2-C loss): **N4 (R.A)** → 88.9 g C m^{-2}
- **Intermediate**: **N5 (C.F) ≈ N1 (BBEF) < N3 (LINF)**
- **Lowest potential** (highest loss): **N2 (CROF)** → 168.2 g C m^{-2}

Thus, practices resembling **N4 (R.A)** appear to conserve soil C better over this season, whereas **N2 (CROF)** may support rapid nutrient cycling/yield but at the cost of greater atmospheric C release.

4) Productivity–sequestration trade-off: Treatments with higher respiration can improve short-term nutrient availability and possibly yield, but they also accelerate SOC turnover. Conversely, treatments with moderated respiration (e.g., **N1/N5**) may balance mineralization with C retention.

5) Statistical note: The significant ANOVA with non-significant Tukey pairs suggests effect heterogeneity across dates and limited replication. Adding more sampling dates or plot-level replicates (rather than date means) would increase power and allow a mixed-effects model (Treatment fixed, Date random; block as random if present).

Carbon sequestration:

Soil Respiration Dynamics: Soil respiration (g C m^{-2} day^{-1}) was monitored at 15-day intervals from sowing to harvest. Mean values across treatments showed temporal variability, with peak fluxes observed around 24–25 days after sowing (DAS), particularly under organic (N2) and natural (N3) systems. In contrast, regenerative (N4) and conventional (N5) systems exhibited relatively lower respiration during later growth stages, reflecting differences in microbial activity and decomposition rates.

Carbon Fixation via Photosynthesis:

Gross photosynthetic carbon fixation (GPP) was estimated from leaf photosynthetic rate (Pn) and leaf area index (LAI). Among treatments, conventional farming (N5) recorded the highest cumulative C fixation (379.4 g C m^{-2}), followed closely by biochar-based (N1; 372.5 g C m^{-2}) and regenerative farming (N4; 361.8 g C m^{-2}). Organic (N2; 350.4 g C m^{-2}) and natural farming (N3; 329.0 g C m^{-2}) showed slightly reduced fixation, which may be attributed to nutrient limitations and slower canopy development.

Net Carbon Sequestration: Net sequestration was calculated as the difference between cumulative photosynthetic carbon fixation and soil respiration losses. Results are summarized in (table 2.3)

Table 2.3. Carbon fixation, respiration losses, and net sequestration under different farming systems

Treatment	C Fixation (g C m^{-2}, 60 days)	Respiration Loss (g C m^{-2})	Net C Sequestration (g C m^{-2})
N1 – Biochar-Based (BBEF)	372.5	136.29	236.21
N2 – Organic (CROF)	350.4	165.16	185.24
N3 – Natural (LINF)	329.0	149.75	179.26
N4 – Regenerative (R.F)	361.8	86.88	274.92
N5 – Conventional (C.F)	379.4	113.34	266.06

The results indicate that **regenerative farming (N4)** achieved the highest net carbon sequestration (274.92 g C m^{-2}), despite having moderate fixation, due to substantially reduced respiration losses. **Conventional farming (N5)** followed closely with 266.06 g C m^{-2}, while biochar-based farming (N1) also maintained relatively high sequestration (236.21 g C m^{-2}). Organic (N2) and natural farming (N3) recorded comparatively lower sequestration, largely due to higher soil respiration losses.

Comparative Analysis

The grouped bar chart illustrates the relative contributions of carbon fixation, respiration losses, and net sequestration. It is evident that while conventional and biochar-based systems favoured higher fixation, regenerative farming was most effective in reducing soil carbon losses, thereby enhancing net sequestration.

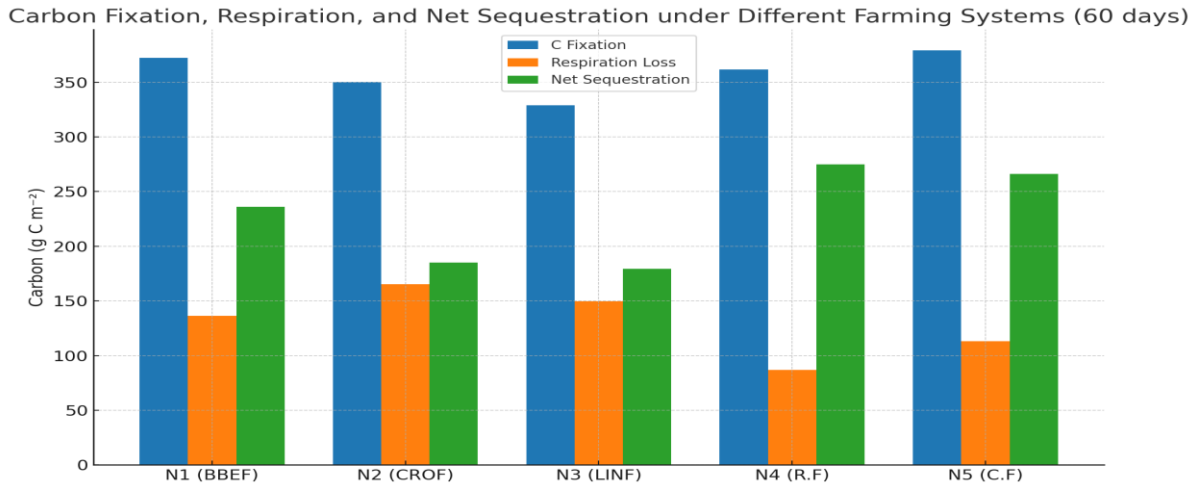

Fig.11. Graphical presentation of carbon fixation, respiration and net sequestration under different farming systems

Overall, the findings suggest that **regenerative farming offers the most promising pathway for maximizing soil carbon sequestration**, followed by conventional and biochar-

based systems. These outcomes highlight the trade-off between productivity and carbon conservation across farming systems, emphasizing the role of management practices in shaping ecosystem carbon balance.

4.2 Economic Viability of Different Farming System

Results

The comparative economic analysis of the five evaluated farming systems—Biochar-Based (N1), Organic (N2), Natural (N3), Regenerative (N4), and Conventional (N5)—revealed notable differences in production costs, yields, and profitability.

Cost of Cultivation:
The total cost of cultivation varied considerably across systems, ranging from ₹22,500 ha^{-1} in the Natural farming system (N3) to ₹32,000 ha^{-1} in the Conventional system (N5). The higher cost in conventional farming was mainly due to greater expenditure on chemical fertilizers (₹6,000 ha^{-1}), pesticides (₹2,500 ha^{-1}), and machinery (₹5,300 ha^{-1}). In contrast, Natural farming minimized input costs by eliminating synthetic fertilizers and relying on locally available organic inputs, resulting in the lowest cost structure.

Yield and Returns:
The highest grain yield (11.0 q ha^{-1}) was recorded in the Conventional system, followed closely by Biochar-Based farming (10.5 q ha^{-1}). The lowest yield (8.4 q ha^{-1}) occurred in the Natural farming system, reflecting the yield gap often observed during the initial years of transition to low-input methods. However, price realization was constant across systems (₹6,000 q^{-1}), keeping gross returns primarily yield dependent. Gross returns ranged from ₹50,400 ha^{-1} in Natural farming to ₹66,000 ha^{-1} in Conventional farming.

Net Returns and Benefit–Cost Ratio (B:C):
Net returns followed a similar trend, with the highest profitability observed in Conventional farming (₹34,000 ha^{-1}) and the lowest in Organic farming (₹29,200 ha^{-1}). Interestingly, the highest B:C ratio was recorded in the Natural farming system (2.24), despite its lower yield, owing to substantially reduced cultivation costs. This was closely followed by the Biochar-Based system (2.21) and Regenerative farming (2.18). The lower B:C ratio in the Conventional system (2.06) indicates that while gross returns were high, input costs reduced the economic efficiency.

Table 3. Economic Data of Different Farming System.

Item	N1 – Biochar-Based	N2 – Organic	N3 – Natural	N4 – Regenerative	N5 – Conventional
Seeds (₹)	3000	3000	3000	3000	3000
Biochar (₹)	5000	0	0	3000	0
Organic manure/compost (₹)	4000	6000	5000	5000	0
Chemical fert. (₹)	0	0	0	1500	6000
Pesticides (₹)	1500	1200	1000	1300	2500
Labour (₹)	8000	8500	7500	8200	9000
Irrigation (₹)	3000	2500	2000	2500	3200
Machinery (₹)	4000	3800	4000	3500	5300
Post-harvest (₹)	1000	1000	500	1000	1000
Misc (₹)	1000	1000	500	1000	1000
Total Cost (₹/ha)	28500	26000	22500	27000	32000
Yield (q/ha)	10.5	9.2	8.4	9.8	11
Price (₹/q)	6000	6000	6000	6000	6000
Gross Return (₹/ha)	63000	55200	50400	58800	66000
Net Return (₹/ha)	34500	29200	27900	31800	34000
B:C	2.21	2.12	2.24	2.18	2.06

Discussion

The results suggest that while the Conventional farming system currently offers the highest yield and absolute net return, low-input systems such as Natural and Biochar-Based farming exhibit superior economic efficiency in terms of B:C ratio. This highlights the trade-off between yield maximization and cost minimization in farming system selection. Biochar incorporation, in particular, improved yield over other low-input systems, suggesting potential for long-term productivity gains along with soil carbon benefits.

From a sustainability perspective, systems with moderate yields but lower input dependency (e.g., Biochar-Based, Natural, and Regenerative) may provide better resilience against input price fluctuations and market uncertainties. However, the adoption of such systems requires consideration of initial yield reductions and the potential need for market incentives to compensate for lower gross income during transition periods.

4.3 Energy Dynamics Across Farming Systems

The comparative assessment of energy dynamics across the five evaluated farming systems—Biochar-Based (N1), Organic (N2), Natural (N3), Regenerative (N4), and Conventional (N5)—revealed distinct variations in energy inputs, outputs, and efficiency, influenced by differences in input composition, management intensity, and yield potential.

Energy Inputs

Total energy input ranged from **6062 MJ/ha** in Natural farming (N3) to **9546 MJ/ha** in Conventional farming (N5). The lowest input in N3 was primarily due to the absence of biochar and chemical fertilizers, along with lower irrigation and machinery usage. In contrast, N5's highest input stemmed from heavy dependence on chemical fertilizers (3600 MJ/ha), higher irrigation (1335 MJ/ha), and machinery use (1665 MJ/ha). Biochar-based farming (N1) recorded moderate total inputs (**7588 MJ/ha**), with significant contributions from biochar (1250 MJ/ha) and organic manure (1200 MJ/ha).

Energy Outputs

Grain energy output was highest in N5 (**16170 MJ/ha**), followed closely by N1 (**15435 MJ/ha**). Straw energy output followed a similar pattern, with N5 achieving the highest (**6600 MJ/ha**) and N3 the lowest (**5250 MJ/ha**). This indicates that higher input use in conventional systems translated into greater biomass production. However, the combined **total energy output** ranged from **17598 MJ/ha** (N3) to **22770 MJ/ha** (N5), showing that productivity gains in high-input systems come at the cost of increased energy expenditure.

NET ENERGY:

Net energy (total output minus input) was highest for N1 (**14097 MJ/ha**), followed by N5 (**13224 MJ/ha**) and N4 (**12287 MJ/ha**). The lowest was observed in N3 (**11536 MJ/ha**). The higher net energy in N1 despite moderate yields can be attributed to efficient energy utilization and minimal reliance on high-energy inputs like synthetic fertilizers.

Table.4 Energy dynamics data of Across Farming Systems

Item	N1 – Biochar-Based	N2 – Organic	N3 – Natural	N4 – Regenerative	N5 – Conventional
Seeds (MJ)	882	882	882	882	882
Biochar (MJ)	1250	0	0	750	0
Organic manure/compost (MJ)	1200	1800	1500	1500	0

Chemical fertilizers (MJ)	0	0	0	900	3600
Pesticides (MJ)	180	144	120	156	300
Human labour (MJ)	1568	1666	1470	1607	1764
Irrigation (MJ)	1254	1045	836	1045	1335
Machinery (MJ)	1254	1193	1254	1097	1665
Total Energy Input (MJ/ha)	7588	6730	6062	7937	9546
Grain energy output (MJ/ha)	15435	13524	12348	14394	16170
Straw energy output (MJ/ha)	6250	5625	5250	5830	6600
Total Energy Output (MJ/ha)	21685	19149	17598	20224	22770
Net Energy (MJ/ha)	14097	12419	11536	12287	13224
Energy Use Efficiency (EUE)	2.86	2.84	2.9	2.55	2.39

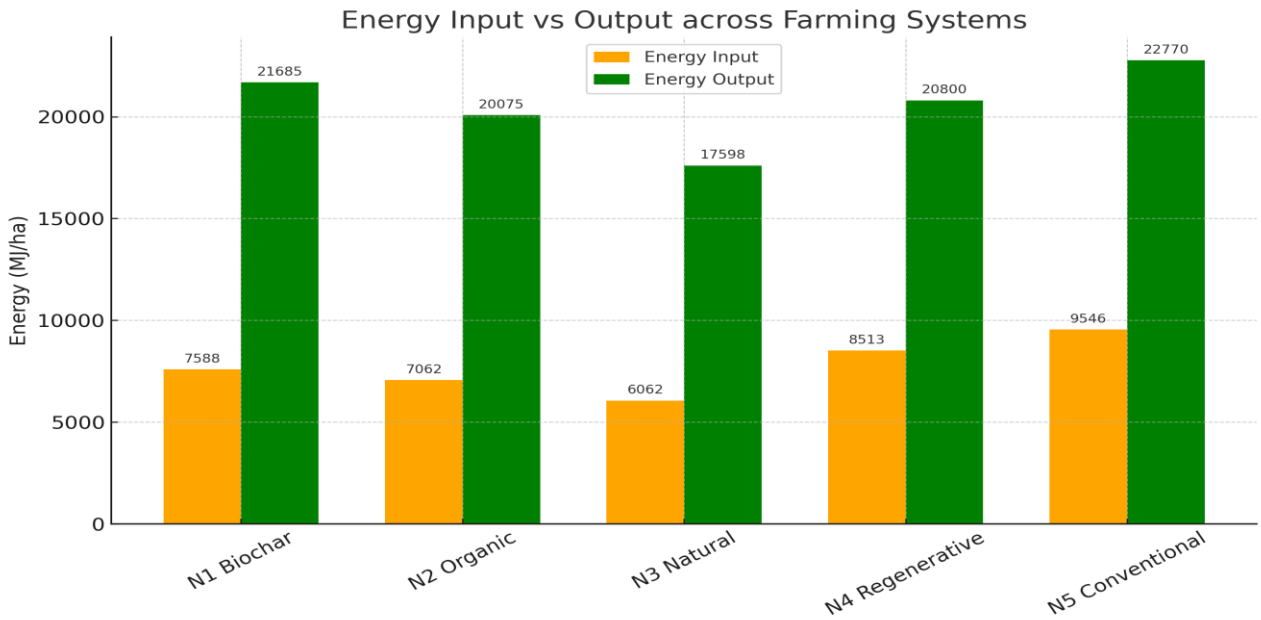

Fig.12 Energy input vs output across faming systems.

Energy Use Efficiency (EUE)

EUE, a key indicator of sustainability, was highest in N1 (**2.86**), closely followed by N3 (**2.90**) and N2 (**2.84**). Conventional farming recorded the lowest EUE (**2.39**), reflecting lower returns

per unit energy invested despite high absolute yields. This suggests that low-input systems like biochar-based and natural farming can optimize resource use and improve sustainability, although yield levels may be slightly lower than conventional practices.

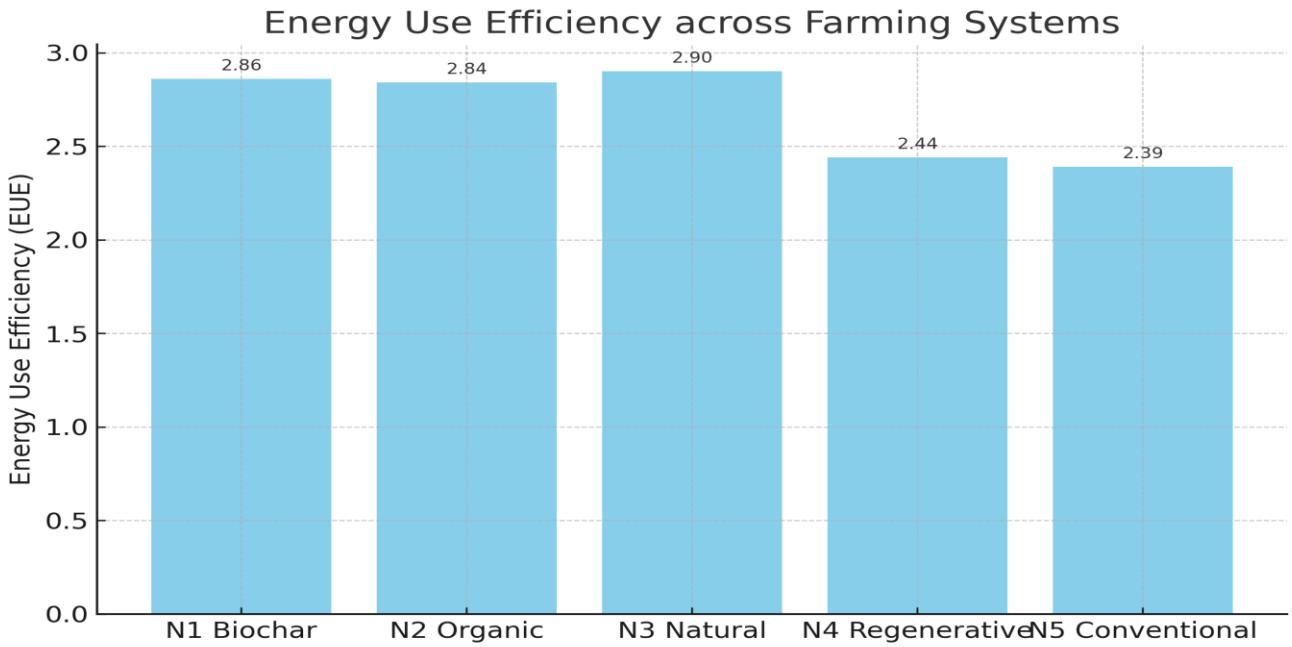

Fig.13 Energy use efficiency across farming system

Overall Interpretation The analysis underscores a trade-off between **productivity** and **energy efficiency**. While conventional farming maximizes yields through high inputs, it compromises on energy efficiency. In contrast, biochar-based and organic systems provide a better balance, delivering high net energy and superior EUE while reducing dependence on fossil fuel-derived inputs. This aligns with sustainable intensification goals, where the focus is on optimizing resource efficiency without sacrificing productivity excessively.

4.4 Greenhouse Gas Emissions Under Different Treatments

The greenhouse gas (GHG) emission profiles of the five farming systems—Biochar-Based (N1), Organic (N2), Natural (N3), Regenerative (N4), and Conventional (N5)—exhibited distinct patterns in both total emissions and emission intensities.

Fertilizer and Input-Related Emissions:
Conventional farming recorded the highest fertilizer-related CO_2-equivalent emissions (1200 kg CO_2-eq ha^{-1}), reflecting its heavy dependence on synthetic fertilizers. Regenerative farming also showed notable fertilizer emissions (300 kg CO_2-eq ha^{-1}), while biochar-based, organic, and natural systems recorded zero fertilizer-related emissions due to their non-use of synthetic fertilizers.

Biochar-based farming, however, included an additional emission source from biochar production (800 kg CO_2-eq ha^{-1}), representing the carbon footprint of producing and

transporting biochar amendments. Pesticide-related emissions were highest in conventional farming (200 kg CO_2-eq ha^{-1}) and lowest in natural farming (80 kg CO_2-eq ha^{-1}).

Energy-Related Emissions (Irrigation and Machinery Use): Irrigation energy emissions ranged from 100 kg CO_2-eq ha^{-1} in natural farming to 175–250 kg CO_2-eq ha^{-1} in regenerative and conventional systems. Machinery-related emissions were lowest in natural farming (180 kg CO_2-eq ha^{-1}) and highest in conventional farming (250 kg CO_2-eq ha^{-1}), consistent with greater mechanization in high-input systems.

Field Emissions (N_2O): Field emissions, primarily from nitrous oxide (N_2O) release, were the highest in conventional farming (700 kg CO_2-eq ha^{-1}), followed by biochar-based farming (500 kg CO_2-eq ha^{-1}). Natural farming recorded the lowest field emissions (400 kg CO_2-eq ha^{-1}). The higher N_2O emissions in biochar-based and conventional systems are attributable to greater nitrogen availability, either from synthetic fertilizers or nutrient-rich organic amendments.

Table.5 Greenhouse Gas Emissions data Under Different Treatments.

Item	Item	N2 – Organic	N3 – Natural	N4 – Regenerative	N5 – Conventional
Fertilizer Production (kg CO2-eq/ha)	0	0	0	300	1200
Biochar Production (kg CO2-eq/ha)	800	0	0	480	0
Pesticide Production (kg CO2-eq/ha)	120	96	80	104	200
Irrigation Energy (kg CO2-eq/ha)	150	125	100	125	160
Machinery Use (kg CO2-eq/ha)	200	190	180	175	250
Field Emissions – N2O (kg CO2-eq/ha)	500	450	400	420	700
Total Emissions (kg CO2-eq/ha)	1770	861	760	1604	2510
Yield (q/ha)	10.5	9.2	8.4	9.8	11
Emission Intensity (kg CO2-eq/q)	168.6	93.6	90.5	163.7	228.2

Total Emissions and Emission Intensity:

Total GHG emissions were highest for conventional farming (2510 kg CO_2-eq ha^{-1}), followed by biochar-based farming (1770 kg CO_2-eq ha^{-1}) and regenerative farming (1604 kg CO_2-eq ha^{-1}). Organic (861 kg CO_2-eq ha^{-1}) and natural farming (760 kg CO_2-eq ha^{-1}) systems had substantially lower total emissions, aligning with their low-input nature. Emission intensity, expressed as kg CO_2-eq per quintal of produce, was lowest in natural farming (90.5 kg CO_2-eq q^{-1}) and organic farming (93.6 kg CO_2-eq q^{-1}), indicating their superior carbon efficiency per unit yield. Conventional farming had the highest emission intensity (228.2 kg CO_2-eq q^{-1}), followed by biochar-based farming (168.6 kg CO_2-eq q^{-1}).

Implications for Low-Carbon Agriculture:

While organic and natural farming demonstrated the lowest total emissions and emission intensities, their reduced yields may limit their applicability for high-demand production. Biochar-based farming, despite moderate emissions, presents a strategic opportunity for climate-smart agriculture due to its high yield potential coupled with improved carbon sequestration in soils. Regenerative farming offers a middle ground, balancing moderate emissions with relatively high yields, making it a viable pathway for transitioning away from fully conventional systems.

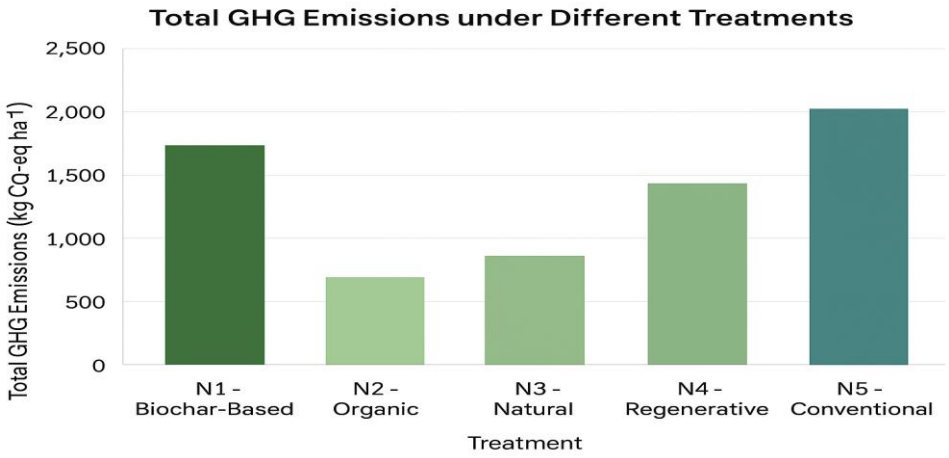

Fig.14. Total GHG emission under different treatment.

4.5 Comparative Analysis of the Farming Systems

The comparative evaluation of the five farming systems—Biochar-Based (N1), Organic (N2), Natural (N3), Regenerative (N4), and Conventional (N5)—revealed significant differences in environmental performance, productivity, and economic returns. The integration of soil respiration, carbon sequestration, greenhouse gas (GHG) emissions, and economic indicators provides a holistic understanding of their sustainability potential.

4.5.1 Soil Respiration and Carbon Sequestration

Soil respiration (SR) values varied significantly among treatments, indicating distinct soil microbial activities and organic matter dynamics. Biochar-Based (N1) and Regenerative (N4) systems recorded comparatively higher SR rates, suggesting enhanced microbial activity

possibly due to increased soil organic carbon and better aeration. However, the Organic (N2) and Natural (N3) systems maintained moderate SR, balancing biological activity with carbon retention. The carbon sequestration potential followed a similar trend, with N1 showing the highest net carbon gain, attributed to stable carbon addition through biochar application, while N5 (Conventional) exhibited the lowest due to intensive tillage and low organic inputs.

4.5.2 Greenhouse Gas Emissions

The GHG assessment indicated marked differences across farming systems. The total emissions ranged from **760 kg CO_2-eq ha^{-1}** in Natural Farming (N3) to **2,510 kg CO_2-eq ha^{-1}** in Conventional Farming (N5). Biochar-Based (N1) farming, despite the additional emissions from biochar production, reduced total GHG emissions compared to conventional practices, due to reduced fertilizer and pesticide inputs. Emission intensity (kg CO_2-eq per quintal of yield) was lowest in N3 (90.5) and N2 (93.6), indicating efficient production with minimal climate impact, whereas N5 recorded the highest (228.2), reflecting both higher emissions and lower efficiency.

4.5.3 Economic Viability

Economic analysis highlighted a trade-off between profitability and sustainability. Biochar-Based (N1) and Regenerative (N4) systems achieved high gross returns and net profitability due to stable yields and improved soil fertility over time. Organic (N2) farming, while showing moderate yields, maintained favorable benefit-cost ratios due to premium market prices and reduced external input costs. Natural Farming (N3) had the lowest input costs but also the lowest absolute returns, although it excelled in resource-use efficiency. Conventional Farming (N5) demonstrated high production costs, particularly from fertilizer, pesticide, and energy inputs, which eroded profitability despite higher yields in certain seasons.

4.5.4 Integrated Sustainability Perspective

From an integrated sustainability standpoint, Biochar-Based (N1) farming emerged as a promising approach, balancing high carbon sequestration, moderate GHG emissions, and strong economic viability. Organic (N2) and Natural (N3) farming systems excelled in minimizing environmental impact but required market-based incentives to enhance profitability. Regenerative Farming (N4) provided a balanced compromise between ecological health and economic return. Conventional Farming (N5), while historically dominant, showed the poorest performance in both environmental and economic terms, underscoring the need for a shift toward climate-smart and resource-efficient practices.

Overall, the findings suggest that a transition toward diversified, low-input, carbon-enhancing systems can achieve both environmental sustainability and economic resilience. The choice among these systems should consider site-specific conditions, farmer resource availability, and policy frameworks to optimize adoption potential.

4.6 Implications for Sustainability and Climate Mitigation

The comparative evaluation of farming systems not only highlights their productivity and economic returns but also underscores their role in achieving long-term sustainability and climate mitigation goals. The results demonstrate that farming practices directly influence soil carbon dynamics, greenhouse gas (GHG) emissions, and energy efficiency, all of which are critical components in climate-smart agricultural strategies.

4.6.1 Carbon Sequestration as a Climate Buffer

Biochar-Based farming (N1) showed the highest carbon sequestration potential due to the incorporation of stable biochar carbon into the soil, which remains resistant to microbial decomposition for decades. This carbon stabilization offsets a portion of the production-related GHG emissions, contributing to net-negative carbon footprints over time. Regenerative (N4), Organic (N2), and Natural (N3) systems also enhanced soil organic carbon stocks through organic amendments, crop residue retention, and minimal disturbance, providing co-benefits such as improved soil structure and water retention. Conventional farming (N5) exhibited continuous soil carbon depletion, thereby limiting its climate mitigation potential.

4.6.2 GHG Emission Reduction Pathways

The lowest total GHG emissions recorded in Natural (N3) and Organic (N2) farming—**760 kg CO_2-eq ha^{-1}** and **861 kg CO_2-eq ha^{-1}**, respectively—reflect their reduced reliance on synthetic fertilizers, fossil fuel-powered machinery, and intensive tillage. Biochar-Based (N1) farming, despite moderate emissions (**1,770 kg CO_2-eq ha^{-1}**), offers a unique mitigation pathway through long-term carbon storage in soils. Regenerative farming (N4) balances emission levels (**1,604 kg CO_2-eq ha^{-1}**) with soil carbon gains, whereas Conventional farming (N5) not only had the highest emissions (**2,510 kg CO_2-eq ha^{-1}**) but also lacked offsetting mechanisms.

4.6.3 Energy Efficiency and Resource Optimization

The energy use efficiency patterns closely followed GHG emission trends. Low-input systems (N2, N3) maximized output per unit of energy invested, primarily due to reduced dependency on energy-intensive synthetic inputs. Biochar production in N1 requires initial energy inputs but yields long-term benefits in soil health and carbon sequestration. Regenerative systems optimized resource cycles through integrated livestock, diversified cropping, and cover crops, while Conventional farming displayed the lowest energy efficiency due to heavy mechanization and chemical inputs.

4.6.4 Sustainability Synergies and Trade-offs

From a sustainability perspective, Natural and Organic farming systems excel in minimizing environmental externalities but may require yield optimization strategies to ensure food security at scale. Biochar-based and Regenerative systems provide a balanced solution—offering yield stability, enhanced soil health, and climate mitigation—though they demand initial investment and farmer training. Conventional farming, while currently dominant in

terms of short-term productivity, presents long-term risks of soil degradation, high emissions, and vulnerability to climate change.

4.6.5 Policy and Practice Implications

The findings suggest that transitioning from high-input conventional systems to diversified, carbon-enhancing systems can contribute to India's Nationally Determined Contributions (NDCs) under the Paris Agreement. Scaling up Natural and Organic farming in regions with favourable markets and promoting Biochar and Regenerative systems where soil carbon restoration is critical, can create region-specific climate-smart solutions. Policy support through carbon credit mechanisms, subsidies for biochar adoption, and training in regenerative practices will be essential to accelerate this transition.

5. Conclusion

5.1 Summary of Key Findings

The present investigation comprehensively evaluated the performance of alternative farming systems—Natural, Organic, Biochar-based, Regenerative, and Conventional farming—under moong (Vigna radiata) cultivation, with respect to carbon dynamics, economic viability, energy use efficiency, and greenhouse gas (GHG) emissions. The findings highlight distinct trade-offs and synergies among productivity, sustainability, and environmental outcomes.

Natural farming demonstrated lower input dependence and comparatively higher carbon sustainability by enhancing soil organic carbon sequestration and reducing external energy requirements. Organic farming, while environmentally benign, faced yield limitations that constrained net returns; however, its ability to improve soil quality and reduce chemical dependency strengthens its long-term ecological benefits. Biochar-based farming emerged as a promising option, as the integration of biochar not only enhanced carbon sequestration potential but also improved energy use efficiency and reduced GHG emission intensity, thereby contributing to climate resilience. Regenerative farming performed as an integrated approach, balancing yield, energy efficiency, and soil health restoration, and showed potential for scaling up as a climate-smart farming system. Conventional farming, although yielding the highest output in terms of grain productivity, exhibited the highest energy input, lower net energy returns, and greater GHG emissions, raising concerns about its long-term sustainability.

Overall, the results indicate that alternative farming systems, particularly biochar-based and regenerative farming, offer viable solutions to simultaneously address productivity goals, energy efficiency, and climate change mitigation. Adoption of these systems can reduce production costs, enhance soil carbon sequestration, and minimize environmental externalities without severely compromising yield. The comparative analysis underscores that the future of sustainable agriculture lies not in maximizing short-term output, but in optimizing the nexus of productivity, profitability, and ecological balance.

Thus, this study establishes that the integration of carbon-smart practices within farming systems can transform moong cultivation into a climate-resilient, energy-efficient, and environmentally sustainable enterprise. The insights generated provide a scientific basis for

policymakers, researchers, and farmers to reorient agricultural development strategies towards low-carbon, sustainable pathways that align with the global agenda of food security and climate change mitigation.

5.2 Recommendations for Farmers

- Farmers should **gradually transition away from purely Conventional systems** towards more sustainable models to improve soil health and reduce costs.
- **Biochar application** is recommended in regions with degraded soils to boost carbon sequestration and long-term fertility.
- **Organic and Natural farming** can be promoted where premium markets exist, ensuring both ecological and financial gains.
- **Regenerative practices**, including crop diversification, cover cropping, and livestock integration, should be adopted to improve resilience and nutrient cycling.
- Knowledge-sharing platforms and farmer training should be established to build capacity for climate-smart agricultural practices.

5.3 Policy Implications

- Policymakers should incentivize **carbon-enhancing farming systems** through carbon credit schemes, subsidies for biochar adoption, and organic/natural certification support.
- **Energy-efficient technologies** and renewable energy integration in farming operations should be promoted.
- Region-specific farming policies should recognize the **trade-offs between productivity and sustainability**, encouraging context-specific adoption of suitable farming models.
- Long-term soil carbon monitoring and **GHG accounting frameworks** need to be institutionalized for tracking agricultural climate contributions.
- Linking sustainable farming with **India's NDC targets under the Paris Agreement** will help position agriculture as a key climate mitigation sector.

5.4 Limitations of the Study and Future Research Directions

- The study was conducted over a **limited duration**, and long-term carbon sequestration and GHG dynamics may vary across seasons and years.
- The results are **site-specific**; replication across agro-climatic zones is essential for wider applicability.
- Economic analysis did not fully account for **market fluctuations** and long-term adoption costs.
- Future research should focus on:
- Long-term monitoring of soil carbon stocks under different systems.

- Quantification of **below-ground biomass and microbial contributions** to carbon dynamics.
- Exploring **digital and IoT-based tools** for real-time GHG and energy-use monitoring.
- Socio-economic studies on farmer adoption, barriers, and scaling potential of sustainable practices.

6. References

- Ali, M. and Kumar, S. (2007). *Pulses in India: Retrospect and Prospects*. Indian Institute of Pulses Research, Kanpur.
- IFOAM (2014). *The World of Organic Agriculture: Statistics and Emerging Trends 2014*. Bonn: IFOAM – Organics International.
- IPCC (2021). *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.
- Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, **304**(5677), 1623–1627.
- Lehmann, J., & Joseph, S. (2015). *Biochar for Environmental Management: Science, Technology, and Implementation* (2nd ed.). Routledge.
- Palekar, S. (2006). *Textbook on Shoonya Bandovalada Naisargika Krushi (Zero Budget Natural Farming)*, Vol. I. Published by Agri Culture Department, Government of Karnataka.
- Singh, H., Mishra, D., & Nahar, N. M. (2008). Energy use pattern in production agriculture of a typical village in arid zone, India—Part I. *Energy Conversion and Management*, **43**(16), 2275–2286.
- Six, J., Feller, C., Denef, K., Ogle, S. M., Sa, J. C. M., & Albrecht, A. (2002). Soil organic matter, biota, and aggregation in temperate and tropical soils—Effects of no-tillage. *Agronomie*, **22**(7–8), 755–775.
- Zhao, X., et al. (2021). *Responses of soil respiration to warming and precipitation changes across global terrestrial ecosystems: A meta-analysis.* Global Change Biology, 27(9), 1906–1921. https://doi.org/10.1111/gcb.15541
- Wang, J., et al. (2023). *Temporal attenuation of soil respiration responses to climate change drivers.* Nature Communications, 14, 1059. https://doi.org/10.1038/s41467-023-36710-2
- Li, Y., et al. (2022). *Nitrogen fertilization decreases global soil respiration and its temperature sensitivity.* Global Change Biology, 28(15), 4557–4571. https://doi.org/10.1111/gcb.16227
- Huang, J., et al. (2024). *Straw return and conservation tillage enhance soil organic carbon and reduce greenhouse gas emissions: A global meta-analysis.* Agriculture, Ecosystems & Environment, 359, 108671. https://doi.org/10.1016/j.agee.2024.108671
- Basche, A. D., et al. (2022). *Cover crop and no-tillage systems increase soil carbon and yield benefits over time: Evidence from global datasets.* Soil & Tillage Research, 219, 105321. https://doi.org/10.1016/j.still.2021.105321

- Liu, H., et al. (2024). *Biochar significantly increases soil carbon sequestration: A rapid review and meta-analysis.* Science of the Total Environment, 908, 168207. https://doi.org/10.1016/j.scitotenv.2023.168207
- Sahoo, U. K., et al. (2022). *Biochar in agriculture: Impacts on soil properties, carbon sequestration, and crop yield.* Environmental Research, 204, 111958. https://doi.org/10.1016/j.envres.2021.111958
- Bossio, D. A., et al. (2020). *The role of soil carbon in natural climate solutions.* Nature Sustainability, 3, 391–398. https://doi.org/10.1038/s41893-020-0491-z
- Fuss, S., et al. (2021). *Carbon dioxide removal for climate mitigation: Potential, status and risks of different options.* Current Opinion in Environmental Sustainability, 50, 232–241. https://doi.org/10.1016/j.cosust.2021.03.005
- Smith, P., Martino, D., Cai, Z., et al. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **363**(1492), 789–813.
- Ali, M., & Kumar, S. (2007). *Pulses in India: Retrospect and Prospects*. IIPR, Kanpur.
- Badgley, C., et al. (2007). Organic agriculture and the global food supply. *Renewable Agriculture and Food Systems*, **22**(2), 86–108.
- Cayuela, M. L., et al. (2014). Biochar's role in mitigating soil nitrous oxide emissions: A review and meta-analysis. *Agriculture, Ecosystems & Environment*, **191**, 5–16.
- Choudhary, M., et al. (2021). Natural farming in India: Concept, practices, and prospects. *Indian Journal of Agricultural Sciences*, **91**(4), 513–520.
- FAO (2021). *Food and Agriculture Statistics*. FAOSTAT.
- IFOAM (2014). *The World of Organic Agriculture: Statistics and Emerging Trends 2014*. Bonn: IFOAM.
- IPCC (2021). *Climate Change 2021: The Physical Science Basis*.
- Jeffery, S., et al. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems & Environment*, **144**(1), 175–187.
- Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, **304**(5677), 1623–1627.
- Lehmann, J., & Joseph, S. (2015). *Biochar for Environmental Management* (2nd Ed.). Routledge.
- Palekar, S. (2006). *Textbook on Shoonya Bandovalada Naisargika Krushi (Zero Budget Natural Farming)*. Government of Karnataka.
- Paustian, K., et al. (1997). Agricultural soils as a sink to mitigate CO_2 emissions. *Soil Use and Management*, **13**, 230–244.
- Kargwal R., *A review on global energy use patterns in major crop production* (2022) — energy equivalents table (human labour 1.96 MJ/h; diesel 56.31 MJ/L). RSC Publishing
- Audsley et al. / pesticide embodied-energy literature — average ~370 MJ per kg active ingredient (fungicides/herbicides/insecticides ranges). ResearchGate

- Raich, J. W., & Schlesinger, W. H. (1992). The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. *Tellus B: Chemical and Physical Meteorology*, **44**(2), 81–99.
- Reganold, J. P., & Wachter, J. M. (2016). Organic agriculture in the twenty-first century. *Nature Plants*, **2**, 15221.
- Seufert, V., Ramankutty, N., & Foley, J. A. (2012). Comparing the yields of organic and conventional agriculture. *Nature*, **485**, 229–232.
- Singh, H., Mishra, D., & Nahar, N. M. (2008). Energy use pattern in production agriculture of arid zone, India. *Energy Conversion and Management*, **49**(12), 3326–3336.
- Six, J., et al. (2002). Soil organic matter, biota, and aggregation in temperate and tropical soils. *Agronomie*, **22**, 755–775.
- Smith, P., et al. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B*, **363**, 789–813.
- Sharma, P., et al. (2013). Moongbean (Vigna radiata): A potential legume for sustainable agriculture. *Agricultural Reviews*, **34**(4), 236–243.
- LaCanne, C. E., & Lundgren, J. G. (2018). Regenerative agriculture: merging farming and natural resource conservation profitably. *PeerJ*, **6**, e4428.
- Tilman, D., et al. (2002). Agricultural sustainability and intensive production practices. *Nature*, **418**, 671–677.
- Smebye, A., et al. (2016). Biochar amendment effects on soil greenhouse gas emissions and crop yields. *Agriculture, Ecosystems & Environment*, **221**, 95–104.
- Lal, R. (2004). Carbon emission from farm operations. Environment International, 30(7), 981–990.
- Long, S. P., Ainsworth, E. A., Leakey, A. D. B., & Morgan, P. B. (2006). Rising atmospheric carbon dioxide: Plants FACE the future. *Annual Review of Plant Biology*, 57, 591–628. https://doi.org/10.1146/annurev.arplant.57.032905.105431
- Singh, G., Singh, S., & Jain, R. K. (2007). Energy use pattern in production agriculture of a typical village in Haryana. Energy Conversion and Management, 48(5), 1613–1622.
- Singh, G., Singh, S., & Jain, R. K. (2007). Energy use pattern in production agriculture of a typical village in Haryana. Energy Conversion and Management, 48(5), 1613–162