# Impact of Organic Amendments on Soil Organic Carbon Dynamics: A Kinetic Modelling Approach

**Abstract**

This study investigates the dynamics of carbon (C) mineralization and carbon dioxide ($CO_2$) emissions in tropical soil treated with different organic amendments over a 120-day incubation period. The findings reveal a notable spike in $CO_2$ emissions during the initial three days, primarily due to the quick breakdown of easily degradable organic materials. Following this peak, emissions decreased significantly until day 24, stabilizing afterward. Among the organic amendments, cow dung manure produced the highest $CO_2$ emissions (129.13 mg C $kg^{-1}$), and maize straw yielded the lowest (98.74 mg C $kg^{-1}$). A combination of cow dung and rice straw resulted in substantial $CO_2$ production (122.66 mg C $kg^{-1}$). When cumulative C mineralization was modeled using first-order and second-order kinetic equations, cow dung manure showed the highest mineralization rates and maize straw the lowest due to its high lignin content. The first-order model effectively characterized long-term C mineralization dynamics, showing the strong $R^2$ values between 0.9198 and 0.9864. This study highlights a crucial paradox in soil management: while organic amendments like cow dung enhance short-term nutrient availability. Conversely, amendments like maize straw, despite their lower mineralization rates, foster the formation of stable C pools essential for sustainable soil health, emphasizing the importance of choosing organic amendments based on their long-term objectives for C management and climate change mitigation.

***Keywords**: Carbon mineralization; $CO_2$ emission; organic amendments; soil health*

## 1. INTRODUCTION

Soil organic carbon (SOC) is essential for terrestrial biological systems, significantly affecting soil health, fertility, and the global C cycle. SOC primarily forms from the decomposition of plant and animal residues, which enhances soil structure and nutrient availability, fostering conditions conducive to plant growth and microbial activity (Lehmann &Kleber, 2015). It serves as a key indicator of soil sustainability, with its concentration affecting various soil properties (Kuzyakov&Bol, 2006). Understanding SOC dynamics involves the process of mineralization, where microbes convert organic carbon into inorganic $CO_2$, impacting atmospheric $CO_2$ levels, influencing soil productivity, and allowing for improved management of organic inputs, which is essential for maintaining long-term soil fertility and aiding in climate change mitigation (Schmidt et al., 2011, Wang et al., 2017).

Recent research emphasizes the importance of C storage and flux in soils, particularly regarding ecosystem productivity (Bernal et al., 1998, Martín et al., 2012, Ali &Nabi., 2016, Kaur, Kommalapati, &Saroa., 2023). Declines in soil fertility are often associated with reduced organic matter (OM) content (Hartemink, 2006). Consequently, organic amendments such as compost and manure have become vital for enhancing SOC levels and soil health. These amendments increase OM, stimulate microbial activity, and affect SOC mineralization rates, which are crucial for sustainable agricultural practices and improving soil resilience (Yang et al., 2021). Comprehending the implications of amendments on soil organic carbon dynamics in the context of diverse temperature and moisture conditions is essential for promoting sustainability and enhancing ecosystem resilience (Rubin et al., 2023). The mineralization of crop residues is particularly important

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for regulating $CO_2$ emissions while providing essential nutrients for crops (Raiesi, 2006). Additionally, organic amendments can enhance soil structure and stability, promoting long-term C sequestration (Bationo et al., 2007).

The interaction between organic amendments and soil properties leads to varying mineralization kinetics, which can be modeled using different kinetic frameworks (Bayer et al., 2006). These models help quantify C release rates and elucidate the mechanisms of SOC mineralization (Robin et al., 2023). Among the various models, first-order and second-order kinetic models are foundational in this research area (Manzoni &Porporato, 2009). The effects of different organic amendments on soil organic carbon (SOC) mineralization rates were thoroughly reviewed and discussed, utilizing both first-order and second-order kinetic models (Gillis & Price 2011, Martin et al., 2012, Guo et al., 2014, Da Silva et al., 2022). This study aims to explore the effects of different organic amendments on SOC mineralization rates using these kinetic models, and to evaluate the comparative efficacy of first-order and second-order kinetic models in forecasting SOC mineralization within the designated study area. This research not only seeks to contribute to the existing body of knowledge regarding SOC dynamics but also aspires to inform sustainable agricultural practices that align with climate resilience objectives.

## 2. MATERIAL AND METHODS

### 2.1 Experimental Site

From April to July 2024, a laboratory incubation experiment was carried out at Experiment and Lecture Building 1 (19° 50′ N, 96° 16′ E), Department of Soil and Water Science, Yezin Agricultural University, Nay Pyi Taw Territory, Myanmar.

### 2.2 Experimental Design and Treatments

### 2.2.1 Experimental Design

In the present study, four commonly utilized organic amendments were evaluated: cow dung manure, chicken manure, rice straw, and maize straw. These amendments were selected due to their prevalent availability in the study region and their recognized potential to positively influence soil health and fertility. The experimental design employed a completely randomized design (CRD) with four replications for the incubation jars. Each incubation jar was comprised of 198 grams of soil and 2 grams of organic amendment, representing 1% of the total soil weight.

### 2.2.2 Experimental Treatments

The treatment details are as follows:

$T_1$ - control
$T_2$ - cow dung manure
$T_3$ - chicken manure
$T_4$ - rice straw
$T_5$ - maize straw
$T_6$ - ½ cow dung manure + ½ rice straw
$T_7$ - ½ cow dung manure + ½ maize straw
$T_8$ - ½ chicken manure + ½ rice straw
$T_9$ - ½ chicken manure + ½ maize straw

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**Table 1. Characteristics of organic amendments used in this experiment**

| Parameters | Organic Amendments | | | |
|---|---|---|---|---|
| | **Cow dung manure** | **Chicken manure** | **Rice straw** | **Maize straw** |
| Total N (%) | 3.37 | 5.09 | 0.73 | 1.19 |
| Organic Carbon (%) | 42.37 | 34.06 | 47.88 | 53.05 |
| C:N ratio | 12.57 | 6.69 | 65.59 | 44.58 |
| pH | 6.40 | 6.30 | 4.70 | 5.80 |
| Lignin (%) | 8.00 | 8.40 | 16.90 | 19.50 |
| Total $P_2O_5$ (%) | 1.60 | 2.29 | 0.69 | 1.45 |
| Total $K_2O$ (%) | 0.69 | 1.93 | 0.80 | 1.20 |

Table 1 summarizes the physicochemical properties of four organic amendments: cow dung manure, chicken manure, rice straw, and maize straw. The key parameters evaluated include total nitrogen, organic carbon, C:N ratio, pH, lignin content, total phosphorus, and total potassium. Cow dung manure showed a moderate organic carbon content of 42.37% and a balanced C:N ratio of 12.57, along with the lowest total potassium percentage at 0.69%, which promotes nutrient mineralization. In contrast, chicken manure had the highest nitrogen content at 5.09% and the lowest C:N ratio of 6.69, indicating a tendency for rapid decomposition. While rice straw displayed the lowest total phosphorus percentage at 0.69%, both rice straw and maize straw were characterized by high organic carbon contents of 47.88% and 53.05%, respectively, along with elevated lignin percentages of 16.90% and 19.50%.

**Table 2. Physicochemical properties of experimental soil**

| Characteristics | Values | Rating |
|---|---|---|
| % sand | 82.9 | |
| % silt | 8.52 | |
| % clay | 8.58 | |
| Texture class | Loamy sand | |
| Bulk density (g $cm^{-3}$) | 1.3 | Low |
| Water holding capacity (%) | 46 | |
| pH | 5.75 | Moderately acid |
| CEC ($cmol_c$ $kg^{-1}$) | 13.26 | Medium |
| EC (dS $m^{-1}$) | 0.03 | Non-saline |
| Organic carbon (%) | 1.35 | Medium |
| Available N ( mg $kg^{-1}$ ) | 25.23 | Very low |
| Available P ( mg $kg^{-1}$ ) | 22.58 | High |
| Available K ( mg $kg^{-1}$ ) | 78.43 | Low |

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Table 2 presents the properties of the soil utilized in the incubation experiment. The predominant texture is loamy sand, consisting of 82.9% sand alongside limited fractions of silt (8.52%) and clay (8.58%). This soil exhibits moderate acidity, as indicated by a pH of 5.75, a medium cation exchange capacity of 13.26 $\text{cmol}_c\ \text{kg}^{-1}$, and a low organic carbon content of 1.35%. Nutrient availability is variable; nitrogen levels are classified as very low (25.23 $\text{mg kg}^{-1}$), phosphorus is considered high (22.58 $\text{mg kg}^{-1}$), and potassium levels are low (78.43 $\text{mg kg}^{-1}$).

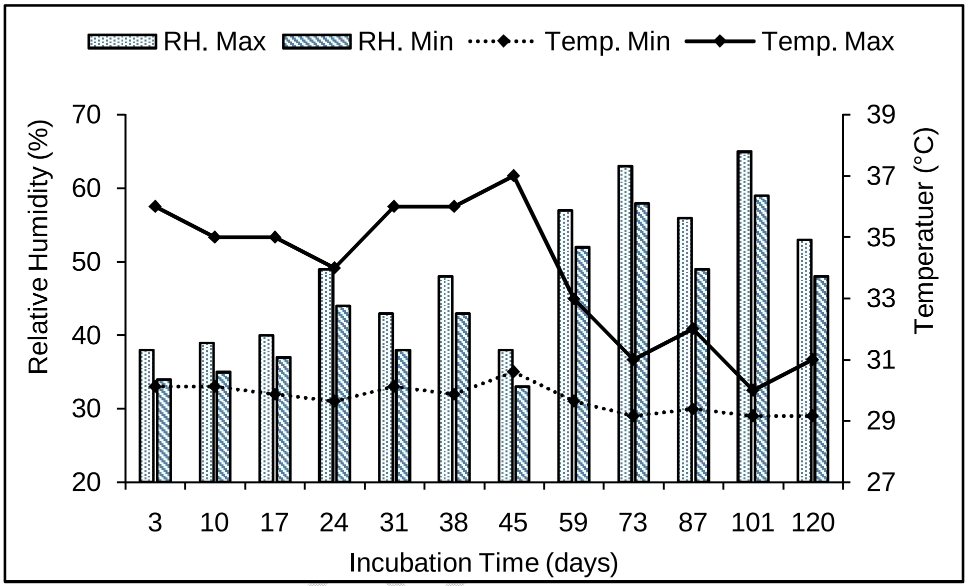

**Figure 1.** Room temperature and relative humidity during the period of incubation.

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## 2.3 Incubation Experiment

Soil samples were collected from a research farm at Yezin Agricultural University, Nay Pyi Taw Territory, Myanmar. Then, these were dried in a shaded area, homogenized, and sieved to 2 mm. A total of 198 grams of prepared soil was placed into incubation jars (6.5 cm diameter, 17 cm height), and two grams of oven-dried organic amendments were ground to pass through a 2 mm sieve. The soil was mixed with the organic amendments, excluding the control treatment, and moisture levels were maintained at 60% of the water-holding capacity to optimize microbial activity. Each jar contained a centrifuge tube with 10 ml of 1 M sodium hydroxide (NaOH), sealed with a lid, and weighed for reference. The jars were incubated in darkness at room temperature for 120 days, with continuous monitoring of temperature and relative humidity. Soil moisture was regulated by weighing the jars and adding deionized water as needed. After incubation, the NaOH solution was extracted and transferred to 100 ml conical flasks, where 2 ml of barium chloride ($BaCl_2$) and phenolphthalein indicator were added, resulting in a violet coloration. This solution was titrated with 0.5 M hydrochloric acid (HCl) until a colorless endpoint was reached. To ensure oxygen replenishment, the jars were left open for three hours during and after titration, after which a fresh NaOH tube was reintroduced, and the jars resealed. Evolved $CO_2$ was quantified on days 3, 10, 17, 24, 31, 38, 45, 59, 73, 87, 101, and 120, respectively (Hopkins, 2008).

### 2.4 Carbon Mineralization Kinetics

In the first-order kinetic model, the cumulative release of $CO_2$ and the kinetics of C mineralization were evaluated through the analysis of $CO_2$-C emissions measured at various intervals across all treatments (Tian, Kang &Brussaard., 1992; Ajwa&Tabatabai, 1994; Saviozzi et al., 1997). This model assumes that the rate of SOC mineralization is proportional to the amount of SOC remaining in the soil (Xue et al., 2022). It is characterized by a simple exponential decay equation outlined below.

$\mathbf{C_{min} = C_0 (1 - e^{-kt})}$(De Neve, Pannier &Hofman, 1996)

and the half-life of C in soil can be calculated by

$$\textbf{Half-life}=\frac{\ln(2)}{k}$$(Qayyum et al., 2012)

where$C_{min}$ is the amount of cumulative mineralized organic C at time t, $C_0$ is the potential available Cat time zero, k is the apparent rate constant, and t is the time (days of incubation).

The second-order kinetic model posits that the rate of SOC mineralization is dependent on the concentration of two reactant species ( Pansu, Thuriès, Larré-Larrouy, & Feller, 2002). Second-order kinetics may better represent scenarios where microbial efficiency increases as more substrates become available.In a general integrated form, the second-order kinetic model is written as

$\mathbf{C_{min} = C_1 (1 - e^{-k1t}) + C_2 (1 - e^{-k2t})}$ (Guo et al., 2014)

where$C_{min}$ is cumulative mineralized organic C, $k_1$ is a smaller and easily mineralizable C pool of higher turnover rate, $k_2$ is a large stable pool with a slow turnover rate, $C_1$ is active C pool, $C_2$ is resistant C pool and t is the time (days of incubation). The slow turnover rate value ($k_2$) was used in calculating the half-life of the most stable C fraction.

$$\textbf{Half-life} = \frac{\ln(2)}{k2}$$ (Qayyum et al., 2012)

The evaluation of the two kinetic models was performed by analyzing the regression coefficients ($R^2$), which facilitated the identification of the most appropriate model for assessing the kinetics of carbon mineralization within the context of this research (Qayyum et al., 2012).

### 2.5 Statistical analysis

The collected data were analyzed using analysis of variance (ANOVA) within a completely randomized design (CRD) framework, using Statistix 8 software (Analytical Software). To differentiate the means, the least significant differences were applied at a significance level of $p \leq 0.05$ (Gomez,1984).

## 3. RESULTS

### 3.1 $CO_2$ evolution rate

During the 120-day incubation period, $CO_2$ evolution rates initially surged within the first three days, followed by a significant decline that persisted until approximately day 24 (Figure 2 and Figure 3). This phase of reduced emissions continued with a steady, even though the lower rate of $CO_2$ production until day 45. Subsequently, $CO_2$ evolution stabilized,

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with emission rates leveling off and remaining relatively constant for the remainder of the observation period.

Figure 2 illustrates $CO_2$ evolution rates over a 120-day incubation period for soils amended with cow dung manure ($T_2$), chicken manure ($T_3$), rice straw ($T_4$), and maize straw ($T_5$). The graph indicates an initial surge in $CO_2$ emissions within the first three days across all treatments, reflecting the rapid decomposition of labile organic matter. Subsequently, emissions decline, stabilizing after 24 days. Among the amendments, $T_3$ demonstrates the highest $CO_2$ evolution rates during the initial phase (days 3 - 10), attributed to its high nitrogen content and low C:N ratio. $T_2$ surpasses other amendments after 17 days, maintaining elevated $CO_2$ emissions. Conversely, $T_5$ consistently exhibits the lowest $CO_2$ emissions due to its high lignin content, which impedes microbial decomposition. These trends underscore the distinct decomposition dynamics influenced by the chemical composition of organic amendments.

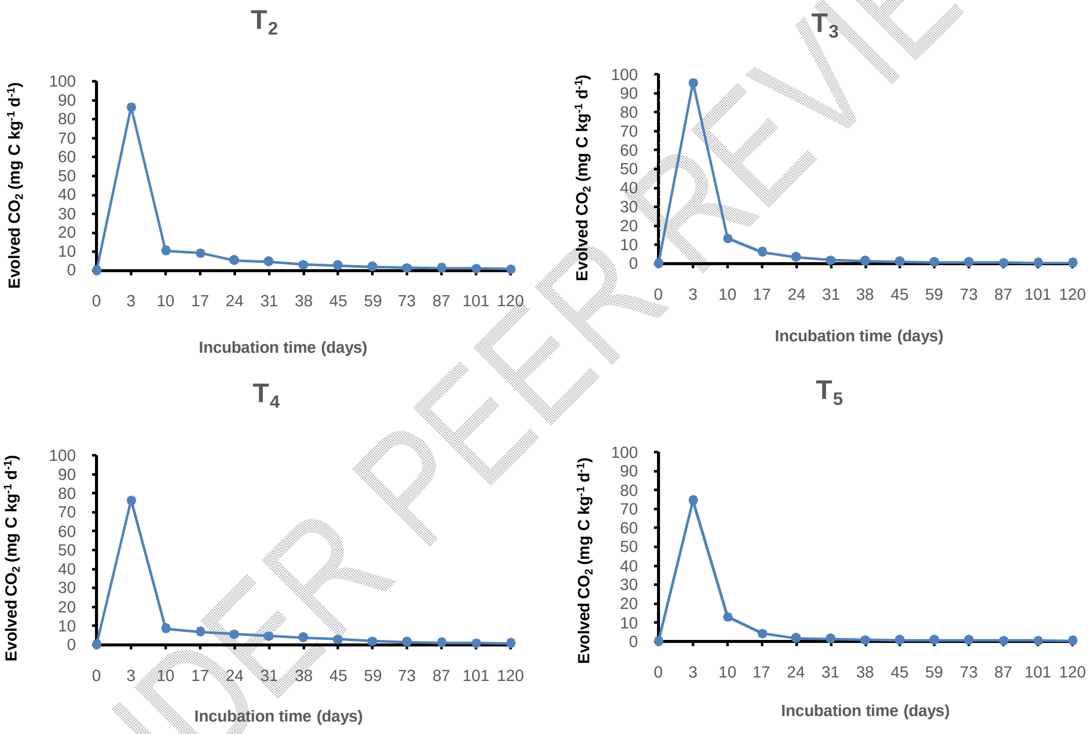

**Figure 2**. $CO_2$ evolution rate in soil amended with solely organic amendments throughout the period of incubation. $T_2$ = Cow dung manure, $T_3$ = Chicken manure, $T_4$ = Rice straw, $T_5$ = Maize straw

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In the combined organic amendment treatments, $T_6$ exhibited the highest rates of $CO_2$ emissions from days 3 to 10 (Figure 3). On days 24 and 31, $T_7$ generated the greatest amount of $CO_2$. From days 38 to 120, treatment that contained $T_8$ consistently produced the highest levels of $CO_2$. Conversely, among the combined treatments, $T_9$ produced the lowest $CO_2$ emissions throughout the incubation period.

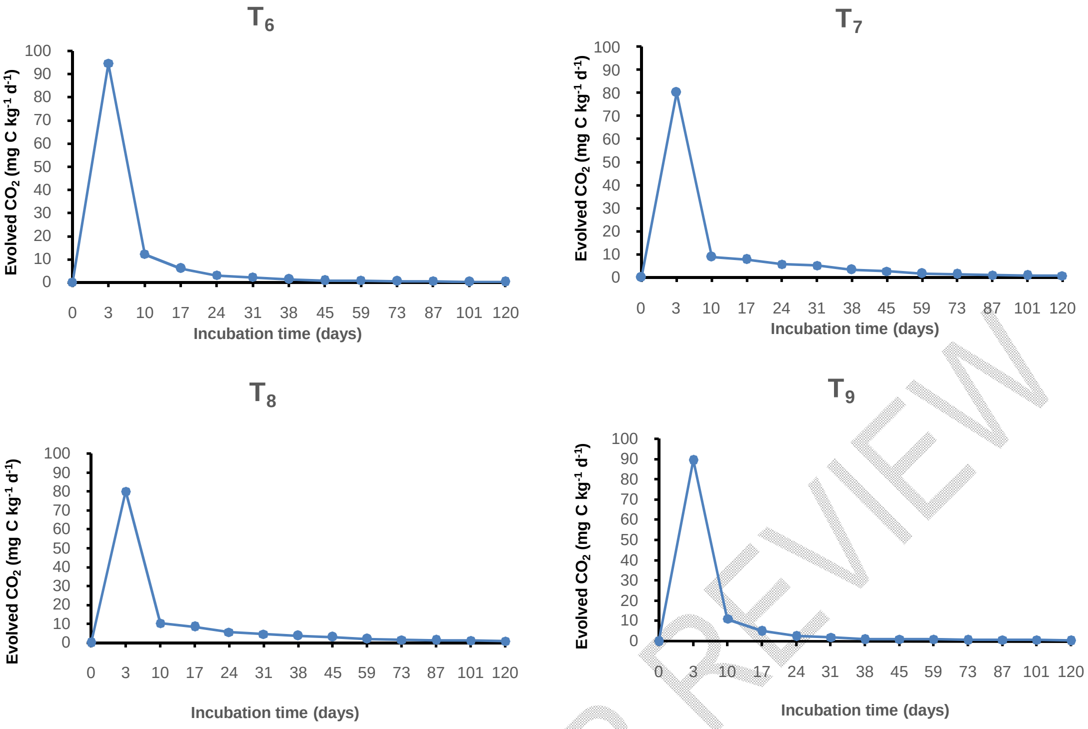

**Figure 3**. $CO_2$ evolution rate in soil amended with combined organic amendments throughout the period of incubation. $T_6$ = ½ Cow dung manure + ½ Rice straw, $T_7$ = ½ Cow dung manure + ½ Maize straw, $T_8$ = ½ Chicken manure + ½ Rice straw, $T_9$ = ½ Chicken manure + ½ Maize straw

The total $CO_2$ evolution observed over the 120-day incubation period exhibited significant variation among the solely organic amendments and the combined treatments (Figure 4). Notably, $T_2$ resulted in the highest $CO_2$ evolution.$T_3$ also demonstrated considerable $CO_2$ evolution, albeit at a lower rate than $T_2$. Treatments that combined rice straw with either type of manure ($T_6$ and $T_8$) exhibited $CO_2$ evolution rates that were statistically indistinguishable from those of $T_3$. In contrast, $T_5$ displayed the lowest rate of $CO_2$ evolution among the amendments tested. Furthermore, the control treatment ($T_1$), which lacked any organic amendment, significantly underperformed in terms of $CO_2$ evolution.

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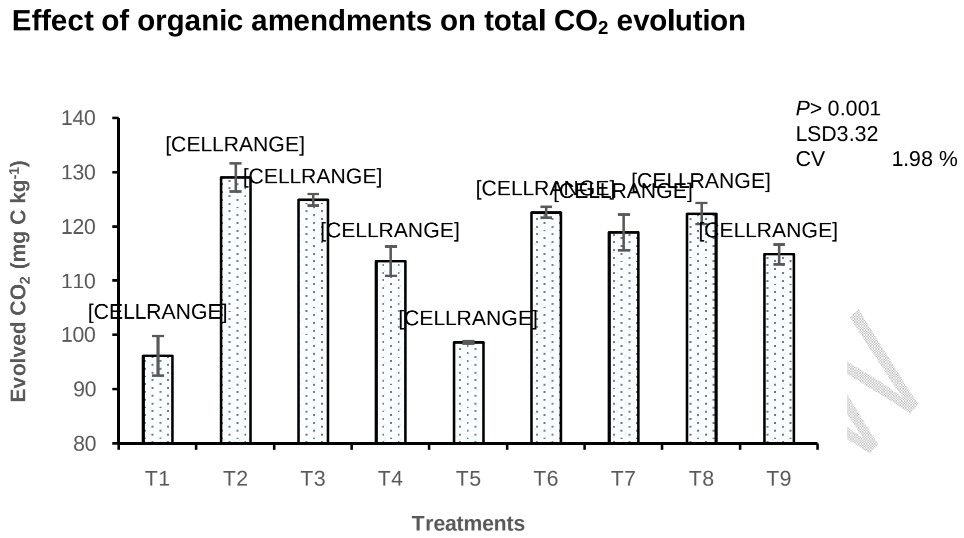

**Figure 4**. Total $CO_2$ evolution over 120 days of incubation period. $T_1$ = Control, $T_2$ = Cow dung manure, $T_3$ = Chicken manure, $T_4$ = Rice straw, $T_5$ = Maize straw, $T_6$ = ½ Cow dung manure + ½ Rice straw, $T_7$ = ½ Cow dung manure + ½ Maize straw, $T_8$ = ½ Chicken manure + ½ Rice straw, $T_9$ = ½ Chicken manure + ½ Maize straw. Columns with different letters indicate significant differences between treatments at P = 0.05. The values are presented as means ± SE from four replicates.

### 3.2 Cumulative C mineralization

During the incubation period, cumulative C mineralization was analyzed and modeled employing both first-order and second-order kinetic equations. Notably, among the treatments consisting solely of applied organic amendments, $T_2$ exhibited a markedly higher rate of C mineralization throughout the entire incubation duration compared to other organic amendments (Figure 5). On the other hand, $T_3$ demonstrated the second-highest cumulative C mineralization, suggesting its relatively effective contribution to soil fertility enhancement. In contrast, $T_5$ was observed as the lowest cumulative C mineralization over the complete 120-day incubation period.

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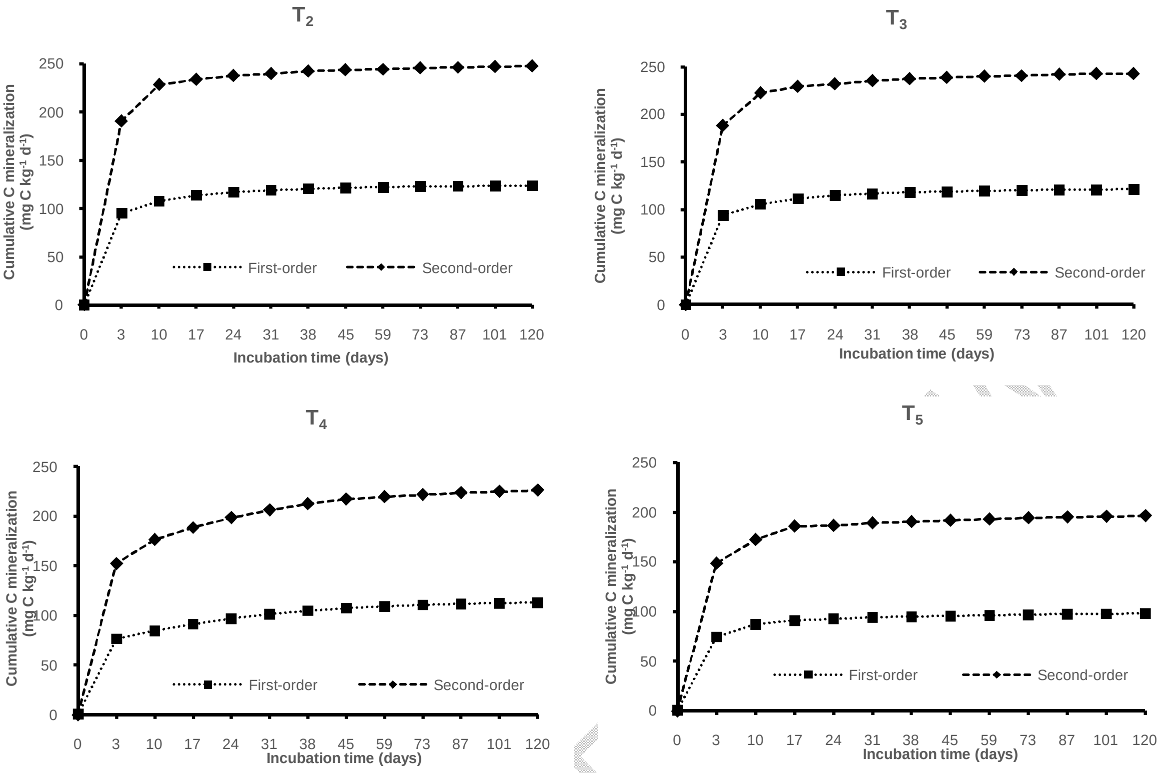

**Figure 5**. Cumulative total C mineralized (mg C kg$^{-1}$ day$^{-1}$) in solely applied organic amendments fitted to first and second-order kinetic models. $T_2$ = Cow dung manure, $T_3$ = Chicken manure, $T_4$ = Rice straw, $T_5$ = Maize straw

In the context of the combined organic amendment treatments, $T_7$ demonstrated significantly elevated rates of cumulative C mineralization at the intervals of days 3, 10, and 17 in both first and second-order kinetic models as illustrated in Figure 6. Subsequently, from day 24 onwards, $T_6$ sustained high rates of cumulative C mineralization throughout the remainder of the incubation period. Among all the combined treatments evaluated, $T_8$ yielded the lowest cumulative C mineralization throughout the entire incubation period.

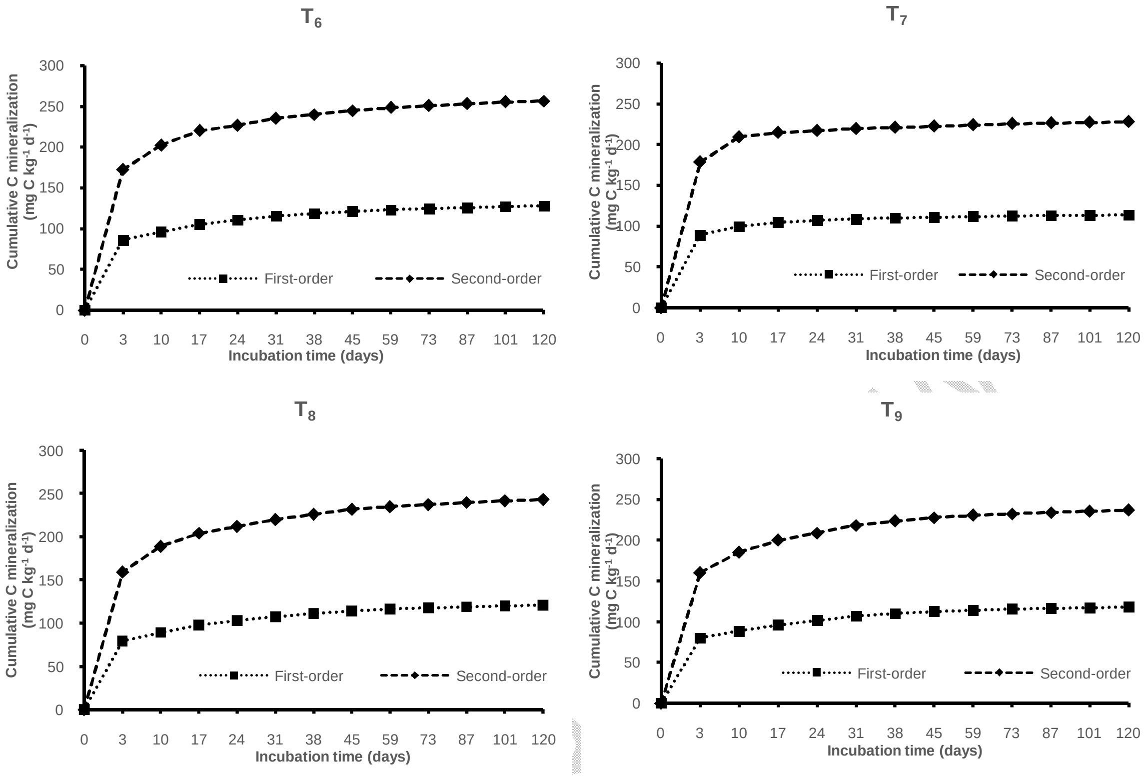

**Figure 6**. Cumulative total C mineralized (mg C kg$^{-1}$ day$^{-1}$) in combined organic amendment treatments fitted to first and second-order kinetic models. $T_6$ = ½ Cow dung manure + ½ Rice straw, $T_7$ = ½ Cow dung manure + ½ Maize straw, $T_8$ = ½ Chicken manure + ½ Rice straw, $T_9$ = ½ Chicken manure + ½ Maize straw

In all treatments, $T_2$ showed the highest levels of cumulative C mineralization. This was followed closely by $T_6$, and $T_3$ (Figure 5 and 6). Throughout the entire incubation period, data demonstrated that $T_5$ contributed the lowest levels of cumulative C mineralization among all treatments analyzed.

### 3.3 Kinetics of Carbon Mineralization and Model Comparisons

The first and second-order kinetic models were employed to elucidate the dynamics of C mineralization associated with various organic amendments. The degree of conformity between the experimental data and the validity of the models was quantified through the R² values (Table 3).

**Table 3. First order and second order kinetic model fit for cumulative C mineralization under different organic amendments after 120 days of incubation.**

| Treatments | First-order model | | | | Second-order model | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $C_0$ (mg kg$^{-1}$) | k (day$^{-1}$) | half-life (year) | $R^2$ | $C_1$ (mg kg$^{-1}$) | $C_2$ (mg kg$^{-1}$) | $k_1$ (day$^{-1}$) | $k_2$ (day$^{-1}$) | half-life (year) | $R^2$ |
| T1 | 12.96 | 2.97E-04 | 6.39 | 0.9752 | 8.74E-02 | 13.22 | 2.96E-01 | 3.09E-04 | 6.13 | 0.9679 |
| T2 | 17.14 | 3.39E-04 | 5.60 | 0.9342 | 1.18E-01 | 17.00 | 2.88E-01 | 3.50E-04 | 5.40 | 0.8975 |
| T3 | 16.90 | 3.38E-04 | 5.61 | 0.9426 | 1.15E-01 | 16.83 | 2.88E-01 | 3.48E-04 | 5.42 | 0.9139 |
| T4 | 17.46 | 2.73E-04 | 6.95 | 0.9804 | 1.01E-01 | 17.34 | 3.00E-01 | 2.82E-04 | 6.70 | 0.9793 |
| T5 | 17.19 | 2.67E-04 | 7.10 | 0.9198 | 9.56E-02 | 17.17 | 3.01E-01 | 2.78E-04 | 6.80 | 0.8839 |
| T6 | 18.13 | 2.99E-04 | 6.35 | 0.9860 | 1.15E-01 | 17.86 | 2.95E-01 | 3.10E-04 | 6.09 | 0.9636 |
| T7 | 16.24 | 3.32E-04 | 5.72 | 0.9506 | 1.09E-01 | 16.24 | 2.89E-01 | 3.42E-04 | 5.53 | 0.9049 |
| T8 | 17.66 | 2.86E-04 | 6.64 | 0.9864 | 1.09E-01 | 17.56 | 2.98E-01 | 2.97E-04 | 6.36 | 0.9671 |
| T9 | 17.67 | 2.84E-04 | 6.70 | 0.9802 | 1.06E-01 | 17.57 | 2.98E-01 | 2.94E-04 | 6.43 | 0.9767 |

$C_0$ = potential available C at time zero, k = apparent rate constant, $C_1$ = active C pool, $C_2$ = resistant C pool, $k_1$ = smaller and easily mineralizable C pool of higher turnover rate, $k_2$ = large stable pool with a slow turnover rate

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### 3.3.1 First-Order Kinetic Model

**$C_0$**: This parameter represents the initial amount of available C in each treatment, with values ranging from 12.96 to 18.13 mg $kg^{-1}$. Notably, $T_6$ exhibited the highest potential available C, indicating a greater initial availability of C under this treatment regime.

**K** : This constant reflects the rate at which C mineralizes. Higher k values, such as those observed in $T_2$ and $T_3$ (approximately 3.39E-04 $day^{-1}$), signify more rapid mineralization rates, whereas lower k values, represented by $T_5$ (2.67E-04 $day^{-1}$), denote slower mineralization processes.

**Half-life**: This metric delineates the duration required for half of the available C to mineralize. Treatments characterized by elevated k values tend to exhibit shorter half-lives, as observed in $T_2$ (5.60 years) and $T_3$ (5.61 years). Conversely, $T_5$, with a k value resulting in a half-life of 7.10 years, demonstrates an extended mineralization timeframe.

**$R^2$**: All treatments yielded high $R^2$ values, ranging from 0.9198 to 0.9864, indicating a robust fit of the first-order model to the experimental data.

### 3.3.2 Second-Order Kinetic Model

**$C_1$**: This parameter reflects a smaller, more readily mineralizable C pool. $C_1$ values range from 0.0874 $mgkg^{-1}$ ($T_1$) to 0.118 mg $kg^{-1}$ ($T_2$), with $T_2$ demonstrating the highest active C pool. This observation suggests that this treatment may facilitate accelerated mineralization due to an augmented availability of readily accessible C.

**$C_2$**: This component denotes a larger and more stable C pool that mineralizes at a slower rate. $C_2$ values exhibited slight variation across treatments, ranging from 13.22 to 17.57 mg $kg^{-1}$, with $T_9$ registering the highest resistant C pool, indicative of a substantial reservoir of stable C.

**$k_1$**: This parameter evaluates the rapid mineralization of the smaller C pool, where $T_1$ displays the highest $k_1$ value (2.96E-01 $day^{-1}$), indicative of a more expedient C release from this pool.

**$k_2$**: This parameter reflects the slower turnover of the larger, stable pool. The $k_2$ values were relatively homogenous across treatments, with $T_2$ presenting the highest $k_2$ value (3.50E-04 $day^{-1}$), thereby indicating a relatively accelerated turnover within its stable pool in comparison to the other treatments.

**Half-life**: The half-lives correspond with their respective k values, where higher k values are associated with shorter half-lives, thereby reflecting more rapid mineralization. Shorter half-lives were observed in $T_2$ (5.40 years) and $T_3$ (5.43 years), whereas the longest half-life was observed in $T_5$ (6.80 years).

**$R^2$** : The second-order model also demonstrated high $R^2$ values, ranging from 0.8839 to 0.9793, signifying a strong fit to the data, albeit the values were marginally lower than those afforded by the first-order model.

Both the first- and second-order kinetic models exhibited excellent alignment with the observed data, as evidenced by high $R^2$ values. Specifically, $T_2$ and $T_6$ demonstrated higher potential available C and active C pools, respectively, suggesting that these conditions may facilitate elevated rates of C mineralization. The findings indicated that $T_5$ and $T_9$ appeared to possess larger stable C pools with slower turnover rates, underscoring their potential for long-term C storage. Both kinetic models adeptly captured the patterns of C mineralization. The first-order model demonstrated a marginally superior statistical fit, suggesting its preferential applicability for characterizing long-term carbon mineralization dynamics within the study area.

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## 4. DISCUSSION

An initial surge in $CO_2$ emissions during the first three days indicated rapid breakdown of readily degradable organic materials. This observation was consistent with findings that organic amendments enhance soil C turnover (Wu et al., 2024). $CO_2$ emissions decreased from day 3 to day 24. Yang et al., 2021 demonstrated that high mineralization rates often decline as labile C sources are exhausted. Marzi, Shahbazi, Kharazi&Rezaei, (2020) also showedan initial rapid increase in decomposition occurs during the first 20 days, followed by a gradual slowdown, ultimately reaching a steady-state condition.Sustained $CO_2$ production from day 24 to day 45 suggests ongoing degradation of more resilient organic compounds, reflecting a prolonged response to organic inputs (Domouso et al., 2024).

Among the different amendments, $T_3$ was the primary contributor to early emissions due to its nutrient-rich profile, supporting previous findings on manure's rapid decomposition (Anderson et al., 2021). This finding is consistent with the study by Hossain et al., (2017), which demonstrated that CO2 emissions were highest in soil mixed with chicken manure, followed by rice straw, vermicompost, cow dung, and rice husk biochar. In contrast, $T_2$showed delayed emissions starting at day 17, attributed to its complex composition and higher C:N ratio (Table 1) that slows decomposition (Liyanage et al., 2021). $T_6$ yielded the highest emissions from days 3 to 10, illustrating diverse nutrient sources was related to decomposition (Surigaoge et al., 2023). $T_5$ exhibited lower emissions due to its high lignin content (Table 1), which impedes decomposition (He et al., 2018). The control treatment underscored the essential role of organic amendments in soil C mineralization. Yang et al., 2023 and Sun et al., 2021 found that significant increases in $CO_2$ emissions following organic application.

During the incubation period, cumulative C mineralization was assessed using first-order and second-order kinetic models. Among the solely organic amendments tested, $T_2$ consistently exhibited the highest rate of C mineralization, indicating its significant potential for enhancing soil fertility and promoting C sequestration (Guo et al., 2023). $T_3$ followed with the second-highest mineralization rate, contributing effectively to soil fertility and C storage (Yang et al., 2024). $T_5$ showed the lowest cumulative C mineralization over the 120-day period, reflecting its limited effectiveness in fostering soil fertility and C retention (Zhou et al., 2024).

In mixed treatments, $T_7$ significantly boosted C mineralization at days 3, 10, and 17. This mixture supports both C release and nutrient availability for plant growth (Wang et al., 2024). Starting from day 24, $T_6$ maintained high mineralization rates, illustrating its long-term benefits for C sequestration and soil health (Singh et al., 2024). $T_9$ yielded the lowest C mineralization, underscoring the importance of selecting suitable organic amendments. Throughout the incubation, $T_2$ led in cumulative C mineralization, followed by $T_6$, and $T_3$due to their lower lignin contents (Table 1). $T_5$ contributed the least cumulative C mineralization, emphasizing the need for careful selection of organic amendments to achieve sustainable soil health and optimal C storage.

The first-order kinetic model elucidates the dynamics of potential available C ($C_0$) across various treatments, revealing a significant range from 12.96 to 18.13 mg $kg^{-1}$. Notably, $T_6$ demonstrated the highest potential available C, highlighting its capacity to enhance C availability at the onset of mineralization. This finding suggests that specific amendments can be strategically employed to optimize C availability, with important implications for nutrient cycling in soil (Desalegn, Herrerod&Turriónb., 2019). An examination of the apparent rate constant (k) indicates substantial variation in mineralization rates across treatments. $T_2$ and $T_3$ exhibited k values of approximately 3.39E-04 $day^{-1}$, indicating a rapid mineralization process that facilitates the swift release of nutrients. In contrast, $T_5$ exhibited a notably lower k value of 2.67E-04 $day^{-1}$, suggesting a slower rate of C mineralization, which could affect the timing of nutrient availability in agricultural practices. This is further

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supported by the half-life metric, where higher k values correspond to shorter half-lives, emphasizing the connection between the rate of mineralization and the duration of C availability (Riffaldi, Saviozzi& Levi-Minzi., 1996).

The second-order kinetic model complements this analysis by introducing active ($C_1$) and resistant ($C_2$) C pools. $T_2$ emerged with the highest active C pool, suggesting that certain organic amendments can promote accelerated mineralization rates by providing easily digestible C sources (Da Silva et al., 2022). $T_9$ exhibited the highest resistant C pool, characterized by slower mineralization rates, underscoring its significance in long-term C storage (Liu et al., 2024, Chen et al., 2014). The high $k_1$ value in $T_1$ indicated rapid mineralization of the active C pool. In all treatments, $T_2$ showed the highest $k_2$value (3.50E-04 $day^{-1}$), reflect a consistent turnover rate within the stable C pool, which is essential for sustaining soil health over time (Eleduma, Aderibigbe&Obabire., 2020).

The strength of both kinetic models is evident from the high $R^2$ values, indicating a strong fit of the models to the experimental data. The superior alignment of the first-order model suggests its applicability in characterizing long-term C mineralization dynamics within the context of this study. This finding is consistent with earlier research (Saviozzi et al., 1997; Kumar et al., 2018; Chen, Pei & Chiang., 2020; Sarkar et al., 2021). Treatments that promote higher potential available C and active C pools, such as $T_2$ and $T_6$, represent opportunities to bolster soil nutrient dynamics. Conversely, treatments with more extensive resistant C pools, such as $T_5$, underscore the importance of incorporating strategies that enhance long-term C storage, thereby contributing to sustainable agricultural practices and improved C management in soils.

## 5. CONCLUSION

The results of this study underscore a critical paradox in soil management practices: while increased C mineralization can enhance nutrient availability in the short term, it may ultimately be detrimental to long-term C sequestration efforts. Specifically, organic amendments such as cow dung and chicken manure, characterized by their rapid decomposition and high mineralization rates, facilitate a swift release of $CO_2$ into the atmosphere. This phenomenon, while beneficial for immediate nutrient cycling and plant growth, poses a significant challenge for sustainable C management. In contrast, amendments like maize straw, despite exhibiting lower rates of C mineralization, play a vital role in fostering the formation of resistant C pools. These resistant pools are essential for long-termC storage, as they are less susceptible to microbial degradation and can persist in the soil for extended periods. The application of kinetic models in this research, particularly the first-order model, has proven effective in elucidating the dynamics of C mineralization across various treatments. The high $R^2$ values associated with this model indicate a robust fit to the experimental data.

The study emphasizes the importance of selecting organic amendments not solely based on their immediate effects on nutrient release but also considering their long-term implications for C sequestration. Moreover, the interplay between C mineralization and sequestration presents a complex challenge for soil management. The insights gained from this study highlight the need for a strategic selection of organic amendments that optimize both nutrient availability and long-term C storage in tropical soil. By prioritizing amendments that enhance resistant C pools, such as maize straw, alongside a thorough understanding of the underlying kinetic models, agricultural practices can be aligned with the dual goals of improving soil health and mitigating climate change. This study detailed the sustainable agricultural practices that align with climate resilience objectives.

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**Disclaimer (Artificial intelligence)**Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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