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Dynamics of Soil CO_2 Flux in Rice Systems Under Biochar and Poultry Manure Application Using a Portable NDIR-Based Sensor System

Muhamad Afif Akbar[1,✉], Cahyo Prayogo[2], Zaenal Kusuma[2]

[1] Study Program of Soil and Water Management, Faculty of Agriculture, Universitas Brawijaya, Malang, INDONESIA.

[2] Soil Science Department, Faculty of Agriculture, Universitas Brawijaya, Malang, INDONESIA.

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Corresponding Author:
✉ afiftnh@gmail.com
(Muhamad Afif Akbar)

ABSTRACT

Soil CO_2 emission from paddy systems is an important component of agricultural carbon fluxes, yet field monitoring remains constrained by labor-intensive methods. This study aimed to examine a portable NDIR-based CO_2 sensor system and to quantify soil CO_2 flux dynamics and vegetative growth of paddy under different organic amendments. A greenhouse pot experiment with four treatments, biochar 30 Mg/ha (B), poultry manure 40 Mg/ha (K), biochar 30 Mg/ha + manure 20 Mg/ha (BK1), and biochar 15 Mg/ha + manure 40 Mg/ha (BK2), was conducted during the vegetative stage of paddy. Soil CO_2 flux was measured daily from 1 to 60 days after transplanting (DAT) using an MH-Z19B sensor inside a closed chamber. Integrated over the vegetative stage, mean soil CO_2 fluxes were 311, 391, 461, and 516 mg $CO_2{\cdot}m^{-2}{\cdot}h^{-1}$ for B, BK1, BK2, and K, respectively, indicating that manure based treatments enhanced respiration compared with sole biochar. Soil CO_2 flux tended to increase from early to late vegetative stages and was positively correlated with plant height and leaf number, indicating a significant positive association between carbon loss and biomass accumulation. These results show that portable low cost sensors can support the design of biochar–manure strategies that sustain paddy growth while moderating manure induced CO_2 emissions.

1. INTRODUCTION

Soil CO_2 emission (soil CO_2 flux) is one of the largest components of carbon flow in agroecosystems and plays an important role in the dynamics of global greenhouse gases. In paddy cultivation systems, soil and plant respiration have been reported to contribute 8–15% of emissions from the agricultural sector (Nurhidayati *et al*., 2023). This contribution is governed by the decomposition of organic matter, root respiration, and microclimatic conditions that change across crop growth stages. Soil CO_2 flux in paddy fields can vary widely, ranging from 150 to more than 1500 mg $CO_2/m^2/h$ depending on growth stage, soil conditions, and fertilization practices (Ray *et al*., 2020; Yin *et al*., 2025). Such variability underscores the need for continuous emission monitoring to more accurately capture plant physiological responses and soil carbon dynamics.

The application of amendments is one of the main strategies to improve soil quality and modulate carbon flows in paddy systems. Biochar is characterized by highly stable carbon and can reduce soil respiration through enhanced carbon retention and improved pore structure (Lehmann & Joseph, 2015). Numerous studies have shown that biochar can decrease CO_2 flux by 10–35% under certain conditions because of its low proportion of labile carbon (Han *et al*., 2023; Seki *et al*., 2022). In contrast, poultry manure is rich in readily decomposable carbon and nitrogen, and thus tends to increase microbial activity and soil respiration, particularly at early growth stages. Increases in CO_2 flux following poultry manure application have been reported to reach 20–60%, depending on application rate and environmental conditions (Ali *et al*., 2025; Haque *et al*., 2020).

The combination of biochar and poultry manure may generate different responses because interactions between stable and labile carbon fractions can alter the balance of decomposition, microbial activity, and nutrient availability (Mon & Ueno, 2024). However, the CO_2 flux response of such combined organic amendments is strongly dependent on their proportion and characteristics, requiring structured quantitative evaluation. Seki *et al*. (2022), estimated cumulative CO_2 fluxes of 2.4, 2.7, 4.0, and 3.7 Mg C/ha in control, biochar, manure, and biochar–manure treatments, respectively, showing that biochar alone did not enhance CO_2 emission, while biochar manure application slightly reduced manure induced CO_2 flux and simultaneously produced the largest increase in soil organic carbon and a positive carbon budget. These results indicate that biochar–manure combinations can attenuate the emission stimulus of labile organic inputs while improving soil carbon sequestration, but their effectiveness is strongly dose dependent, thereby justifying further quantitative evaluation under different paddy management scenarios.

The dynamics of CO_2 flux in paddy systems are strongly influenced by the crop growth stage. Fluxes are usually low during the early stage when root biomass and vegetative tissues are still limited, and then increase sharply at the maximum vegetative stage (30–60 days) in response to enhanced root respiration and the formation of new tissues (Ben-Noah & Friedman, 2018; Min & Rulík, 2020). Yin *et al*. (2025) reported that CO_2 flux in paddy systems can increase by 2–4 times at the active vegetative stage compared with the early stage because of the high metabolic rate of plants. The close relationship between vegetative growth (plant height and leaf number) and plant respiration makes these parameters important for interpreting CO_2 flux. Therefore, CO_2 flux monitoring needs to be carried out comprehensively to quantitatively capture this physiological relationship.

Conventional chamber based techniques that rely on alkali absorption or intermittent sampling, although widely used for measuring soil CO_2 flux, still present several practical limitations, measurements are discontinuous, require intensive laboratory processing, and may underestimate actual fluxes because CO_2 is not fully captured during the incubation period (Ferreira *et al*., 2018). Non-dispersive infrared (NDIR) sensor technology offers a more practical alternative with the capability to record continuous data at high temporal resolution (Ferreira *et al*., 2018). Recent studies have shown that low cost NDIR sensors can yield strong linear relationships (R^2 = 0.90–0.95) with reference instruments when properly calibrated (Curcoll *et al*., 2022). However, the use of portable sensors for continuous monitoring of CO_2 flux in paddy systems, particularly for comparing the responses of biochar, poultry manure, and their combinations, remains very limited.

Based on this background, three gaps remain insufficiently documented: limited quantitative comparison of CO_2 flux among biochar, poultry manure, and their combinations during the vegetative stage of paddy; limited understanding of the relationship between CO_2 flux and vegetative growth under organic amendments; and limited use of portable NDIR sensors for daily CO_2 flux monitoring from 1 to 60 DAT. This study, therefore, aimed to analyze the dynamics of soil CO_2 flux under four organic soil amendment treatments, biochar (B), poultry manure (K), a combination of biochar and poultry manure at a lower dose (BK1), and a higher dose (BK2) using a portable NDIR-based CO_2 sensor system. In addition, the study evaluated the relationship between CO_2 flux and vegetative growth of paddy to provide a quantitative understanding of how organic amendments influence soil biological activity. The findings are expected to provide empirical information that supports soil carbon management practices and promotes the use of portable sensors in field based agronomic research.

2. MATERIALS AND METHODS

The study was conducted from April to June 2025 in a greenhouse at the Faculty of Agriculture, Universitas Brawijaya (7°57'15.76" S, 112°36'41.09" E). The greenhouse environment allowed temperature, humidity, and light intensity to be controlled, making it suitable for continuous monitoring of soil respiration during the vegetative stage of paddy.

2.2. Instruments and Materials

The main instrument used was a portable CO_2 sensor system based on the MH-Z19B NDIR module connected to a microcontroller for automatic data acquisition. The system was equipped with a BMP280 air temperature–pressure sensor, a DS18B20 soil temperature sensor, and a SEN0193 capacitive soil moisture sensor. Measurements were carried out inside an acrylic chamber with dimensions of 20 cm × 20 cm × 90 cm. The KOH titration method was used as a reference for sensor calibration.

The experimental materials consisted of paddy soil as the growth medium, biochar, poultry manure, and seeds of a local paddy variety. Biochar and poultry manure were applied according to the treatment doses before transplanting. The plants were grown in pots with dimensions of 20 cm × 20 cm × 10 cm.

2.3. Portable CO_2 Sensor System and Calibration

The CO_2 sensor system was designed as a portable, stand alone unit powered by a battery (Figure 1). The MH-Z19B module was selected because it can directly and stably measure CO_2 concentration in ppm within a range suitable for field measurements.

Figure 1. Portable CO_2 sensor with the MH-Z19B module

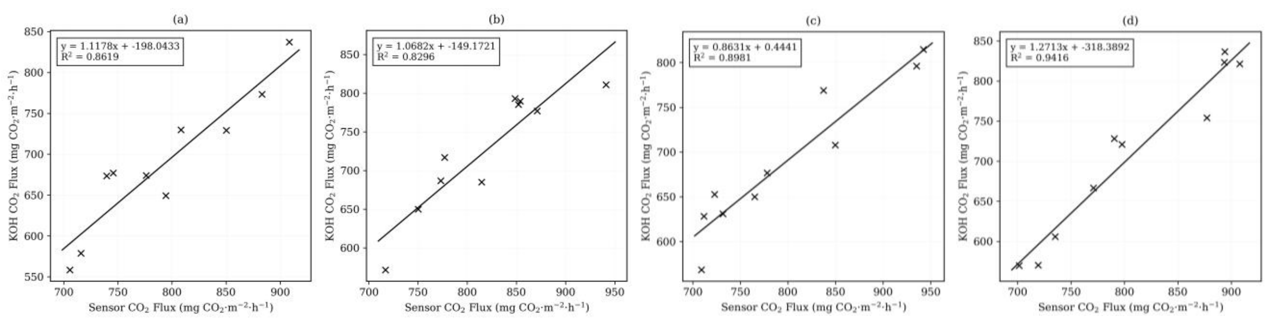

Figure 2. Calibration of the CO_2 sensor against the KOH method: (a) sensor 1, (b) sensor 2, (c) sensor 3, and (d) sensor 4.

Linear regression analysis (Figure 2) showed that all sensors exhibited a strong linear relationship with the KOH method, with coefficients of determination (R^2) ranging from 0.829 to 0.942. Sensor 4 showed the best performance (R^2 = 0.9416), followed by sensor 3 (R^2 = 0.8981), sensor 1 (R^2 = 0.8619), and sensor 2 (R^2 = 0.8296). Differences in slope among sensors reflect variations in internal sensitivity, but the stable linear patterns confirm the consistent performance of all sensor units.

To support the interpretation of calibration performance, the coefficient of determination (R^2) values were converted into correlation coefficients (*r*) using $r = \sqrt{R^2}$. Criteria commonly applied for correlation strength based on absolute *r* values are as follows: very weak ($r < 0.20$), weak ($0.20 \leq r < 0.40$), moderate ($0.40 \leq r < 0.60$), strong ($0.60 \leq r < 0.80$), and very strong (≥ 0.80). In this study, the R^2 values of the four sensors ranged from 0.8296 to 0.9416, corresponding to *r* values of 0.911–0.970 (Table 1). These values indicate a very strong relationship between the portable NDIR based CO_2 sensor readings and the KOH reference method, confirming the suitability of the sensor system for soil CO_2 flux monitoring.

Table 1. Interpretation of sensor calibration performance based on *r* values

Sensor	R^2 value	$r = \sqrt{R^2}$	Interpretation
Sensor 1	0.8619	0.928	Very strong
Sensor 2	0.8296	0.911	Very strong
Sensor 3	0.8981	0.948	Very strong
Sensor 4	0.9416	0.970	Very strong

2.4. Experimental Design

Before the treatments were applied, the soil used as the planting medium was prepared as a homogeneous composite medium to minimize initial variability among experimental units. The collected soil was air dried, cleaned of visible plant residues and stones, crushed, and thoroughly mixed. The homogenized soil was then weighed equally into each pot before the application of biochar and poultry manure according to the treatment doses. This procedure was carried out to ensure relatively uniform initial planting medium conditions, thereby supporting the use of a completely randomized design under greenhouse conditions.

The treatments represented contrasting amendment inputs, including a biochar dominant treatment, a manure dominant treatment, and two biochar manure combinations with different proportions. The selected rates were adapted from previous studies that evaluated biochar and organic manure amendments in rice and soil amendment experiments, including biochar application rates of 10–40 Mg/ha in paddy systems and biochar poultry litter combinations of up to 30 + 30 Mg/ha (Suswana & Maulana, 2022; Yang *et al*., 2021).

The experiment was arranged in a completely randomized design (CRD) with four organic soil amendment treatments and five replications, resulting in a total of 20 experimental units. Each experimental unit contained one paddy hill and was randomly placed inside the greenhouse. Table 2 presents treatment combinations used in the study.

Table 2. Treatment combinations exploited to evaluate dynamics of soil CO_2 flux in rice systems

No	Treatment Code	Description
1	B	30 Mg/ha biochar
2	K	40 Mg/ha poultry manure
3	BK1	30 Mg/ha biochar + 20 Mg/ha poultry manure
4	BK2	15 Mg/ha biochar + 40 Mg/ha poultry manure

2.5. Soil CO_2 Flux Measurement

Soil CO_2 flux was measured daily from 1 to 60 days after transplanting (DAT) using a closed acrylic chamber placed on the soil surface. The MH-Z19B CO_2 sensor was placed inside the chamber to record changes in CO_2 concentration (ppm) over 60 minutes. Daily measurements were conducted to capture short term temporal variation in soil respiration, as soil CO_2 flux can fluctuate substantially over daily and seasonal time scales (Curcoll *et al*., 2022; Jian *et al*., 2018). However, for graphical presentation, representative weekly observation points (1, 7, 14, 21, 28, 35, 42, 49, 56, and 60 DAT) were displayed to improve figure readability while retaining the overall temporal trend.

The calculation of soil CO_2 flux followed the closed chamber method based on NDIR as described by Dossa *et al*. (2015). The first step was to convert Δppm into CO_2 mass concentration (mg CO_2/m^3) using the ideal gas equation, incorporating air pressure (P), air temperature (T, in Kelvin), the gas constant (R), and the molar mass of CO_2 (MCO_2 = 44 g/mol). The conversion formula is as follows:

$$C_{CO2} = \Delta ppm \times \frac{M_{CO2} \times P}{R \times T} \tag{1}$$

where C_{CO2} is the CO_2 concentration in mg CO_2/m^3. The second step was to calculate soil CO_2 flux based on the chamber volume, chamber surface area, and measurement duration. The soil respiration rate was calculated using the following equation:

$$F = \frac{C_{CO2} \times V}{t \times A} \tag{2}$$

where F is the soil CO_2 flux (mg CO_2/m²/h), V is the chamber volume (m³), A is the chamber cross sectional area (m²), and t is the measurement duration (h).

2.6. Plant Measurements

Plant height and leaf number were measured daily from 1 to 60 days after transplanting (DAT). Plant height was measured from the base of the stem at the soil surface to the highest growing point, while leaf number was counted as the total number of fully expanded active leaves. Daily observations were conducted to follow the progressive vegetative development of paddy, particularly during tillering, leaf emergence, and stem elongation. Similar to the CO_2 flux data, representative weekly observation points were presented in the figures to improve visual clarity. The 60 DAT observation period was selected to represent the vegetative monitoring phase, as the vegetative stage of transplanted rice generally extends from transplanting to panicle initiation and may last approximately 1.5–3 months depending on cultivar and environmental conditions.

2.7. Data Analysis

CO_2 concentration data were converted into flux units and analyzed using analysis of variance (ANOVA) to test the effects of the treatments. When the ANOVA indicated significant effects, mean separation was conducted using the Least Significant Difference (LSD) test at the 5% significance level. Plant growth data were analyzed using the same procedure.

Sensor calibration data were analyzed using linear regression to obtain the slope, intercept, and coefficient of determination (R^2). In addition to ANOVA and mean comparison, Principal Component Analysis (PCA) was performed to explore treatment clustering patterns based on the combination of soil CO_2 flux and vegetative growth of paddy. All data analyses were carried out using Python in the Visual Studio Code environment.

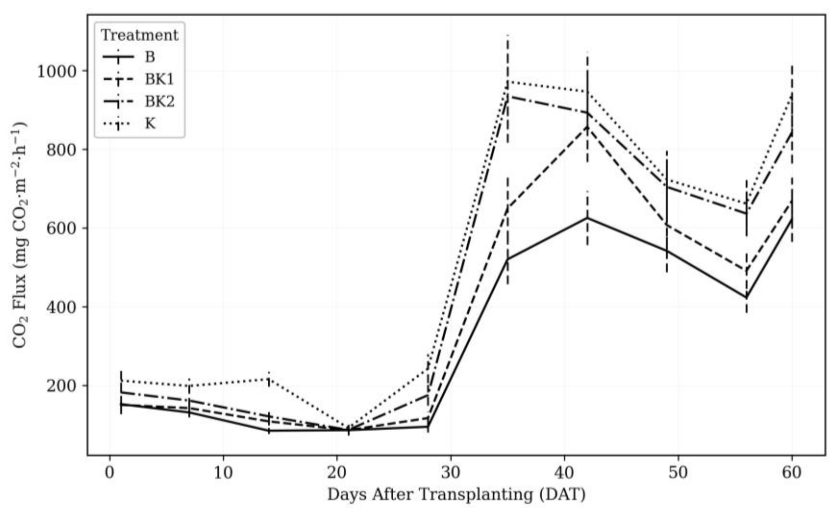

Figure 3. Soil CO_2 flux under four treatments from 1 to 60 DAT. [Daily measurements were conducted, but representative weekly observation points are shown for visual clarity.]

3. RESULTS AND DISCUSSION

3.1. Soil CO_2 Emission

The dynamics of soil CO_2 flux from 1 to 60 days after transplanting (DAT) showed a clear temporal pattern closely linked to the vegetative growth stages of paddy (Figure 3). During the early growth stage, soil CO_2 flux values were relatively low, ranging from 50 to 376 mg $CO_2 \cdot m^{-2} \cdot h^{-1}$ with an average of 142 mg $CO_2 \cdot m^{-2} \cdot h^{-1}$. These low fluxes reflect the limited root biomass and vegetative tissues, so that autotrophic respiration was still minimal (Ben-Noah & Friedman, 2018). In addition, soil microbial activity had not yet reached its peak because the availability of carbon substrates was still low.

As the crop entered the maximum vegetative stage (> 30 DAT), soil CO_2 flux increased sharply, reaching 298–1302 mg $CO_2 \cdot m^{-2} \cdot h^{-1}$ with an average of 713 mg $CO_2 \cdot m^{-2} \cdot h^{-1}$. Comparable magnitudes have been reported for paddy fields elsewhere: in situ soil respiration measured across an entire rice growing season ranged from 26.9 to 1293.6 mg $CO_2 \cdot m^{-2} \cdot h^{-1}$ in karst paddy soils and from 63.0 to 1501.2 mg $CO_2 \cdot m^{-2} \cdot h^{-1}$ in non-karst paddy soils, at soil temperatures of 27–36 °C (Zhou *et al*., 2023). The fluxes recorded in the present study fall within this range. This pronounced increase is associated with the accumulation of root and shoot biomass, which enhances root respiration and the supply of organic exudates, thereby intensifying plant metabolic activity and soil microbial processes (Min & Rulík, 2020; Yin *et al*., 2025). Yin *et al*., (2025) reported that CO_2 flux in paddy systems can increase by 2–4 times at the late vegetative stage compared with the early stage.

Throughout the observation period, clear differences in soil CO_2 flux were observed among treatments. The poultry manure treatment (K) consistently produced the highest CO_2 flux at most measurement times. For example, Seki *et al*. (2022) reported that cumulative CO_2 emission over 27 months reached about 4.0 Mg C/ha in plots receiving poultry manure, much higher than the 2.4 Mg C/ha observed in control plots without organic amendments. Similar increases were observed in another study where the application of composted livestock manure raised CO_2 flux to 9.38 Mg/ha over a single growing season, the highest among the treatments tested (Min & Rulik, 2020). In contrast, the sole biochar treatment (B) tended to produce the lowest CO_2 flux. Cumulative CO_2 emission with biochar alone was reported to be only about 2.7 Mg C/ha (Seki *et al*., 2022), and several analyses even indicated that biochar does not substantially increase CO_2 emission (Shrestha *et al*., 2023). The combined biochar + poultry manure treatments generated intermediate flux values. The BK2 treatment (low dose biochar + high dose poultry manure) tended to approach the flux level of poultry manure alone, whereas BK1 (high dose biochar + low dose poultry manure) occupied an intermediate position. Data from Seki *et al*. (2022) indicate that the combination of biochar and poultry manure resulted in cumulative CO_2 emission of approximately 3.7 Mg C/ha, slightly lower than that of poultry manure alone (4.0 Mg C/ha). This pattern is consistent with the findings of the present study, in which the poultry manure treatment produced the highest soil CO_2 flux, followed by BK2, BK1, and the lowest values under biochar (B).

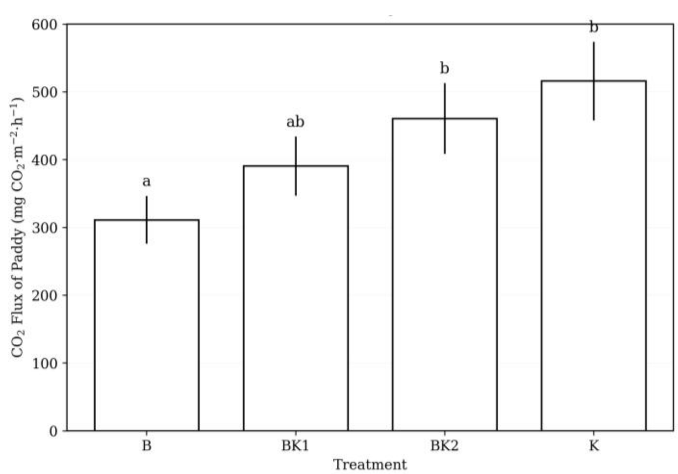

Figure 4. Average soil CO_2 flux of paddy during the vegetative stage

The ANOVA conducted on the mean CO_2 flux over the entire vegetative period showed a significant effect of organic amendment treatments ($F_{(3,16)} = 3.40$, $p = 0.043$). Mean flux values ranged from 311 to 516 mg $CO_2 \cdot m^{-2} \cdot h^{-1}$ across treatments (Figure 4). The poultry manure treatment (K) produced the highest mean flux, 516 mg $CO_2 \cdot m^{-2} \cdot h^{-1}$, followed by the low biochar, high manure combination (BK2) with 461 mg $CO_2 \cdot m^{-2} \cdot h^{-1}$ and BK1 with 391 mg $CO_2 \cdot m^{-2} \cdot h^{-1}$, whereas sole biochar (B) resulted in the lowest mean flux, 311 mg $CO_2 \cdot m^{-2} \cdot h^{-1}$. The LSD test at the 5%

level ($LSD_{0.05}$ = 144 mg $CO_2 \cdot m^{-2} \cdot h^{-1}$) grouped the treatments into B (group a), BK1 (group ab), and BK2 and K (group b), indicating that manure based treatments, particularly K and BK2, induced significantly higher CO_2 flux than B, while BK1 did not differ significantly from either B or the higher flux treatments. This pattern confirms that the availability of labile organic carbon from poultry manure is a major driver of increased soil respiration when fluxes are integrated over the whole vegetative period. The consistently lower flux under sole biochar (B) suggests that converting part of the labile carbon into more recalcitrant biochar effectively dampens CO_2 release compared with manure only applications, while mixed treatments (BK1 and BK2) partially moderate the manure effect. Similar trends have been reported in paddy systems, where medium biochar application rates (~20 Mg/ha) reduced cumulative CO_2 emissions by 1.6–8.8% relative to non-amended controls (Yang *et al*., 2018), and a recent synthesis showed that straw derived biochar at 10–40 Mg/ha can lower CO_2 emissions from flooded rice systems by up to 12–37% (Sun *et al*., 2024). In line with our finding that manure alone (K) generated the highest fluxes, studies in other cropping systems also demonstrate that biochar either reduces or does not enhance CO_2 emissions compared with labile organic amendments: wheat straw biochar produced 90% lower CO_2 emissions than raw straw (Wang *et al*., 2020), and blending biochar with manure reduced manure induced CO_2 emissions by about 60% in an agricultural soil (Lebrun *et al*., 2024).

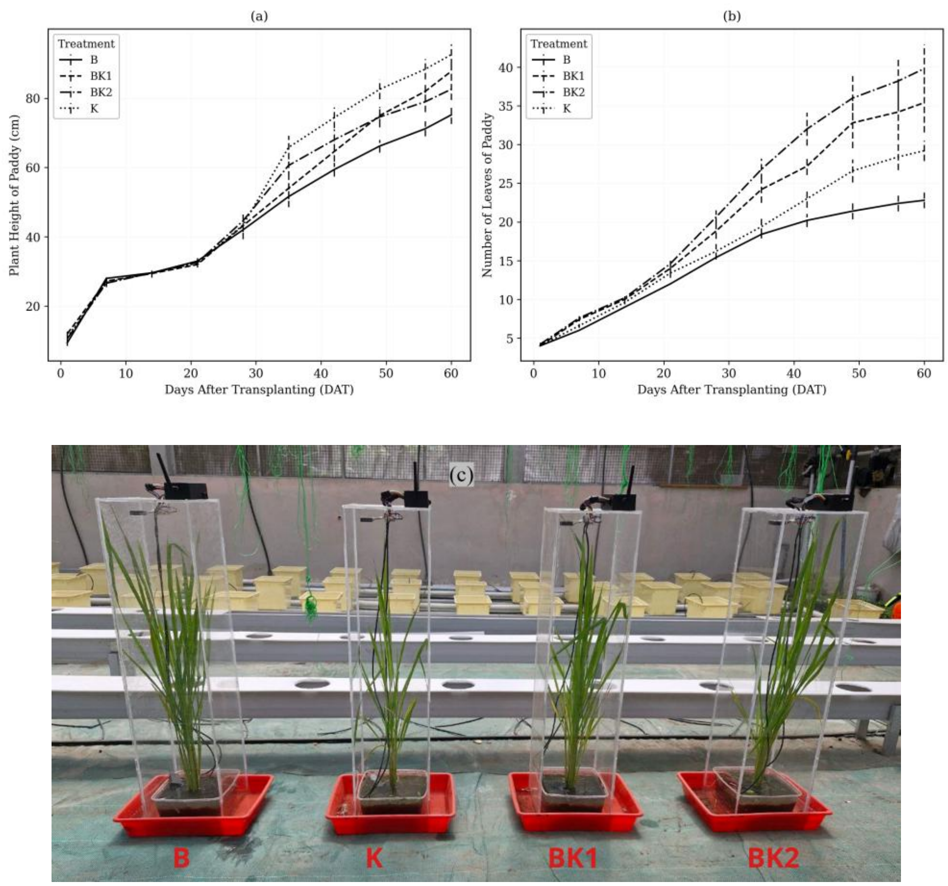

Figure 5. Vegetative growth of paddy based on daily observations, with representative weekly observation points shown for visual clarity: (a) plant height, (b) leaf number, and (c) plant condition at 60 days after transplanting (DAT).

3.2. Vegetative Growth of Paddy

Vegetative growth of paddy showed distinct patterns among treatments and was closely related to the dynamics of soil CO_2 flux measured over the same period. The two main parameters observed, plant height and leaf number, exhibited consistent responses to the application of biochar, poultry manure, and their combinations (Figure 5). During the early growth phase (1–14 DAT), plant growth was relatively uniform across all treatments. This reflects the initial adaptation phase, when root and shoot biomass were still limited and the effects of organic amendments had not yet become pronounced. Differences among treatments began to emerge from 21 DAT and became more apparent during the active growth phase (around 28–49 DAT), when plants experienced rapid biomass accumulation along with more vigorous root and canopy development.

The poultry manure treatment (K) produced the greatest plant height at most observation times. The high availability of nitrogen and readily decomposable carbon from poultry manure provides abundant nutrients for plants, thereby supporting the formation of new tissues and optimal stem elongation (Zhang *et al*., 2020). The low biochar, high manure combination (BK2) showed plant height comparable to that under K. This indicates a synergy between the two amendments, for example through improved soil water retention and nutrient availability, together with stimulation of soil microbial activity (Ali *et al*., 2025). Increases in soil water content, porosity, and nutrients such as N and P under combined biochar–manure applications have been reported to be significant compared with soils without amendments (Ali *et al*., 2025). As a result, the improved growth medium promotes stronger vegetative growth. The lower dose combination treatment (BK1) produced intermediate plant height. In contrast, the sole biochar treatment (B) consistently resulted in the lowest plant height throughout the vegetative phase. Biochar provides predominantly stable carbon fractions and nutrients in organic forms that require time to decompose, so that the direct nutrient supply to plants is relatively limited (Zhang *et al*., 2020). Consequently, plants under the B treatment grew slower because nutrient availability was lower than in treatments receiving additional inputs from poultry manure.

The pattern of leaf number followed a trend similar to that of plant height. At the peak vegetative phase (around 28–49 DAT), the BK2 treatment produced the highest leaf number, followed by the other organic treatments (K and BK1). The increase in leaf number under treatments with nutrient rich organic amendments reflects a greater photosynthetic and metabolic capacity of the plants. Conversely, the biochar only treatment (B) resulted in the lowest leaf number, again indicating that nutrient availability in this treatment was relatively lower than in those containing poultry manure, thereby constraining leaf formation.

3.3. Relationship between CO_2 Flux and Plant Growth

The relationship between CO_2 flux and vegetative growth of paddy was evaluated using plant height and leaf number as the main indicators. Pearson correlation analysis showed strong positive correlations between CO_2 flux and plant height ($r = 0.729$, $p < 0.001$) and between CO_2 flux and leaf number ($r = 0.698$, $p < 0.001$).

The relationship between CO_2 flux and plant height as well as leaf number showed a consistent positive trend, in which CO_2 flux increased with increasing growth parameters (Figure 6). To reflect the nonlinear response of respiration to biomass related drivers, the relationships were fitted using an exponential regression model ($y = a \cdot \exp(bx)$). The exponential model in Figure 6a produced the equation $y = 145.05 \cdot \exp(0.0194x)$ with $R^2 = 0.479$, indicating that plant height explained about 47.9% of the variation in CO_2 flux. In Figure 6b, the exponential model yielded $y = 219.27 \cdot \exp(0.0327x)$ with $R^2 = 0.381$, suggesting that leaf number accounted for approximately 38.1% of the variation in CO_2 flux.

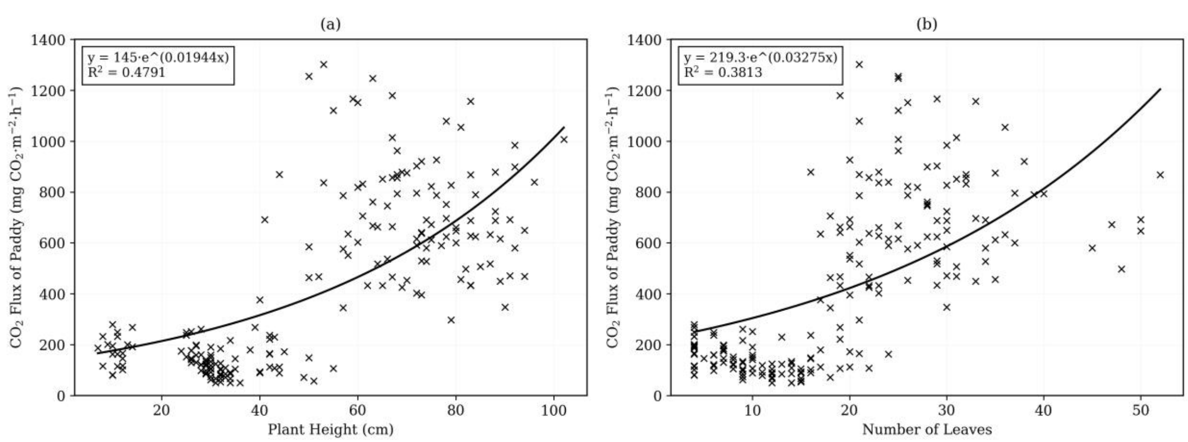

Figure 6. Relationship of CO_2 flux and plant growth of paddy during the vegetative stage: (a) plant height, (b) number of leaves

Similar results were reported by Min & Rulik (2020), who found a significant positive relationship between paddy plant height and CO_2 emission flux ($R^2 = 0.69$). Faster growing plants with greater biomass require higher respiratory energy, thereby increasing CO_2 release (Ben-Noah & Friedman, 2018; Choi *et al*., 2018). Consistent with this mechanism, soil respiration has been reported to increase nonlinearly with biomass related drivers, including an exponential relationship with root biomass (Lee, 2018). Plant-derived CO_2 is a major component of soil CO_2 efflux in paddy systems, as ^{13}C partitioning has shown that planted rice soil emits substantially more CO_2 than unplanted soil (Zhu et al., 2018).

PCA was performed to explore the multivariate association among soil CO_2 flux, plant growth, and soil–environmental variables at 60 DAT (Figure 7). The first two principal components explained 61.04% of the total variance, with PC1 and PC2 accounting for 33.31% and 27.73%, respectively. This indicates that the PC1–PC2 plane captured a substantial proportion of treatment-related variation, although the pattern should be interpreted as exploratory.

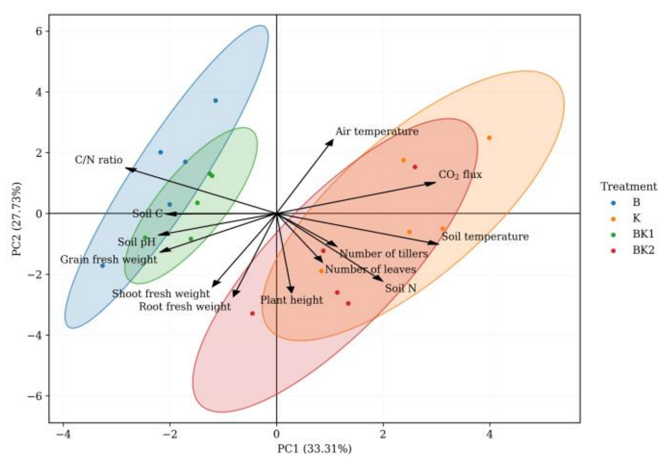

Figure 7. PCA biplot showing treatment clustering at 60 DAT based on soil CO_2 flux, plant growth, and soil–environment variables (95% confidence ellipse for each treatment).

The poultry manure treatment (K) was positioned on the positive side of PC1 and was closely associated with CO_2 flux, soil temperature, and air temperature, indicating higher respiration activity under manure application. The low-biochar, high-manure treatment (BK2) was also located on the positive side of PC1 but was more closely associated with plant growth variables, including plant height, number of leaves, number of tillers, and soil N. In contrast, the sole biochar treatment (B) was positioned on the negative side of PC1 and was more closely related to soil chemical properties such as C/N ratio, soil C, and soil pH. The BK1 treatment showed an intermediate position, closer to B than K.

Overall, the PCA results support the univariate findings that manure-rich treatments were more strongly associated with soil CO_2 flux and vegetative growth, whereas sole biochar showed a lower association with CO_2 emission. These patterns suggest that labile organic inputs from manure stimulated soil respiration and plant growth, while biochar acted more as a physical–chemical soil conditioner with a moderating effect on CO_2 flux.

4. CONCLUSION

A portable NDIR-based CO_2 sensor system was successfully applied to monitor soil CO_2 flux in paddy under different organic amendments. Across the vegetative period, poultry manure (K) produced the highest mean flux (516 mg $CO_2{\cdot}m^{-2}{\cdot}h^{-1}$), followed by BK2 (461 mg $CO_2{\cdot}m^{-2}{\cdot}h^{-1}$) and BK1 (391 mg $CO_2{\cdot}m^{-2}{\cdot}h^{-1}$), whereas biochar alone (B) yielded the lowest flux (311 mg $CO_2{\cdot}m^{-2}{\cdot}h^{-1}$). Soil CO_2 flux increased from early to late vegetative stages and was positively associated with plant height and leaf number, confirming the close coupling between vegetative growth and respiratory carbon loss. These results indicate that partially substituting poultry manure with biochar, or applying biochar with manure at appropriate proportions, can moderate CO_2 emissions while maintaining the growth benefits of organic amendments.

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DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE MANUSCRIPT PREPARATION

Not applicable. The authors did not use any generative AI tools or services in the preparation of this manuscript. All content is entirely the intellectual work of the authors.

AUTHOR CONTRIBUTION

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
MAA	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓
CP	✓	✓			✓	✓				✓		✓		✓
ZK	✓	✓								✓		✓		

C: Conceptualization	Fo: Formal Analysis	O: Writing - Original Draft	Fu: Funding Acquisition
M: Methodology	I: Investigation	E: Writing - Review & Editing	P: Project Administration
So: Software	D: Data Curation	Vi: Visualization	
Va: Validation	R: Resources	Su: Supervision	

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