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Research Article

Exploring the mystery of soil carbon mineralization: Insights from incubation experiments and kinetic modeling

Libi Robin. P*
Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University (TNAU), Coimbatore – 641003 (Tamil Nadu), India
Kaleeswari. R.K.
Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University (TNAU), Coimbatore – 641003 (Tamil Nadu), India
Janaki. P
Nammazhvar Organic Farming Research Centre, Tamil Nadu Agricultural University (TNAU), Coimbatore – 641003 (Tamil Nadu), India
Uma. D
Department of Biochemistry, Tamil Nadu Agricultural University (TNAU), Coimbatore – 641003 (Tamil Nadu), India
Karthikeyan. S
Centre for Post Harvest Technology, Tamil Nadu Agricultural University (TNAU), Coimbatore – 641003 (Tamil Nadu), India

*Corresponding author. E-mail: libirobin.p@gmail.com

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Abstract

Soil carbon mineralization is vital for carbon sequestration but affected by factors like soil type and residue quality. Understanding the process and factors is still incomplete, including the interplay between soil properties and organic residues and the need for accurate kinetic models. Research faces significant challenges in describing carbon mineralization dynamics. The present study aimed to investigate carbon mineralization in three soils located in Tamil Nadu, India (S_1, S_2 and S_3) that possess distinct textures. The study also focused on the effects of five different plant residues (Rice, maize, sugarcane, cotton and turmeric) on carbon mineralization in these soils. Incubation experiments were conducted for 150 days, and CO_2 evolution was measured at different time intervals of 7, 10, 15, 30, 60, 90, 120 and 150 days. The performance of three kinetic models (Zero order model, exponential kinetic model and first order model) was also evaluated in predicting carbon mineralization using experimental data. The results showed that the rate and extent of carbon mineralization varied significantly among the different soils and residues. The highest carbon mineralization was observed in rice (989.02 µg C/g/day) and maize (966.53 µg C/g/day) residue, while the lowest was in sugarcane (752.09 µg C/g/day) residue. Among the kinetic models, the first-order kinetic model provided the best fit for all treatments (R^2=0.98). The findings suggest that soil texture and residue quality play crucial roles in carbon mineralization. The first order kinetic model can be useful for predicting carbon mineralization in different soil-residue systems. These results have implications for managing soil carbon sequestration and mitigating climate change.

Keywords: Carbon mineralization, climate change mitigation, kinetic models, organic residues and soil properties

INTRODUCTION

Soil organic carbon (SOC) is a crucial component of the global carbon cycle and is vital in regulating atmospheric CO_2 concentrations. Soil carbon mineralization is the process by which soil organic carbon is converted to CO_2 through microbial activity, and it is influenced by a range of factors, including soil properties, climate, and residue quality. In recent years, there has been increasing interest in understanding the effects of different plant residues on soil carbon mineralization. This can have important implications for soil fertility, nutrient cycling, and greenhouse gas emissions. Carbon mineralization of crop residues is important because it regulates carbon dioxide (CO_2) emissions into the atmosphere and releases nutrient elements essential to crop growth (Raiesi, 2006; Guntinas, 2012).

Crop residues play a pivotal role in regulating the sequestration of soil carbon by managing the balance between the input and mineralization of residue carbon (Leavit, 1998 and; Hewins *et al*., 2017). It is important to acknowledge that various types of crop residues, such as roots, stems, and leaves, exhibit distinctive chemical compositions and C/N ratios, as observed in studies conducted by Abiven *et al*. (2005) and Redin *et al*. (2014). Crop residues have been demonstrated to influence the decomposition of indigenous soil organic carbon (SOC) through a phenomenon known as the priming effect (Bingeman *et al.* 1953). The addition of organic substances to soil can not only accelerate the mineralization of native SOC, resulting in a positive priming effect, but also have the opposite effect and retard the mineralization of SOC, leading to a negative priming effect (Dalenberg and Jager 1989; Kuzyakov *et al.,* 2000; Kirkby *et al.,* 2014 ; Zhang *et al*., 2019).

Several studies have investigated the impacts of plant residues on soil carbon mineralization using incubation experiments. Incorporating maize residue into the soil substantially enhanced carbon mineralization rates (Xu *et al.,* 2019). Similarly, Datta *et al.* (2019) observed that adding rice residue to soil increased carbon mineralization rates more than adding another crop residue.

Understanding the kinetics of this process is essential for predicting soil carbon sequestration potential and managing agricultural systems. In this regard, several mathematical models have been developed to describe carbon mineralization kinetics. Among these, three distinct models have been commonly employed.

Recent studies have utilized these models to describe the kinetics of carbon mineralization. The zero-order model to elucidate carbon mineralization in different composts (Fernandez *et al*., 2007). Similarly, Cely *et al.* (2014) employed the exponential model to investigate the impacts of biochar on carbon mineralization in soil. Furthermore, Zhang *et al.* (2020) conducted a study on the effects of temperature and moisture on carbon mineralization in paddy soils. Li and colleagues assessed the first-order kinetic model as a predictor of carbon mineralization (Li *et al*., 2013). These models have been extensively employed to predict carbon mineralization in different soil types and management practices, and comprehending their strengths and weaknesses can aid researchers and practitioners in effectively managing soil carbon stocks.

This study aimed to determine the mineralization rates of different residues in soil, their impact on soil carbon storage, and the underlying microbial mechanisms driving these processes. The present study conducted an incubation experiment to investigate the impacts of five different plant residues (rice, maize, sugarcane, cotton and turmeric) on soil carbon mineralization. Three different soil types were used to capture the potential variability in microbial activity and mineralization rates across soils.

MATERIALS AND METHODS

Characteristics of soil and crop Residues

The soils used in the incubation experiments were selected from a soil survey conducted in the western zone's maize-based cropping system. Three soils (S_1, S_2 and S_3) were chosen from the survey area, each with low, medium, and high organic carbon levels, respectively. The soil samples were collected from the top arable layer (0-15 cm) of three different locations, namely Korikadavu in Palani district (10°33’13.50” N, 77°28’09.78” E), Malaipalayam in Coimbatore district (10°49'48.33"N, 77°11'22.36"E), and Thadicheri in Theni district (09°55’48.68” N, 77°30’00.48” E).

The collected soil samples were air-dried, and visible impurities were removed. The soil was then sieved using a 2 mm mesh. The pH of the soil was found to be neutral to slightly alkaline (Table 1). The total organic carbon content ranged from 6.11 to 10.5g/kg, with S2 having the highest organic carbon content. The C:N ratio ranged from 8.58:1 to 9.11:1 in S2 and S1 soils, respectively. The clay content varied between 26.3% to 30.2%, with S2 having the highest clay content. The maximum silt content (22.7%) was recorded in S2, while S1 had the highest sand content (66.2%).

For this study, residues of rice, maize, sugarcane, cotton, and turmeric were specifically selected since these crops were dominant in the maize-based cropping systems of the western zone of Tamil Nadu. The residues were collected at harvest from the plot where soil samples were obtained. The plant residues were dried at 55°C in a hot air oven and used for chemical analysis. The total carbon, total nitrogen, and their C:N ratios of different residues are presented in Table 2. Maize had the highest total carbon content compared to the other residues, and accordingly, it had the highest C:N ratio among the residues.

Incubation experiment

In the incubation treatment, a quantity of approximately 50 g of soil was selected and blended with 0.5 g of finely ground residue. The resulting mixture was then placed into a 500 mL conical flask, and its bulk density was normalized by tapping the bottom. The moisture content was maintained at 60% of the maximum water holding capacity (MWHC), representing the ideal moisture level for maximal microbial activity in soil. Fifteen treatments (comprising of three soils and five residues) were utilized in addition to four blank treatments (two solely consisting of soil and the remaining two with no soil), each replicated three times. The experimental design adopted was a factorial, completely randomized design (CRD). Approximately 10 mL of 0.5 M sodium hydroxide (NaOH) solution was dispensed into 20 mL capacity vials, which were then placed inside the conical flask. The flasks were incubated for a duration of 150 days at room temperature, following pre-incubation for 10 days. Subsequently, the NaOH solution was extracted from the flask and transferred to a 100 mL conical flask, where it was diluted with 25 mL of distilled water. Following the addition of 1 mL of saturated barium chloride ($BaCl_2$) and phenolphthalein indicator, the sample underwent a color change to violet and was subsequently titrated against 0.5 M HCl (Alef, 1995). CO_2 evolution was measured at days 7, 10, 15, 30, 60, 90, 120, and 150.

Kinetic models

In this experiment, three distinct models were employed to describe the C mineralization in the samples under study. The first model, referred to as the zero-order model, was formulated by Seyfried and Rao in 1988 (Seyfried and Rao, 1988).

This model is represented by the equation

$C_t = k_t + intercept$ Eq. 1

where C_t denotes the cumulative organic carbon mineralized (mg $C\text{-}Co_2$ kg^{-1}) at time t (days), k (mg kg^{-1} day^{-1}) represents the zero-order rate constant, and the intercept refers to a pool of highly mineralizable carbon.

The second model, introduced by Levi-Minzi and colleagues in 1990 (Levi-Minzi *et al.,* 1990), employs an exponential kinetic to describe net mineralization:

$C_t = kt^m$. Eq. 2

Here, k and m are constants, where k characterizes the units used for the variables (mg kg^{-1} day^{-1}), and m reflects the shape of the curve.

Lastly, Murwira and colleagues in 1990 used a first-order exponential equation to describe C mineralization, which is represented by the equation (Murwira *et al.,* 1990).

$C_t = C_0(1\text{-}e^{-kt})$ Eq. 3

In this equation, C_0 denotes the total potentially mineralizable C (mg kg^{-1}), and k represents the mineralization rate constant (day^{-1}).

Soil and crop residue analysis

Soil pH was determined using the Jackson method (Jackson, 1967). Total nitrogen in soil and residue samples was analyzed using the Kjeldahl method (Horwitz, 2010). Total organic carbon (TOC) was measured using a TOC analyzer. The soil texture, i.e., the proportion of sand, silt, and clay, was assessed using the international pipette method (Piper, 1966). The total carbon (TC) content in crop residue was estimated using a CHNS elemental analyzer via the dry combustion method.

Model validation

A reliable carbon mineralization model is crucial for accurately predicting the conversion rate of organic carbon to CO_2 in soil. In order to explore various models for predicting soil carbon mineralization, this study chose three models: the zero-order, exponential, and first-order. To assess the performance of these models, statistical comparison criteria such as the coefficient of determination were calculated (Table 3). Non-linear least-squares regression analysis provided by SPSS software was employed to estimate the model parameters for these three models (Table 3). This approach enabled the calculation of accurate parameter estimates, which is essential for building robust and reliable models for predicting soil carbon mineralization.

RESULTS

During the initial 10 days of soil incubation, a substantial surge in CO_2 production was observed across all the samples, irrespective of the type of residue or application method (Fig 1). This sharp rise in CO_2 evolution was followed by a rapid decline in CO_2-C from day 10 until day 30, after which the rate of CO_2 emission decreased more gradually until day 60. CO_2 evolution nearly stabilized and remained constant for the remaining 90 days of incubation. Importantly, a significant difference in CO_2 evolution was observed between the amended and control soil up to day 60, indicating a clear impact of the treatment on the carbon mineralization process. These findings highlight the importance of considering the temporal dynamics of soil carbon mineralization and the impact of residue management practices when predicting soil carbon sequestration potential.

Fig. 2 shows that all three types of soil- Soil 1, Soil 2, and Soil 3 – exhibited higher carbon mineralization rates the control sample. This is not surprising, as the control sample was expected to contain less organic matter, which served as a food source for microorganisms involved in the carbon mineralization process. Notably, Soil 2 displayed the lowest carbon mineralization rates, especially at later time points (90, 120, and 150 days). In contrast, Soil 1 and Soil 3 exhibited higher carbon mineralization rates, although the differences are relatively small.

Interestingly, Soil 3 exhibited the highest carbon mineralization rates at earlier time points (7 and 10 days), but this trend was inconsistent across later time points. It is possible that other factors may be influencing carbon mineralization rates in Soil 3. Overall, these observations suggest that the soil type can considerably impact carbon mineralization rates. A better understanding of these processes is crucial for predicting and mitigating the effects of climate change, as elevated carbon mineralization rates can lead to increased greenhouse gas emissions.

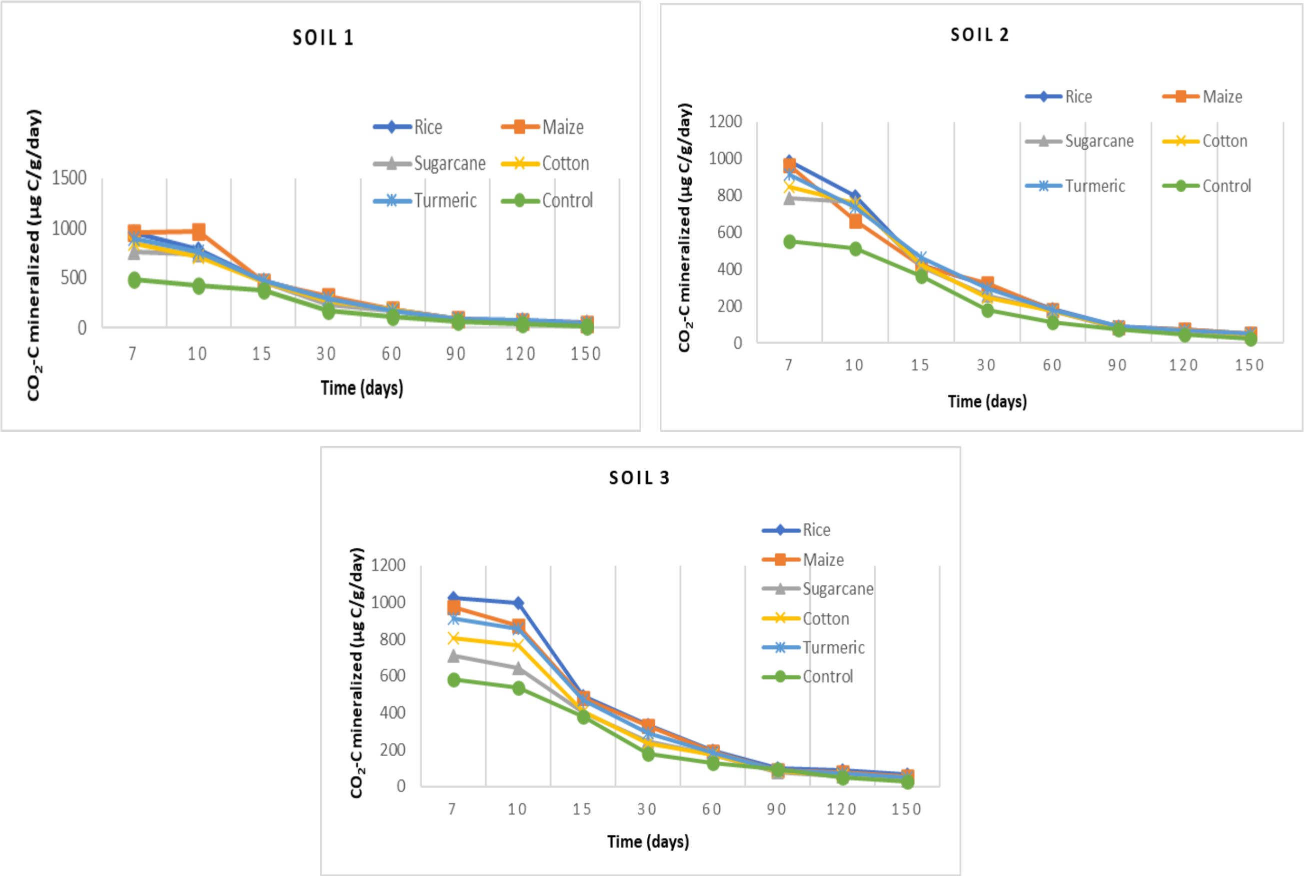

Fig. 1. *Fluxes of carbon dioxide (CO_2-C) in micrograms of carbon per gram of soil per day, at different sampling dates during an incubation period*

Table 1. Characteristics of experimental soils of Tamil Nadu

Soil type	pH	TOC	TN	C:N Ratio	Texture (%)		
		g/kg			Clay	Silt	Sand
S1	7.92	6.11	0.67	9.11:1	26.3	6.9	66.2
S2	8.35	7.64	0.89	8.58:1	30.2	22.7	46.7
S3	6.1	10.5	1.16	9.05:1	28.6	12.6	58.4

Analysis of Fig 3 reveals that rice residue exhibited the highest carbon mineralization rate during initial intervals (7-15 days), followed by turmeric, maize, cotton, and sugarcane residue. However, at longer time intervals (30-150 days), the differences in carbon mineralization rates between the various residue types became less discernible. This indicated that the rate of carbon mineralization slowed down over time, as microbial activity decreased. Furthermore, the carbon mineralization rate was generally higher at the initial time intervals (7-15 days) than at the longer intervals (30-150 days).

This is likely due to the increased microbial activity at the initial stages of decomposition, when there was greater availability of labile carbon compounds in the residue. It is worth noting that the observed differences in carbon mineralization rates between the various types of crop residue could be influenced by several factors, including the chemical composition of the residue, temperature, moisture, and microbial community. Therefore, further investigation is needed to understand how these variables influence carbon mineralization rates and to identify potential strategies for mitigating carbon loss from soils.

Regarding the different types of crop residue, it was observed that rice residue generally had the highest cumulative carbon mineralization rate at the initial time intervals (7-15 days), followed by turmeric, maize, cotton, and sugarcane residue (Fig 4). However, the differences in carbon mineralization rates between the residue types became less pronounced at longer intervals (30-150 days), suggesting that the carbon mineralisation rate decreased over time as microbial activity slowed. It is important to note that the differences in carbon mineralization rates between the residue types

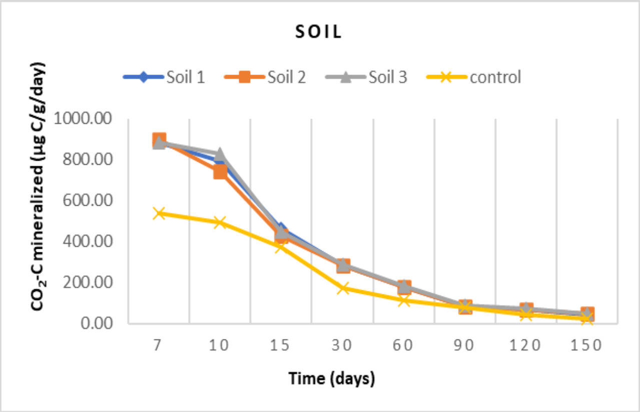

Fig. 2. *Soil CO_2-C fluxes in micrograms of carbon per gram of soil per day, at different sampling dates during an incubation period*

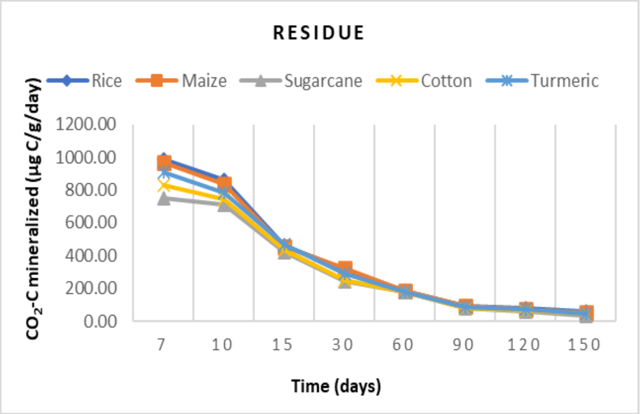

Fig. 3. *Effect of residue CO_2-C fluxes in micrograms of carbon per gram of soil per day, at various sampling dates during an incubation period*

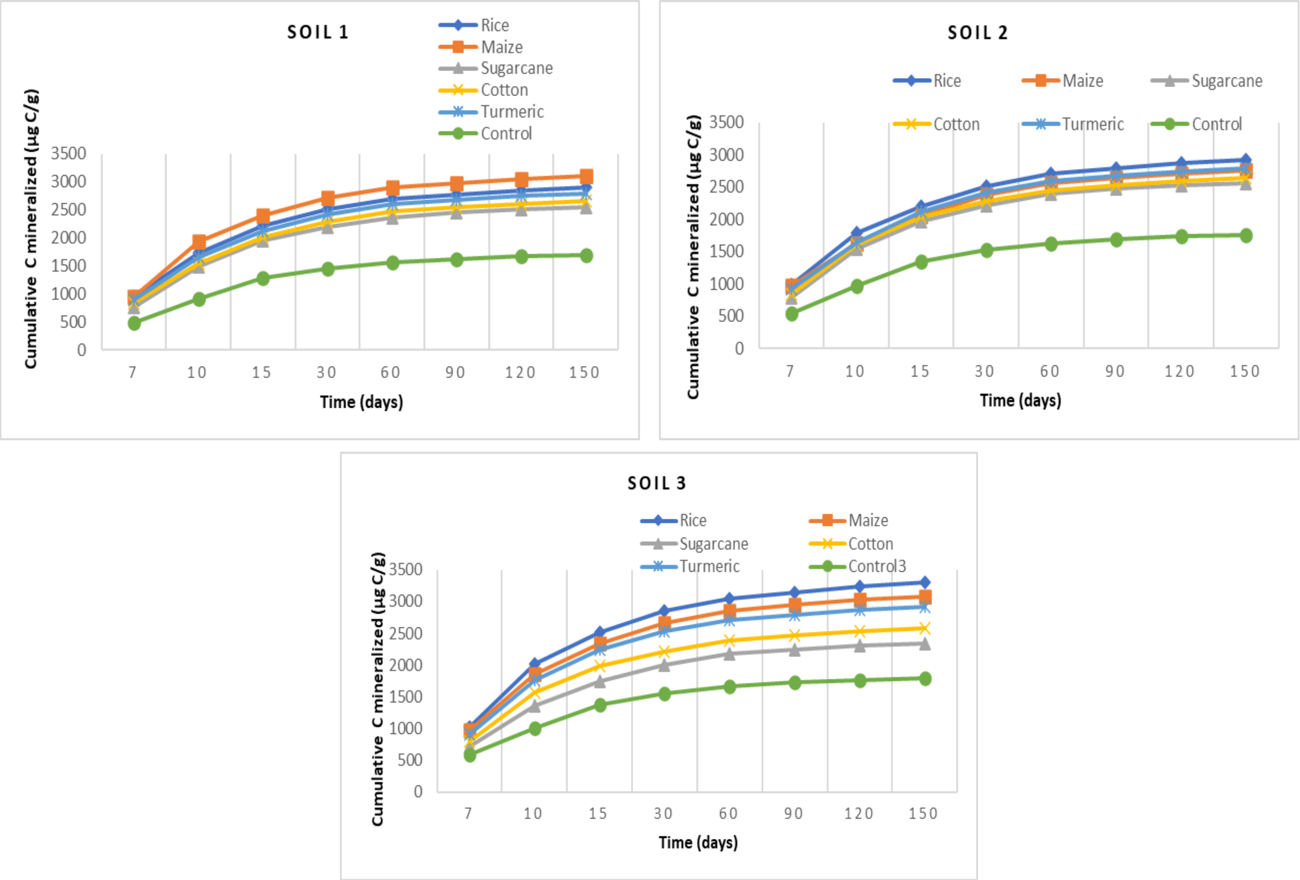

Fig. 4. *Cumulative mineralization of carbon (in micrograms of carbon per gram of soil) at various sampling dates during an incubation period*

may be influenced by a variety of factors, including the chemical composition of the residue, temperature, moisture, and microbial community. Therefore, further studies are needed to understand the mechanisms underlying these observations.

The control treatment, consisting of soil without added crop residue, also showed carbon mineralization over time. This suggests that a baseline level of carbon mineralization occurred in the soil, likely due to the activity of the native microbial community.

DISCUSSION

The present study investigated the effect of incorporating different agricultural residues into three different soil types on CO_2 evolution over 150 days. The results demonstrated that adding residues significantly increased CO_2 evolution, indicating enhanced microbial activity and SOM decomposition. The present findings were consistent with previous studies showing that SOM decomposition positively correlated with microbial

Table 2. Characteristics of experimental crop residues

Soil type	Plant Residue														
	Total C (%)					Total N (%)					C:N Ratio				
	Rice	Maize	Sugarcane	cotton	Turmeric	Rice	Maize	Sugarcane	cotton	Turmeric	Rice	Maize	Sugarcane	cotton	Turmeric
S_1	41.23	42.11	36.24	37.27	38.94	0.48	0.49	0.48	0.61	1.28	85.90	85.94	75.50	61.10	30.42
S_2	41.37	41.88	38.54	39.21	39.65	0.52	0.39	0.44	0.64	1.35	79.56	107.38	87.59	61.27	29.37
S_3	42.35	42.56	36.78	37.87	39.47	0.56	0.48	0.47	0.68	1.48	75.63	88.67	78.26	55.69	26.67

activity (Zibilske, L.M. and Bradford, J.M. 2007). The highest CO_2 evolution was observed in treatments that included rice and maize residues. This result was consistent with previous studies showing that these residues are rich in carbon and nutrients, making them an excellent energy source for soil microorganisms (Rakesh *et al.,* 2021).

The incorporation treatment was effective in enhancing microbial activity and SOM decomposition, with the highest CO2 evolution observed in the first week of incubation. This result was consistent with previous studies that have shown that SOM decomposition followed a rapid initial phase, followed by a slower phase (Fernndez *et al.,* 2006; Kaur *et al.,* 2023). The results also demonstrated that the moisture content significantly influenced CO_2 evolution, with the highest CO_2 evolution observed at 60% MWHC. This result is consistent with previous studies showing that moisture content is a critical factor in regulating microbial activity and SOM decomposition (Rakesh *et al.,* 2021). The experimental design adopted in this study was a factorial completely randomized design, which allowed for the evaluation of the individual and interactive effects of soil type and residue type on CO_2 evolution. This design has been widely used in similar studies and effectively minimises experimental error and increases statistical power (Franzluebbers, 2020; Rakesh *et al.,* 2021). Additionally, using NaOH solution to extract the CO_2 from the soil sample was an effective method in similar studies, as it eliminated the need for gas sampling and avoided contamination (Alef, 1995).The zero-order model, formulated by Seyfried and Rao (1988), assumes a constant rate of C mineralization over time. This model has been widely used in soil carbon research, and several studies have supported its applicability (Fernandez *et al.,* 2007 and Temesgen *et al.,* 2019).

The exponential kinetic model, introduced by Levi-Minzi and colleagues in 1990 (Levi-Minzi *et al.,* 1990), assumes that the rate of C mineralization decreases exponentially over time. This model has been shown to fit well with the C mineralization data in several studies (Temesgen *et al.,* 2019), indicating its potential for use in describing the complex processes involved in soil carbon cycling. Lastly, Murwira *et al.* (1990) used a first-order exponential equation to describe C mineralization. This model assumes that the rate of mineralization is proportional to the remaining amount of potentially mineralizable carbon. Several studies have used this model to describe C mineralization in soils (Marinari *et al.,* 2010; Ghimire *et al.,* 2017; Kaboneka *et al.,* 2019 ; Kaur *et al.,* 2023). Test statistics revealed that (R^2 =0.98) first order kinetic model gave the best fit towards the calculative value. The statement suggests that the results align with previous studies (Kaboneka *et al.,* 2019).

Table 3. Model parameters and R^2 values of the various kinetic models

Kinetic Models								
		Parameter						
Soil	Residue	$C_t = k_t + intercept$		$C_t = kt^m$			$C_t = C_0(1-e^{-kt})$	
		k	R^2	K	m	R^2	k	R^2
Soil 1	Rice	9.55	0.92	2.91	0.27	0.94	0.046	0.98
	Maize	10.09	0.93	2.93	0.26	0.93	0.004	0.99
	Sugarcane	8.65	0.92	2.93	0.3	0.94	0.004	0.97
	Cotton	8.95	0.92	2.7	0.26	0.92	0.006	0.99
	Turmeric	9.33	0.91	3.4	0.32	0.94	0.006	0.98
Soil 2	Rice	9.47	0.9	2.93	0.27	0.94	0.008	0.98
	Maize	9.13	0.92	2.9	0.27	0.94	0.01	0.98
	Sugarcane	8.61	0.92	2.9	0.29	0.93	0.004	0.98
	Cotton	8.71	0.93	3.1	0.24	0.92	0.006	0.99
	Turmeric	9.32	0.91	3.5	0.34	0.91	0.007	0.98
Soil 3	Rice	10.88	0.89	2.96	0.28	0.93	0.004	0.98
	Maize	10.2	0.89	3	0.29	0.95	0.006	0.98
	Sugarcane	8.08	0.93	2.6	0.31	0.96	0.005	0.98
	Cotton	8.55	0.91	3.15	0.26	0.93	0.004	0.99
	Turmeric	9.6	0.91	3.32	0.36	0.94	0.005	0.98

The results of the present study have several implications for soil management and agricultural practices. Incorporating agricultural residues can significantly enhance microbial activity and SOM decomposition, leading to increased soil fertility and carbon storage. Therefore, using of agricultural residues as a soil amendment can effectively enhance soil health and mitigate climate change. However, the effect of residue type on CO_2 evolution and SOM decomposition was influenced by soil type, suggesting that soil-specific management practices may be necessary to optimize the use of agricultural residues as soil amendment.

Conclusion

The present study on the impact of adding agricultural residues to various soil types on the evolution of carbon dioxide (CO_2) and the decomposition of soil organic matter (SOM) employed a factorial, completely randomized design, encompassing 15 treatments and four blank treatments that were replicated three times. CO_2 evolution was monitored at different intervals throughout 150 days, and the results revealed that adding residues significantly affected the increase of CO_2 evolution and SOM decomposition. The treatments that incorporated rice straw and maize residues exhibited the highest levels of CO_2 evolution. Moreover, the impact of the type of residue on CO_2 evolution was influenced by the soil type, with sandy loam soil demonstrating the highest levels of CO_2 evolution, followed by loam and clay soils. The study also noted that the moisture content of the soil played a vital role in influencing CO_2 evolution, with the highest levels observed at 60% of the maximum water-holding capacity. The results using various kinetic models showed that the first-order kinetic model provided the most accurate fit. The findings of this study have significant implications for soil management and agricultural practices, as they suggest that incorporating agricultural residues can enhance microbial activity and SOM decomposition, leading to improved soil health and crop productivity.

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Conflict of interest

The authors declare that they have no conflict of interest.

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