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Kinetics of native and added carbon mineralization on incubating at different soil and moisture conditions in Typic Ustochrepts and Typic Halustalf

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ABSTRACT

The carbon dynamics in soils is of great importance due to its links to the global carbon cycle. The prediction of the behavior of native soil organic carbon (SOC) and organic amendments via incubation studies and mathematical modeling may bridge the knowledge gap in understanding complex soil ecosystems. Three alkaline Typic Ustochrepts and one Typic Halustalf with sandy, loamy sand, and clay loam texture, varying in percent SOC of 0.2; S_1, 0.42; S_2, 0.67; S_3 and 0.82; S_4 soils, were amended with wheat straw (WS), WS + P, sesbania green manure (GM), and poultry manure (PM) on 0.5% C rate at field capacity (FC) and ponding (P) moisture levels and incubated at 35 °C for 1, 15, 30 and 45 d. Carbon mineralization was determined via the alkali titration method after 1, 5, 7 14, 21, and 28 d. The SOC and inorganic carbon contents were determined from dried up (50 °C) soil samples after 1, 15, 30, and 45 d of incubation. Carbon from residue mineralization was determined by subtracting the amount of CO_2-C evolved from control soils. The kinetic models; monocomponent first order, two-component first order, and modified Gompertz equations were fitted to the carbon mineralization data from native and added carbon. The SOC decomposition was dependent upon soil properties, and moisture, however, added C was relatively independent. The carbon from PM was immobilized in S_4. All the models fitted to the data predicted carbon mineralization in a similar range with few exceptions. The residues lead to the OC build-up in fine-textured soils having relatively high OC and cation exchange capacities. Whereas, fast degradation of applied OC in coarse-textured soils leads to faster mineralization and lower build-up from residues. The decline in $CaCO_3$ after incubation was higher at FC than in the P moisture regime.

1. Introduction

The anthropogenic-driven climate change contributing more CO_2 than natural sources and sinks in the carbon cycle is a major threat to modern society (Amelung et al., 2020; Dong et al., 2019; Falkowski et al., 2000; Pires, 2017; Ruddiman, 2003). The carbon cycle is the flux of carbon among four main reservoirs: fossil carbon, the atmosphere, the oceans, and the terrestrial biosphere (Grace, 2004; Schimel, 1995; Smith, 2004). The part of the earth covered by soil (pedosphere) within the terrestrial ecosystem supports all biotic activity and interacts with the atmosphere, lithosphere, biosphere, and hydrosphere (Lal et al., 1997, 2018). Among all the interactive processes playing a major role in the global carbon cycle are between pedosphere, atmosphere, and biosphere (Lal et al., 2018). Carbon sequestration in the soil organic carbon (SOC) is one of the recognized approaches by major parties dedicated to this goal since the 21st United Nations Climate Change Conference in Paris (UNFCCC, 2015). Among these initiatives is '4 parts per thousand in a year' which signifies that a

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small proportional increase of 4 per thousand in the top 0.3–0.4 m of the non-permafrost soil will be equal to the annual global net atmospheric CO_2 growth (Chabbi et al., 2017; Rumpel et al., 2020). According to Lal (2016), the world's cropland soils could sequester as much as 62 t ha^{-1} over the next 50–75 years (0.8–1.2 t ha^{-1} y^{-1}) with a total C sink capacity of ~88 Gt (~97 billion t) on 1400 M ha. The increase in SOC via carbon sequestration in soil enhances its quality and its environmental regulatory (Iizumi & Wagai, 2019; Lal, 2015; Lal et al., 2018; Westermann et al., 1989) capacity such as drought tolerance in dry-land regions (Iizumi & Wagai, 2019). Organic wastes offer the best possible means of restoring and maintaining the productivity of agricultural soils (Fu et al., 2021; Torma et al., 2017). They protect soil from wind and water erosion and are a large reservoir of plant nutrients and maintain the physical environment of soil as a desirable medium for plant growth (Lal, 2015). The decomposition rate and release of nutrients from residues depend upon the soil, climatic conditions, and C:N ratio of plant residues (Prasad & Power, 1991).

The adoption of site-specific recommended management practices (RMPs) has the potential of sequestering 50–1000 kg^{-1} ha^{-1} y^{-1} offsetting 1/3–1/4th of the annual global CO_2 increase of 3.3 pg C y^{-1}. The implementation of the ‘4 per thousand’ is very complex and varies with each site. The lab scale studies imitating the target soil's environmental conditions provide an assessment of its carbon sequestration potential (Amelung et al., 2020). The effect of soil management practices on the changes in labile carbon pool (potassium permanganate oxidizable carbon) is one of the methods to determine the carbon mineralization/sequestration potential of residues/soils (Blair et al., 1995; Zhang et al., 2020). The parameters from incubation studies can quickly help to monitor the status of soils under similar field conditions as well (Gasser et al., 2022). There are studies indicating that the addition of wheat residues and Sesbania green manure improve soil physicochemical properties and improve crop yields (Kwesiga et al., 1999; Naher et al., 2019; Sidhu & Beri, 1989). The soils and amendments were selected to include a range of OC and C/N ratios, respectively via diverse sources. Moreover, *Sesbania aculeate* or Dhaincha (C/N ratio (15:5) is widely grown in developing countries to incorporate as green manure (GM) and N source (Rani et al., 2021; Sharma & Ghosh, 2000) at the 60-d stage. Poultry manure (PM) has a low C/N ratio (12.9) in a similar range but differs in properties and characteristics such as anaerobic microbial community. The carbon mineralization kinetics in soils varying in OC (and residues of varied characteristics) at different moisture levels have not been reported earlier to the best of our knowledge.

The objectives of this research were to determine the decomposition kinetics of native and added carbon via GM, PM, and WS in soils of varied physico-chemical characteristics and moisture levels via an incubation study.

2. Materials and methods

In this study, four soils of varied organic carbon content were amended with wheat straw (WS), WS along with 20 ppm orthophosphate (WS + P), GM, and PM through 0.5% organic carbon addition at field capacity (FC) and ponding (P) moisture contents. The effect of moisture and native soil properties on the labile native and added carbon dynamics via soil respiration was determined in an incubation study. The carbon mineralization dynamics was further explored with several non-linear regression models.

2.1. Collection, preparation, and analysis of soil samples

Four bulk surface (0–15 cm) soil samples having organic carbon contents of 0.26, 0.42, 0.67, and 0.82% were collected from different sites. The samples were dried in shade, ground in a wooden pestle and mortar, passed through a 2 mm sieve, and preserved in polythene bags for subsequent experimentation. The soil samples were analyzed for pH (1:2 soil: water suspension) using a glass electrode, electrical conductivity (EC, 1:2 soil: water supernatant) using a conductivity meter, and particle size distribution by the international pipette method (USDA, 1930). Available P was determined by extracting the soil samples with 0.5 M $NaHCO_3$ (Olsen et al., 1954) and the ascorbic acid method (Murphy & Riley, 1962). Available K was extracted with 1 N ammonium acetate (pH 7.0) and determined on a flame photometer (Merwin & Peech, 1951). Calcium carbonate was determined by titrating soil suspension (soil, water, calcium sulfate powdered, and aluminum chloride) with 0.5 N H_2SO_4 in the presence of bromothymol blue and bromocresol green indicators (Puri, 1950). The SOC was determined by the wet digestion method (Walkley & Black, 1934). Mineral-N (nitrate-N; NO_3^--N + ammonical-N; NH_4^+-N) was determined by extracting the soil samples with 2 M KCl, followed by steam distillation of the extract using MgO and Devarda's alloy (Mulvaney, 2018). The soils were alkaline (pH 8.0 to 8.3) in reaction, calcareous ($CaCO_3$ 2.9–7.9%), medium to high in available P and sandy to clay loamy in texture (Table 1.).

2.2. Organic amendments

The above-ground wheat (*Triticum aestivum* L.) and *Sesbania* residues were collected at maturity and 50–55 d stage, respectively, and dried in a hot air oven at 60 °C. These residues were

Table 1
Physico-chemical properties of experimental soils.

Parameter	S_1	S_2	S_3	S_4
Chemical Properties				
pH	8.2	8.0	8.1	8.3
EC (dS m^{-1})	0.25	0.37	0.34	0.4
OC (%)	0.26	0.42	0.67	0.82
$CaCO_3$ (%)	2.9	7.9	5.6	4.6
CEC (C mol kg^{-1})	0.63	4.2	4.9	6.9
Available P (kg ha^{-1})	21.0	38.2	65.0	36.0
Mineral N (mg kg^{-1})	2.8	16.8	12.6	39.0
Soil Separates (%)				
Sand	99.5	98.4	82.7	37.0
Silt	0.2	1.0	15.8	47.0
Clay	0.3	0.6	0.5	16.0
Texture	Sand	Sand	Loamy sand	Clay Loam
USDA Classification	Typic Ustochrepts	Typic Ustochrepts	Typic Ustochrepts	Typic Halustalf
Moisture Retention (%)				
Saturation (S)	47.5	58.3	51.5	65.6
Field Capacity (FC)	23.8	29.2	25.8	32.8

Table 2
Characteristics of wheat straw (WS), Sesbania (GM) and poultry manure (PM).

Parameter	WS	GM	PM
Ultimate analysis			
Total N (%)	0.44	3.44	1.87
Total C (%)	54.7	53.2	24.2
Total P (%)	0.09	0.33	1.27
C/P	67.8:1	161.2:1	19.1:1
C/N	124.3:1	15.5:1	12.9:1
Compositional analysis			
Hemicellulose (%-TS)	27.41	33.64	25.00
Cellulose (%-TS)	33.26	24.21	63.00
Lignin (%-TS)	13.45	8.11	5.00
Ash (%-TS)	10.10	7.45	7.00

ground in a Wiley mill with stainless steel blades and stored in polythene bags. The PM was passed through a 2 mm sieve before characterization. Total nitrogen was determined by the Kjeldahl method which involved steam distilling the extract obtained by digesting the organic material in the presence of an acid digestion mixture containing 480 g K_2SO_4, 20 g $CuSO_4$, 3 g HgO and 1 g Se powder. Total phosphorus was determined by digesting the organic material in a diacid mixture ($3HN_3$: 1 $HClO_4$) followed by the vanadomolybdophosphoric yellow color method in nitric acid. The biochemical composition of residues; cellulose, hemicellulose, lignin, and ash was determined by NDF and ADF solutions (Goering, 1970). The total carbon was determined by the loss of ignition method by igniting the plant residue at 550 °C.

2.3. Mineralization of native and applied organic matter

The mineralization of native and added carbon was studied by measuring the amount of CO_2-C evolved during the incubation of soils alone (controls) and organic materials incubated together. The amount of carbon released as CO_2 from the residues was determined by subtracting the control values from residue treatments (Bremer et al., 1991; Ladd et al., 1995). This method is based on the assumption that the addition of organic materials to the soil does not alter the decomposition rate of native carbon. One hundred gram soil was weighed and transferred to 250 mL conical flasks, and thoroughly mixed with the weighed amounts of organic amendments to attain 0.5% carbon (or 0.5 g carbon) in duplicate treatments. In WS + P treatment, 20 ppm orthophosphate concentration was achieved through a mono-calcium phosphate solution. The moisture content was maintained at two levels by adding the measured quantity of distilled water for each soil (Table 1.). A glass vial with 10 mL of 2N NaOH was suspended in each treatment flask to absorb the CO_2. The flasks were sealed by using air-tight rubber corks (Benbi & Khosa, 2014; Yin et al., 2019). The samples were incubated in a BOD incubator at 35 °C. The moisture (corresponding to each soil and moisture regime) was maintained by adding water (equivalent to the loss in weight at the beginning) to flasks at periodic intervals. The CO_2-C evolution was measured 1, 2, 5, 7, 14, 21, and 28 d after incubation by titrating the excess alkali (after precipitating the carbon dioxide with $BaCl_2$) with 2 M HCl and phenolphthalein indicator as described in earlier studies (Alef & Paolo, 1995; Benbi & Khosa, 2014; Yin et al., 2019). The soil samples after incubation (1, 15, 30, and 45 d) were dried in an oven at 50 °C, ground in a wooden pestle and mortar, and analyzed for SOC and $CaCO_3$ contents as described earlier in section 2.1.

2.4. Modeling C mineralization kinetics

The process was also simulated by a modified Gompertz equation (Eq. (1).), which is commonly employed for simulating biomethane production as a direct function of the methanogenic bacteria during anaerobic digestion (Ellert & Bettany, 1988; Kaur & Kommalapati, 2021a, 2021b, 2021c).

$$C(t) = Co \times exp\left\{ - exp\left[\frac{R_m e}{C_o}(\lambda - t) + 1\right]\right\} \tag{1}$$

$C(t)$ = The mineralized carbon (mg CO_2-C 100 g^{-1}) at incubation time t (d).

C_o = Mineralization potential (mg CO_2-C 100 g^{-1}).

R_m = Maximum daily rate of carbon mineralization (mg 100 g^{-1} d^{-1}).

λ = lag phase (d), the minimum time for bacterial acclimation

e = Mathematical constant, exp (1) = 2.718.

The mineralization potential refers to the maximum carbon mineralized to CO_2 from the native and added organic amendments. For soils, the maximum value is corresponding to % OC in 100 g of each soil while for amendments the maximum value is 500 mg 100 g^{-1} of soil.

The first-order mono-component (Eq (2).), as well as two-component (Eq. (3).) models, have been successfully used for soil carbon mineralization studies (Benbi & Richter, 2002; Dodor et al., 2019; Kafle & Chen, 2016; Levi-Minzi et al., 1990) and were also fitted.

$$C\ min = Co\left(1 - e^{-kdt}\right) \tag{2}$$

$$C\ min = Cd\left(1 - e^{-kdt}\right) + Cr\left(1 - e^{-krt}\right) \tag{3}$$

C_d and C_r (500 − C_d) represent the decomposable and recalcitrant fractions of potentially mineralizable native and added carbon and their sum was initially kept constant at 500 mg 100 g^{-1} of soil while fitting equation to the experimental data. Whereas, K_d and K_r represent disintegration rate constants of decomposable and recalcitrant carbon fractions, respectively.

The model fits were evaluated by calculating the relative root mean square error (*rRMSE*) as described by Kafle et al. (2016b) utilizing eq. (4).

$$rRMSE = \left(\frac{1}{m}\sum_{j=1}^{m}\left(\frac{d_j}{Y_j}\right)^2\right)^{\frac{1}{2}} \tag{4}$$

where m is the number of data pairs, j is jth values, Y is measured carbon mineralized (mg CO_2-C 100 g^{-1}), and d is the deviation between measured and predicted carbon mineralization values.

3. Results and discussion

3.1. Decomposition of soil organic matter

The mineralization of native carbon was fast during the first week and it slowed down subsequently. The rate of CO_2-;C evolution varied from 6.9 (S_1) to 23.1 mg 100 g^{-1} d^{-1} (S_3) during the first d at FC (Fig. 1.). On the 28th d of incubation, the rate was minimum

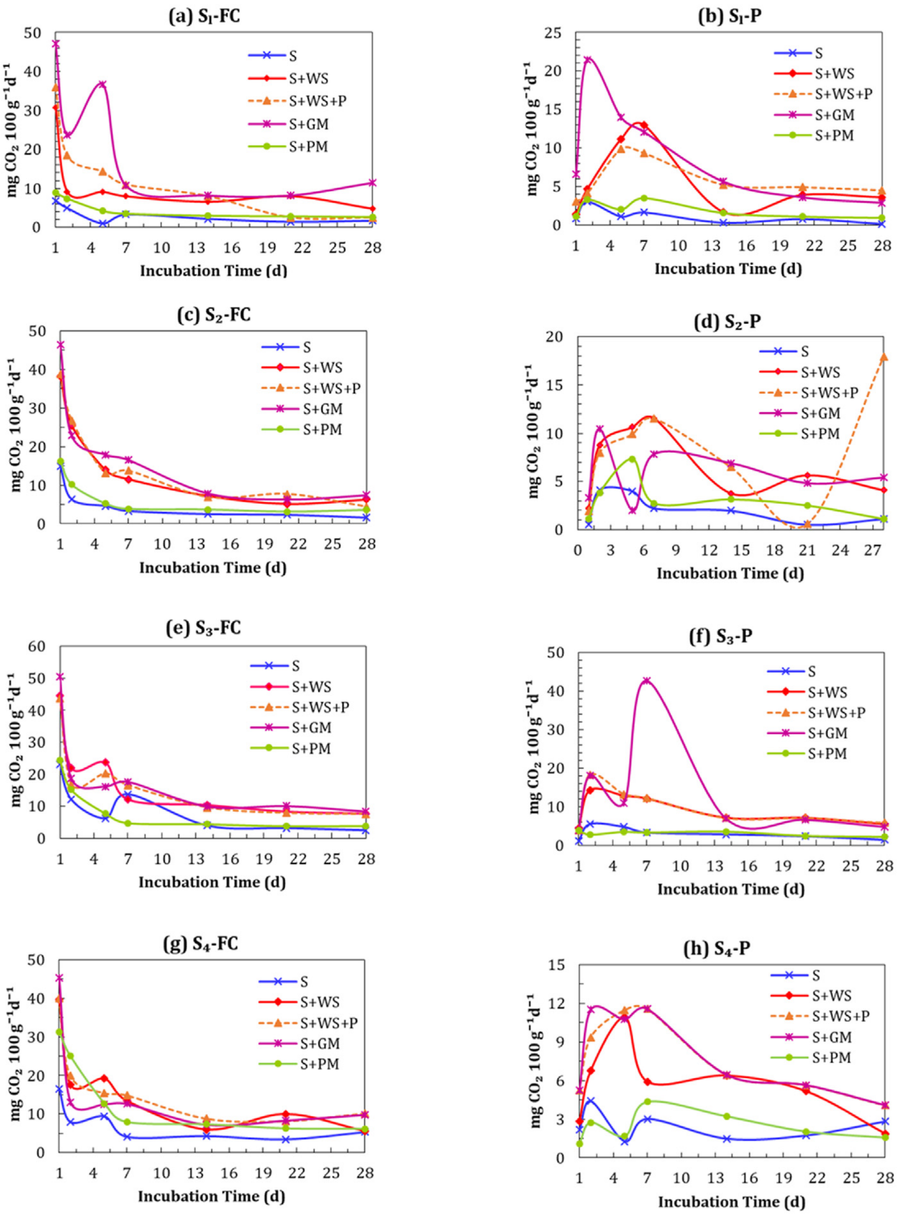

Fig. 1. (a–h). Daily CO_2-C evolution rate at field capacity (FC) and ponding (P) moisture levels.

and it varied from 1.6 to 2.5 mg 100 g^{-1} d^{-1} at FC for soils with 0.42 and 0.67% organic carbon, respectively. Under the P moisture regime, the CO_2-C evolution rate was slower during the first d and then reached a peak of 3.0, 4.1, 5.5, and 4.4 mg 100 g^{-1} d^{-1} in soils with initial OC contents of 0.26, 0.42, 0.67 and 0.82%, respectively, at 2^{nd} d of incubation (Fig. 1 b, d, f, and h). The increase in CO_2-C evolution rate at the 2^{nd} d over the 1st d varied between 2.0 and 7.5 times with a subsequent decline.

As the four soils differed in native SOC contents (0.26–0.82%, Table 1.), their incubation resulted in differential amounts of cumulative CO_2-C evolution (Fig. 2 a, c, e & g). In 28 d at FC moisture, the highest amount (152.9 mg CO_2-C 100 g^{-1} soil) evolved from S_4 having the highest SOC of 0.82% (Fig. 2g.) while the lowest amount of 58.8 mg CO_2-C 100 g^{-1} from S_1 with the least SOC of 0.26% (Fig. 2a). The amount of CO_2-C evolved up to 21 d of incubation was in the order: $S_3>S_4>S_2>S_1$. However, after 28 d it was $S_4>S_3>S_2>S_1$. Lower CO_2-C evolution was observed in ponding than in FC (Fig. 2.). The amounts of CO_2-C evolved at FC and P were 19.3 and 58.8 mg 100 g^{-1}, respectively in S_1. Only 18.6–22.6% and 7.4–11.0% of the native SOC content was mineralized up to 28 d of incubation at FC and P moisture levels, respectively. The ponding of soils resulted in a lowering of the evolution of CO_2-C by 51.3–60.2% of the FC. The results that in addition to native SOC content, the moisture content also strongly influences the decomposition of organic matter, have earlier been reported by several researchers (Orchard & Cook, 1983; Yin et al., 2019; Zaman & Chang, 2004). It may be attributed to the

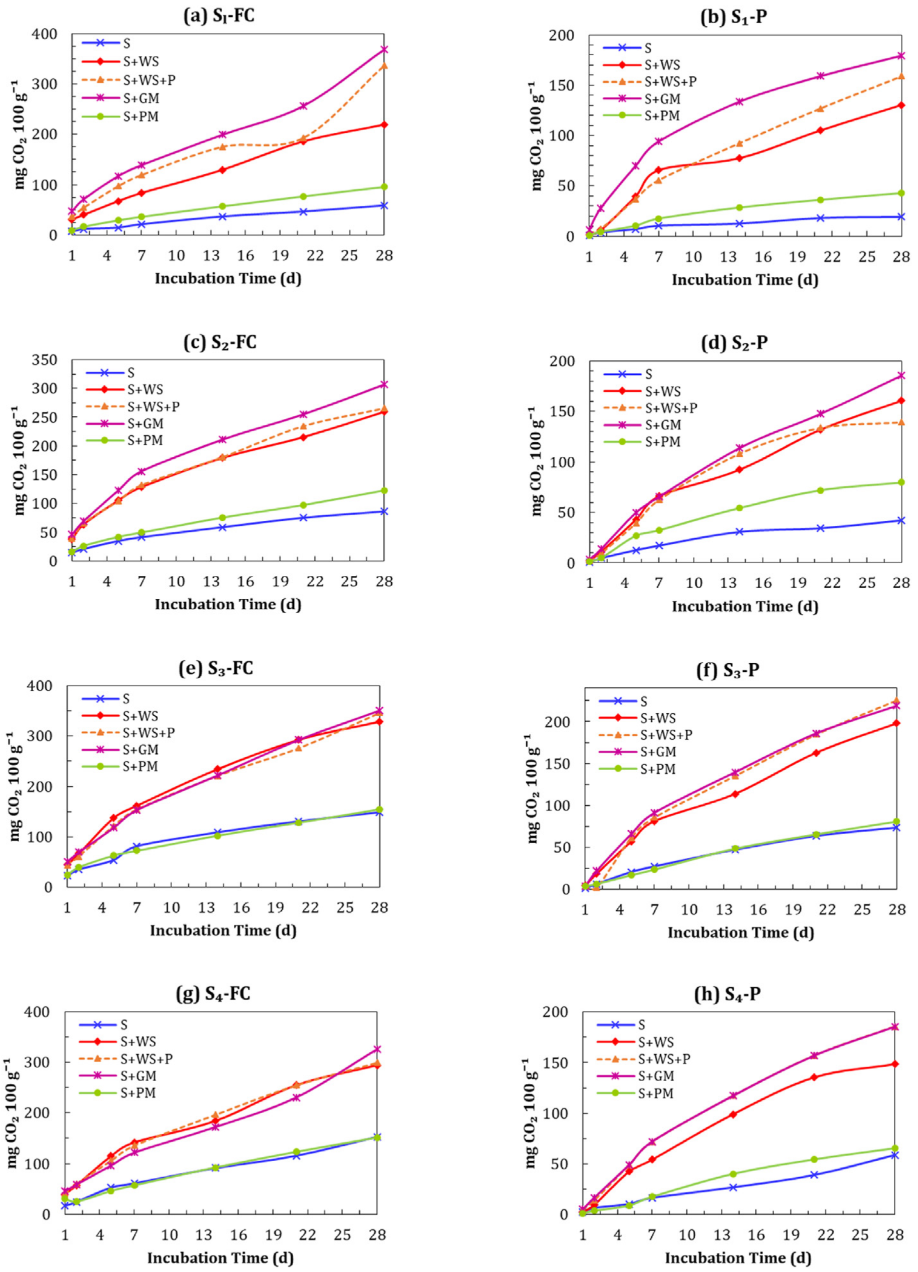

Fig. 2. (a–h). Cumulative CO_2-C at field capacity (FC) and ponding (P) moisture levels.

lower microbial activity/respiration of the aerobic population at moisture contents higher than FC (Murwira et al., 1990; Yadav et al., 1989). The observation that the carbon mineralization and potentials are positively correlated to the CEC of the soil (higher in fine-textured S_4 and S_3 soils; Table 1.) was corroborated by Riffaldi et al. (1996).

3.2. Decomposition of applied organic matter

The organic materials differed considerably both in the total amounts and rates of carbon mineralization. Irrespective of the organic materials added there was an initial flush (4–5 d) of CO_2-C followed by a slow rate (Fig. 1.). During this time the CO_2-C evolution from S_1 ranged between 36.7 and 47.2 mg CO_2-C 100 g^{-1}, 14.3–36 mg CO_2-C 100 g^{-1} d^{-1}, 9.2–30.8 mg CO_2-C 100 g^{-1} and 4.2–8.9 mg CO_2-C 100 g^{-1} in GM, WS + P, WS and PM treatments. Similarly, in soils with 0.42, 0.67, and 0.82% OC, the rate of CO_2-C evolution from GM treatment ranged between 17.9 and 46.5, 16.1–50.6, and 12.6–45.4 mg CO_2-C 100 g^{-1} d^{-1}, respectively. Similar results of higher daily mineralization rates during the first week ranging between 8.3–44.8 and 7.6–24.6 mg CO_2-C 100 g^{-1} d^{-1} for GM and WS, respectively have been reported by Benbi and Khosa (2014). The WS + P application to these soils gave CO_2-C evolution rates of 13.1–38.8, 16.8–43.7, and 15.4–40 mg CO_2-C 100 g^{-1} d^{-1}. The CO_2-C evolution rate in S_2, S_3, and S_4 soils treated with WS was 13.9–38.2, 22.0–44.6, 17.6–39.6 mg CO_2-C 100 g^{-1} d^{-1} and 5.2–6.2, 7.7–24.5, 25.1–31.4 mg CO_2-C 100 g^{-1} d^{-1} in PM treated soils having 0.26, 0.42 and 0.82% native OC.

After the first flush, the CO_2-C evolution rate declined and it was the least on the 28th d of incubation. At the 28th d incubation stage and FC moisture, the rate of CO_2-C evolution from four soils (range; minimum to maximum) varied between 1.6 and 5.3 mg CO_2-C 100 g^{-1} d^{-1}. Similarly, the CO_2-C evolution rates from soils treated with GM, WS + P, WS, and PM varied from 7.4 to 11.5, 2.5–10.1, 4.8–7.7, and 2.7–6.2 mg CO_2-C g^{-1} d^{-1}, respectively at FC moisture at the 28th d.

At FC moisture, the highest amounts of 368.5, 306.7, 350.7, and 325.6 mg CO_2-C 100 g^{-1} evolved from the decomposition of GM in treated S_1, S_2, S_3, and S_4, respectively. While in WS + P treatment 336.6, 265.3, 346.5, and 299.1 mg CO_2-C 100 g^{-1}, WS; 219.4, 259.3, 328.9, and 294.2 mg 100 g^{-1} and the least amounts of 95.4, 122.9, 154.5 and 151.7 mg CO_2-C 100 g^{-1} soil were evolved from PM treated S_1, S_2, S_3, and S_4 in 28 d (Fig. 2.) at FC. The least amount of CO_2-C evolved from PM-treated soils as compared to other organics may be due to the higher anaerobic digestion in PM and higher cellulose fraction (Table 2). The application of P significantly enhanced the CO_2-C evolution rate and total amount only in the S_1 testing medium in available P (Table 1.). The addition of P to WS enhanced the CO_2-C evolution to 9.4–16.9% and 6.9–7.6% of added carbon at FC and P moisture regimes, respectively. Similar results on the effect of added P on residue decomposition have earlier been reported by Saggar et al. (2000) and Connell and Mendham (2004). Averaged over four soils, the cumulative CO_2-C evolved in 28 d of incubation was 192.3, 177.3, 146.3, and 67.3 mg 100 g^{-1} soil from GM, WS + P, WS, and PM treated soils. At FC moisture 7.7 to 10.8 percent of WS-added carbon was mineralized in 28 d in all the soils. At P moisture its mineralization was further reduced only to 4.9–6.1%. Only 2% of the PM carbon was mineralized in S_1 and S_2, whereas a value of 3.3% was observed in S_3. There was immobilization of PM carbon S_4 (SOC; 0.82%) (see Table 3).

3.3. Kinetics of carbon mineralization

The cumulative data fitting (Tables, 3–7 & Figs. 3–7) to all of the three non-linear regression models yielded a high coefficient of determination (R^2) and low rRMSE values indicating fairly good carbon mineralization prediction. As reported previously (Benbi & Khosa, 2014) FO kinetic model was the best fit but it varied with the soil and its moisture. The two-component first-order model behaved the same way as that of the mono-component. It may be

Table 3
Kinetic parameters of the first order (single and two-component) and modified Gompertz models in different soils with different moisture contents.

Model	*E*	*C_m*	*K_m*	*C_r*	*K_r*	*λ*	*R_m*
S_1	58.8, 19.3	–	–	–	–	–	–
FO	–	95.5, 21.3	0.03	–	–	–	–
FOTC	–	78.2, 21.4	0.04, 0.08	0, 238.6	0.03, 0	–	–
MGM	–	64.9, 18.7	–	–	–	0, 0	2.7, 1.3
S_2	86.3, 42.1						
FO	–	89.2, 53.4	0.09, 0.05	–	–	–	–
FOTC	–	78.3, 42.1	0.1, 0.08	32.7, 346.6	0.01, 0	–	–
MGM	–	81.8, 40.5	–	–	–	0, 0.7	5.8, 2.6
S_3	148.9, 73.7	–	–	–	–	–	–
FO	–	153.5, 109.4	0.01, 0.04	–	–	–	–
FOTC	–	9.3, 109.3	0.4, 0.04	159.6, 0	0.09, 0.02	–	–
MGM	–	149.9, 76.6	–	–	–	0.6, 0.6	3.9, 7.7
S_4	152.9, 86.3	–	–	–	–	–	–
FO	–	182.6, 89.2	0.06, 0.09	–	–	–	–
FOTC	–	0, 17.3	0, 0.9	746.0, 113.6	0.00, 0.03	–	–
MGM	–	149.9, 342.8	–	–	–	0.6, 0	7.7, 3.3

The E, C_m, and C_r, represent experimental and simulated carbon mineralization potentials (mg CO_2-C 100 g^{-1}), of decomposable and recalcitrant carbon fractions corresponding to each model (FO; first order, FOTC; first order two-component and MGM; modified Gompertz models, respectively); K_m and K_r (d^{-1}) represent the disintegration rate constants; λ and R_m (mg CO_2-C 100 g^{-1} d^{-1}) represent the lag phase (d) and maximum daily rate (mg 100 CO_2-C g^{-1} d^{-1}) of carbon mineralization from Modified Gompertz model.

Table 4
Kinetic parameters of the first order (single and two-component) and modified Gompertz models of WS in different soils with different moisture contents.

Model	*E*	*C_m*	*K_m*	*C_r*	*K_r*	*λ*	*R_m*
S_1	160.5, 111.7	–	–	–	–	–	–
FO	–	209.8, 145.6	0.05, 0.05	–	–	–	–
FOTC	–	215.5, 145.6	0.05, 0.05	0.1, 0	0.014, 0	–	–
MGM	–	200.0, 106.2	–	–	–	0, 0.34	2.3, 5.9
S_2	173.0, 118.5						
FO	–	170.8, 215.9	0.1, 0.03	–	–	–	–
FOTC	–	58.9, 286.2	0.4, 0.02	573.7, 0	0.01, 0.01	–	–
MGM	–	681.8, 134.9	–	–	–	0, 0.3	6.5, 5.2
S_3	180.0, 124.4	–	–	–	–	–	–
FO	–	192.7, 181.3	0.09, 0.04	–	–	–	–
FOTC	–	66.1, 181.3	0.27, 0.06	429.4, 0	0.0, 0.01	–	–
MGM	–	643.9, 137.4	–	–	–	0, 0	7.1, 5.4
S_4	141.3, 89.6	–	–	–	–	–	–
FO	–	147.3, 119.8	0.1, 0.06	–	–	–	–
FOTC	–	55.6, 119.8	0.4, 0.06	436.6, 0	0, 1.7	–	–
MGM	–	602.3, 93.5	–	–	–	0.6, 0	5.6, 10.7

The E, C_m, C_r, represent experimental and simulated carbon mineralization potentials (mg CO_2-C 100 g^{-1}), of decomposable and recalcitrant carbon fractions corresponding to each model (FO; first order, FOTC; first order two-component and MGM; modified Gompertz models, respectively); K_m and K_r (d^{-1}) represent the disintegration rate constants; λ and R_m (mg CO_2-C 100 g^{-1} d^{-1}) represent the lag phase (d) and maximum daily rate (mg CO_2-C 100 g^{-1} d^{-1}) of carbon mineralization from Modified Gompertz model.

Table 5
Kinetic parameters of the first order (single and two-component) and modified Gompertz models of WS + P in different soils with different moisture contents.

Model	*E*	C_m	K_m	C_r	K_r	λ	R_m
S_1	277.7, 140.0	–	–	–	–	–	–
FO	–	452.1, 365.1	0.03, 0.02	–	–	–	–
FOTC	–	162.6, 126.0	0.05, 0.02	404.5, 299.2	0.01, 0.01	–	–
MGM	–	200.0, 106.2	–	–	–	98.7, 1.4	221.7, 6.5
S_2	179.0, 97.2						
FO	–	170.8, 215.9	0.09, 0.1	–	–	–	–
FOTC	–	40.7, 128.2	0.6, 0.1	240.7, 45.5	0.03, 0	–	–
MGM	–	681.8, 134.9	–	–	–	0, 1.8	6.9, 8.2
S_3	197.6, 151.8	–	–	–	–	–	–
FO	–	322.5, 276.6	0.07, 0.03	–	–	–	–
FOTC	–	26.1, 258.4	0.6, 0.03	503.6, 343.6	0.01,0.0	–	–
MGM	–	465.5, 156.4	–	–	–	0, 1.1	7.2, 7.6
S_4	146.2, 126.5	–	–	–	–	–	–
FO	–	159.0, 165.5	0.09, 0.06	–	–	–	–
FOTC	–	29.6, 167.6	0.5, 0.05	173.1, 8.5	0.04, 0.01	–	–
MGM	–	573.6, 126.2	–	–	–	0, 1.0	5.8, 8.4

The E, C_m, C_r, represent experimental and simulated carbon mineralization potentials (mg CO_2-C 100 g^{-1}), of decomposable and recalcitrant carbon fractions corresponding to each model (FO; first order, FOTC; first order two-component and MGM; modified Gompertz models, respectively)*;* K_m and K_r (d^{-1}) represent the disintegration rate constants*;* λ and R_m (mg CO_2-C 100 g^{-1} d^{-1}) represent the lag phase (d) and maximum daily rate (mg CO_2-C 100 g^{-1} d^{-1}) of carbon mineralization from Modified Gompertz model.

Table 6
Kinetic parameters of the first order (single and two-component) and modified Gompertz models of GM in different soils with different moisture contents.

Model	*E*	C_m	K_m	C_r	K_r	λ	R_m
S_1	309.6, 160.1	–	–	–	–	–	–
FO	–	394.1, 172.5	0.05, 0.09	–	–	–	–
FOTC	–	362.5, 140.7	0.05, 0.1	322.8, 124.8	0.02, 0.01	–	–
MGM	–	844.7, 500.0	–	–	–	0, 13.7	10.8, 7.6
S_2	220.3, 143.4						
FO	–	219.3, 273.3	0.1, 0.03	–	–	–	–
FOTC	–	71.1, 120.2	0.4, 0.04	386.9, 252.6	0.02, 0.01	–	–
MGM	–	853.4, 158.3	–	–	–	0, 0.6	8.3, 6.5
S_3	201.8, 145.2	–	–	–	–	–	–
FO	–	282.8, 185.7	0.04, 0.05	–	–	–	–
FOTC	–	21.4, 108.4	4.2, 0.07	676.8, 203.8	0.01, 0.01	–	–
MGM	–	501.9, 145.8	–	–	–	0, 0	7.5, 7.6
S_4	172.7, 126.5	–	–	–	–	–	–
FO	–	331.0, 71.6	0.02, 0	–	–	–	–
FOTC	–	19.7, 157.5	5.3, 0.06	976.5, 274.8	0.01, 0	–	–
MGM	–	500, 126.7	–	–	–	1.8, 0.9	6.3, 8.2

The E, C_m, C_r, represent experimental and simulated carbon mineralization potentials (mg CO_2-C 100 g^{-1}), of decomposable and recalcitrant carbon fractions corresponding to each model (FO; first order, FOTC; first order two-component and MGM; modified Gompertz models, respectively)*;* K_m and K_r (d^{-1}) represent the disintegration rate constants*;* λ and R_m (mg 100 g^{-1} d^{-1}) represent the lag phase (d) and maximum daily rate (mg CO_2-C 100 g^{-1} d^{-1}) of carbon mineralization from Modified Gompertz model.

Table 7
Kinetic parameters of the first order (single and two-component) and modified Gompertz models of PM in different soils with different moisture contents.

Model	*E*	C_m	K_m	C_r	K_r	Λ	R_m
S_1	36.6, 23.6	–	–	–	–	–	–
FO	–	49.6, 139.5	0.05, 0.01	–	–	–	–
FOTC	–	6.7, 16.6	0.4, 0.02	140.9, 129.6	0.01, 0.01	–	–
MGM	–	39.5, 23.2	–	–	–	0, 2.5	1.7, 1.4
S_2	36.6, 37.6						
FO	–	55.0, 53.3	0.03, 0.05	–	–	–	–
FOTC	–	0.2, 47.6	0.5, 0.01	186.4, 159.6	0.01, 0.01	–	–
MGM	–	158.7, 39.5	–	–	–	1.0, 0.8	2.0, 2.3
S_3	5.7, 7.2	–	–	–	–	–	–
FO	–	0, 210.5	0.01, 0	–	–	–	–
FOTC	–	0, 0	0.53, 0.02	0, 72.5	0.01, 0	–	–
MGM	–	602.3, 87.1	–	–	–	0, 26.6	5.6, 2.0
S_4	−1.14, 6.6	–	–	–	–	–	–
FO	–	2.6, 29.3	0.04, 0.2	–	–	–	–
FOTC	–	0.0, 20.9	0.6, 0.2	62.8, 325.0	0, 0	–	–
MGM	–	1.0, 11.8	–	–	–	0, 6.9	0, 8.8

The E, C_m, C_r, represent experimental and simulated carbon mineralization potentials (mg CO_2-C 100 g^{-1}), of decomposable and recalcitrant carbon fractions corresponding to each model (FO; first order, FOTC; first order two-component and MGM; modified Gompertz models, respectively); K_m and K_r (d^{-1}) represent the disintegration rate constants*;* λ and R_m (mg CO_2-C 100 g^{-1} d^{-1}) represent the lag phase (d) and maximum daily rate (mg CO_2-C 100 g^{-1} d^{-1}) of carbon mineralization from Modified Gompertz model.

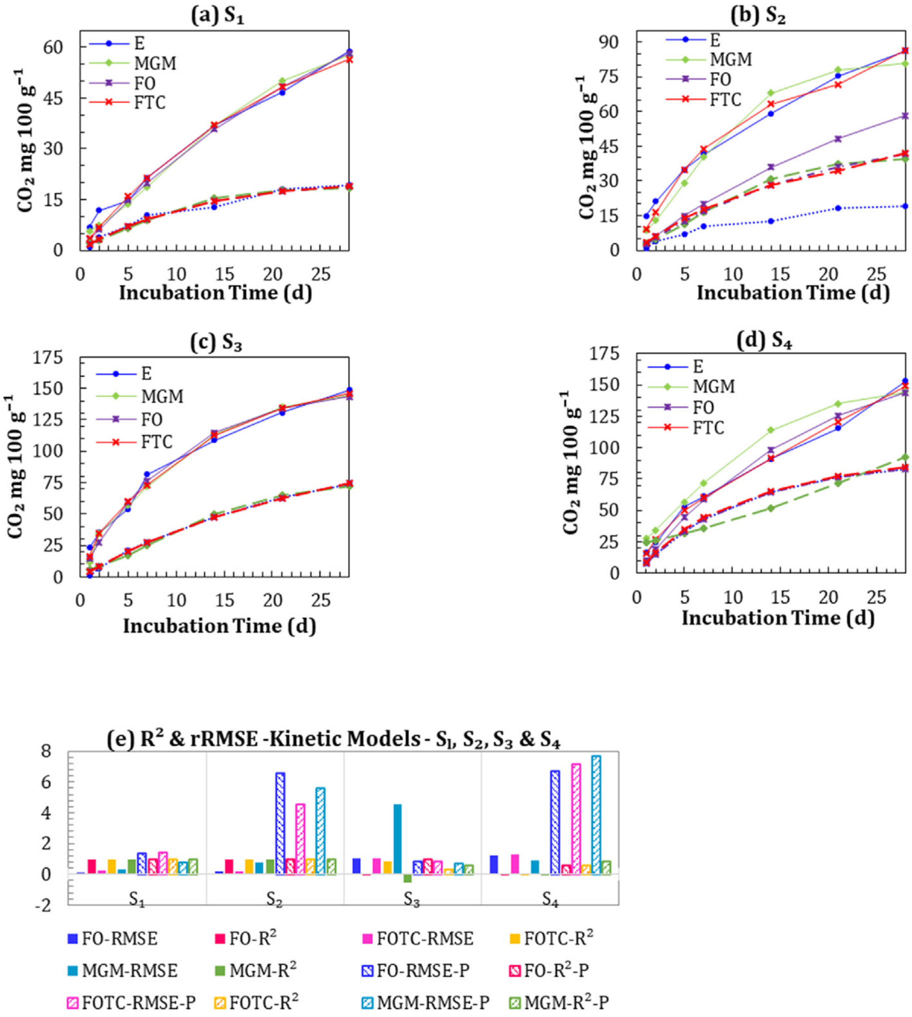

Fig. 3. (a–**e**). Experimental and model (FO; first order; FOTC, first order two component, MGM, modified Gompertz model) simulated cumulative CO_2-C (mg 100 g^{-1}) of four soils at field capacity (solid lines) and ponding moisture (dotted lines) levels, **(e)** Coefficient of determination (R^2) and relative root mean square errors (rRMSE) corresponding to each model at both moisture levels.

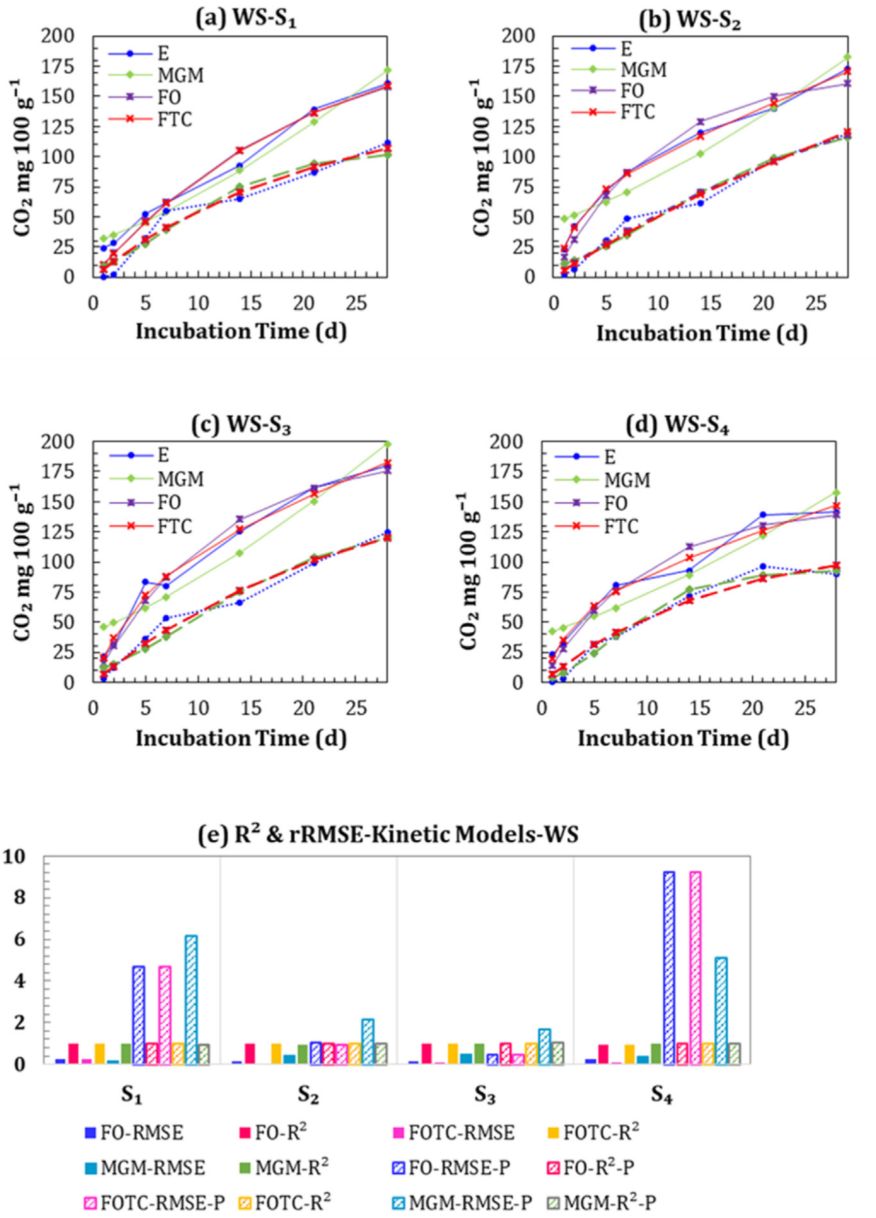

Fig. 4. (a–**e**). Experimental and model (FO; first order; FOTC, first order two component, MGM, modified Gompertz model) simulated cumulative CO_2-C (mg 100 g^{-1}) of wheat straw (WS) in four soils at field capacity (solid lines) and ponding moisture (dotted lines) levels, **(e)** Coefficient of determination (R^2) and relative root mean square errors (rRMSE) corresponding to each model at both moisture levels.

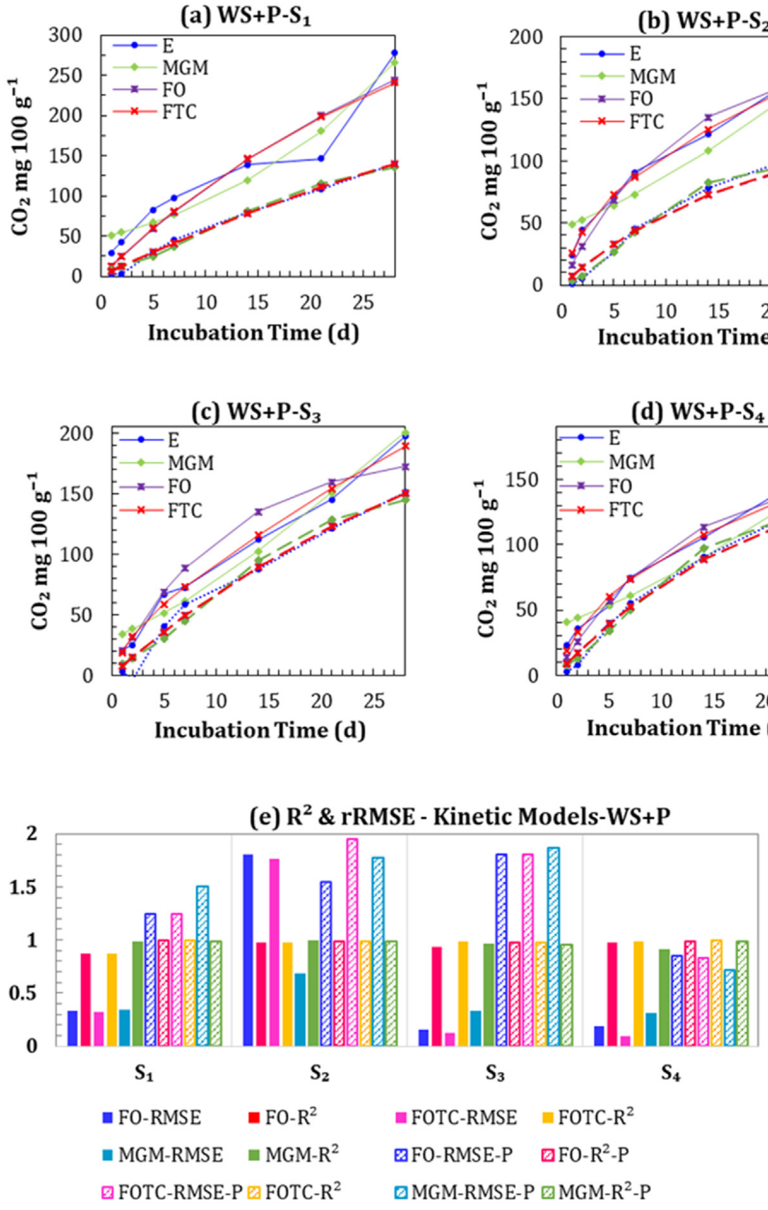

Fig. 5. (a–**e**). Experimental and model (FO; first order; FOTC, first order two component, MGM, modified Gompertz model) cumulative CO_2-C (mg 100 g^{-1}) of wheat straw with supplemental phosphorus (WS + P) in four soils at field capacity (FC, solid lines) and ponding moisture (P, dotted lines) levels, **(e)** Coefficient of determination (R^2) and relative root mean square errors (rRMSE) corresponding to each model at both moisture levels.

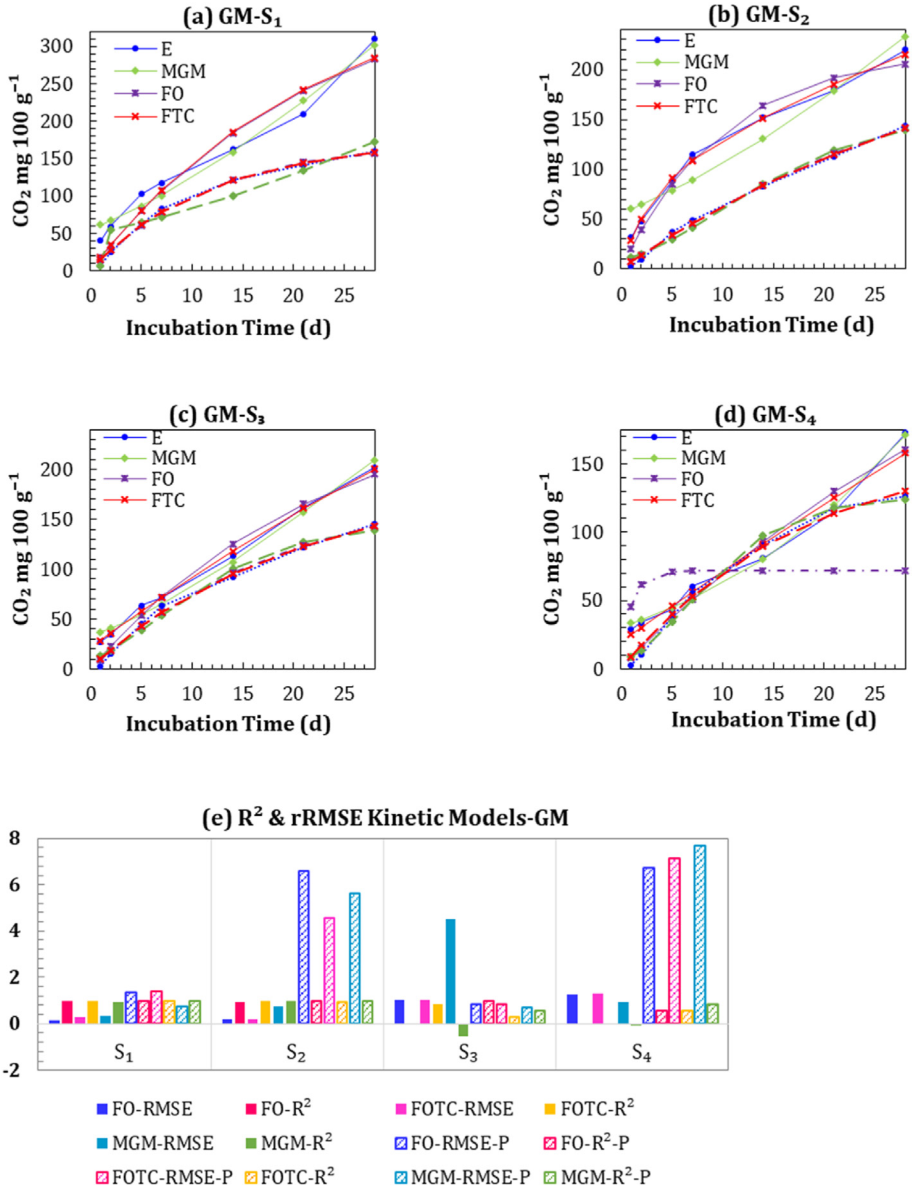

Fig. 6. (a–**e**). Experimental and model (FO; first order; FOTC, first order two component, MGM, modified Gompertz model) simulated cumulative CO_2-C (mg 100 g^{-1}) of green manure (GM) in four soils at field capacity (FC, solid lines) and ponding moisture (P, dotted lines) levels, **(e)** Coefficient of determination (R^2) and relative root mean square errors (rRMSE) corresponding to each model at both moisture levels.

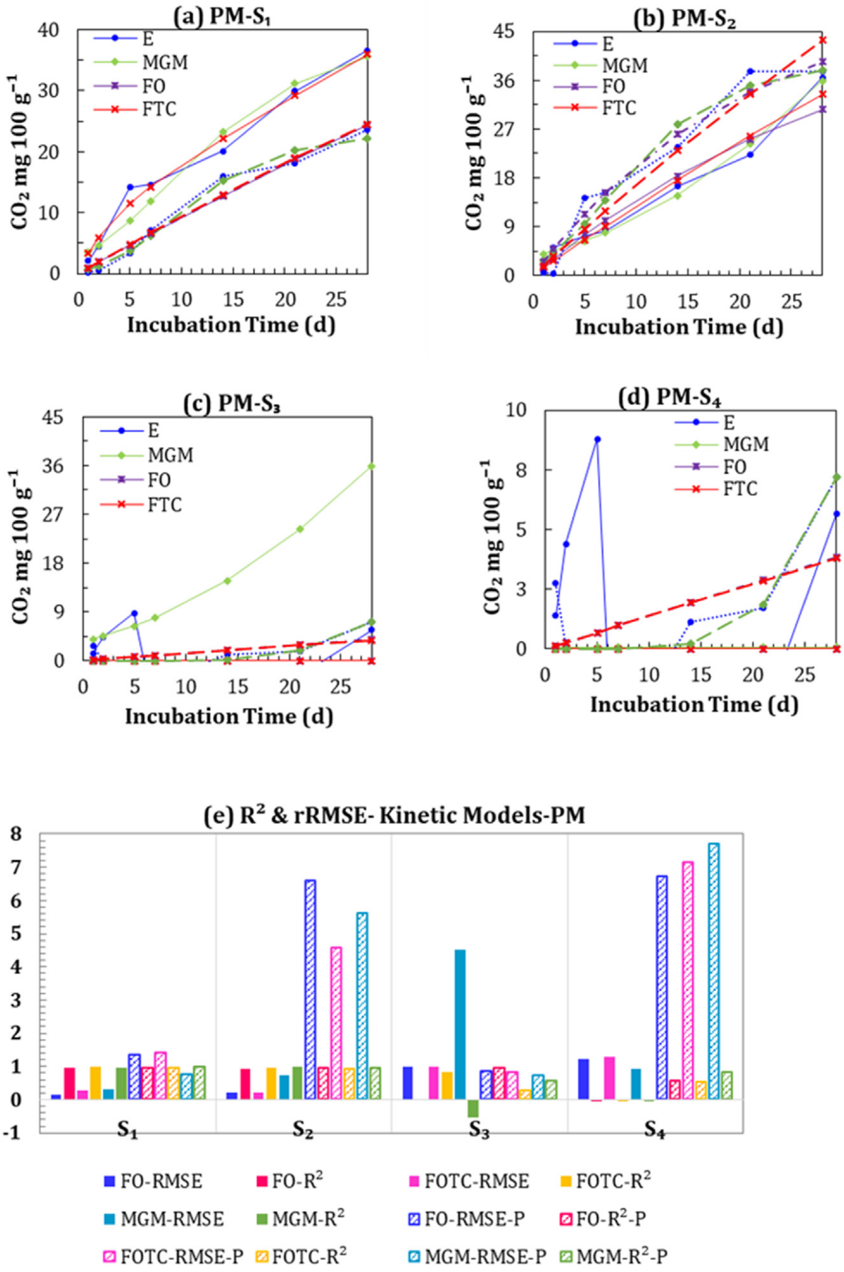

Fig. 7. (a–**e**). Experimental and model (FO; first order, FOTC; first order two component, MGM; modified Gompertz models) simulated cumulative CO_2-C (mg 100 g^{-1}) of poultry manure (PM) in four soils at field capacity (FC, solid lines) and ponding moisture (P, dotted lines) levels, **(e)** Coefficient of determination (R^2) and relative root mean square errors (rRMSE) corresponding to each model at both moisture levels.

due to the extra time for the recalcitrant carbon to start mineralization. A similar observation in an incubation study was reported by Riffaldi et al. (1996). The potentially mineralizable C (or mineralization potential; Fig. 8) in direct proportion to the soil carbon content is called normalized mineralization potential (Riffaldi et al., 1996). The normalized mineralization potential over the native soil carbon was determined by dividing the experimental and simulated values of each soil by their corresponding SOC contents (Table 1.). The experimental and simulated normalized mineralization potential was 0.2 for SOC in all experimental soils at FC. Similarly, at P, simulated and experimental values were 0.1 in S_2, S_3, and S_4, while the simulated varied between 0.02 and 0.07 in S_1. The highest mineralization potential per unit of added carbon (500 mg carbon through each residue treatment) 0.6 (for WS and GM) was observed in S_1 while the least (0.3) in S_4. The same trend of the highest and the lowest (two and three times lower than FC, respectively) was observed at the P moisture level. Among amendments; the simulated normalized mineralization potential of WS was the highest (0.4) in S_3 and S_1 and similar (0.3) in the rest of the soils at FC. The S_1 had the least available P (Table 1), consequently, the additional P application increased the experimental normalized mineralization potential to 0.6 at FC.

The mineralization rate constant (K_m) for WS varied between 0.05 and 0.1 (S_1 and S_4) at FC and 0.03 (S_2) to 0.06 (S_4) at P moisture levels. The WS disintegrated at higher rates of 0.09 per d in S_2 and S_4 at FC and 0.1 in S_2 at P with the addition of phosphorus. It may be

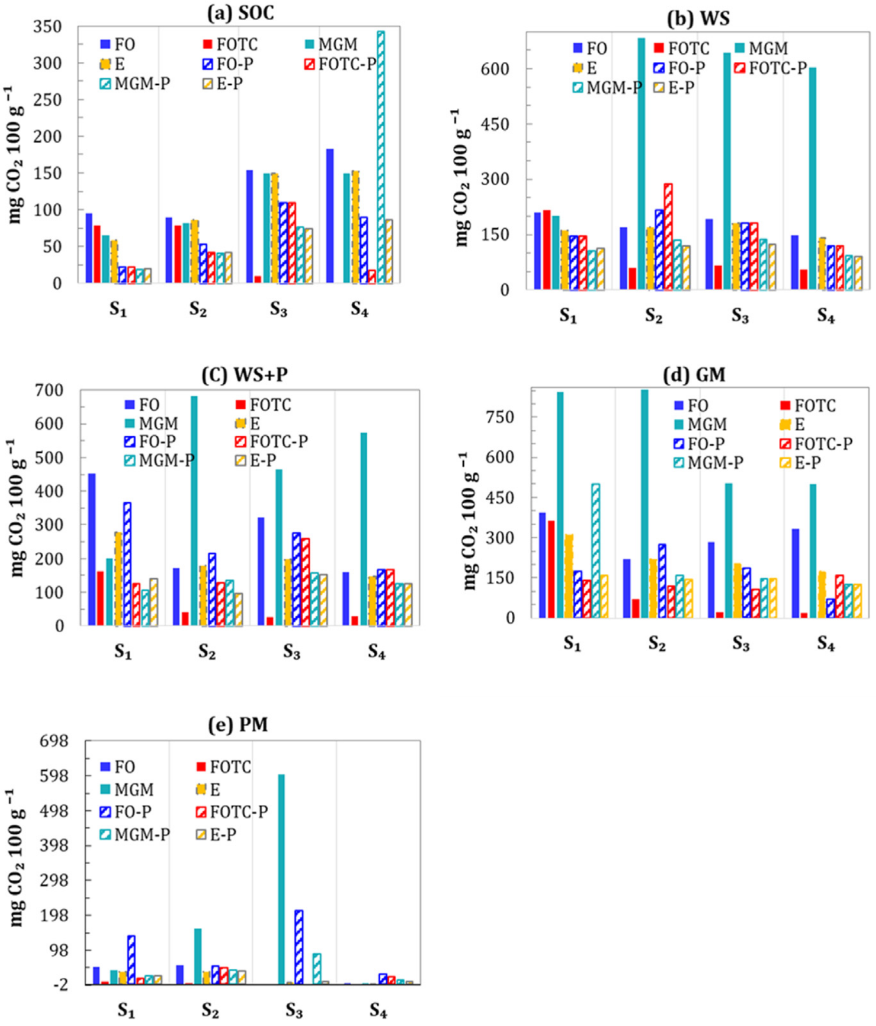

Fig. 8. (a–e). Experimental and simulated mineralization potentials (mg CO_2-C 100 g^{-1}) for native (SOC), wheat straw (WS), green manure (GM) and poultry manure (PM) added carbon in different soils at FC and P moisture (pattern columns).

due to the lower native available P content in these soils (38.2 and 36.0 kg ha^{-1}; Table 1). Although the S_1 had the least available P (Table 1) there was not any effect on kinetics with additional P application. It may be due to N insufficiency for microbial growth as S_1 was deficient (2.8 kg ha^{-1}) in mineral N (Table 1.). The highest mineralization rate constant of 0.1 was observed in S_2, whereas a little lower value of 0.09 was observed in S_1. The carbon added through PM was hardly decomposable at both moisture levels in S_3 and S_4 and was reflected by the kinetic models too.

Martín et al. (2012) report 20 and 12% mineralization of PM carbon in acidic and basic soils having 11 and 35% clay contents, respectively. Murwira et al. (1990) reported the highest mineralization (22.7 mg CO_2-C g^{-1}) at 48% of FC and attributed the lower carbon mineralization at higher moisture levels to lower aerobic activity than anaerobic at ponding. Yin et al. (2019) also stated that the optimum moisture for carbon mineralization was 30% of WHC in top soils. Our observation that both the potentially mineralizable pools and the rates of disintegration varied among soils and the residue depending upon their properties, clay content most prominently was in agreement with previous studies (Martín et al., 2012; Riffaldi et al., 1996; Saroa & Lal, 2003).

3.4. *Effect of organic amendments on soil organic and inorganic carbon contents*

The SOC varied among test soils upon incubation (Fig. 9.). Generally it increased after 1 d at both moisture regimes. In S_1 and S_2 (low to medium SOC; 0.26–0.42%), the OC increased by 76.9 and 33.3%, respectively of the initial contents but in S_3 and S_4 (0.67–0.82), it declined by 6 and 16.3%, respectively of the initial values after 45 d at FC. The decline in OC content with time may be due to the loss of C as CO_2-C during organic matter decomposition.

The addition of organic materials increased the OC content in all the soils (Fig. 9.). After 1 d incubation, the highest increase in SOC was observed with the addition of GM at both moisture levels. The differences in SOC treated with different organics narrowed down subsequently indicating the fast decomposition of GM, attributed to its favorable C-to-N ratio of 15.5 for microbial degradation (Brust, 2019). The lower OC content in WS + P treated soil testing medium in available P indicates that phosphorus application to low P soils enhanced the organic matter decomposition by the microbial process leading to higher CO_2-C evolution, hence the buildup of carbon was lower in WS + P treatment as compared to WS alone.

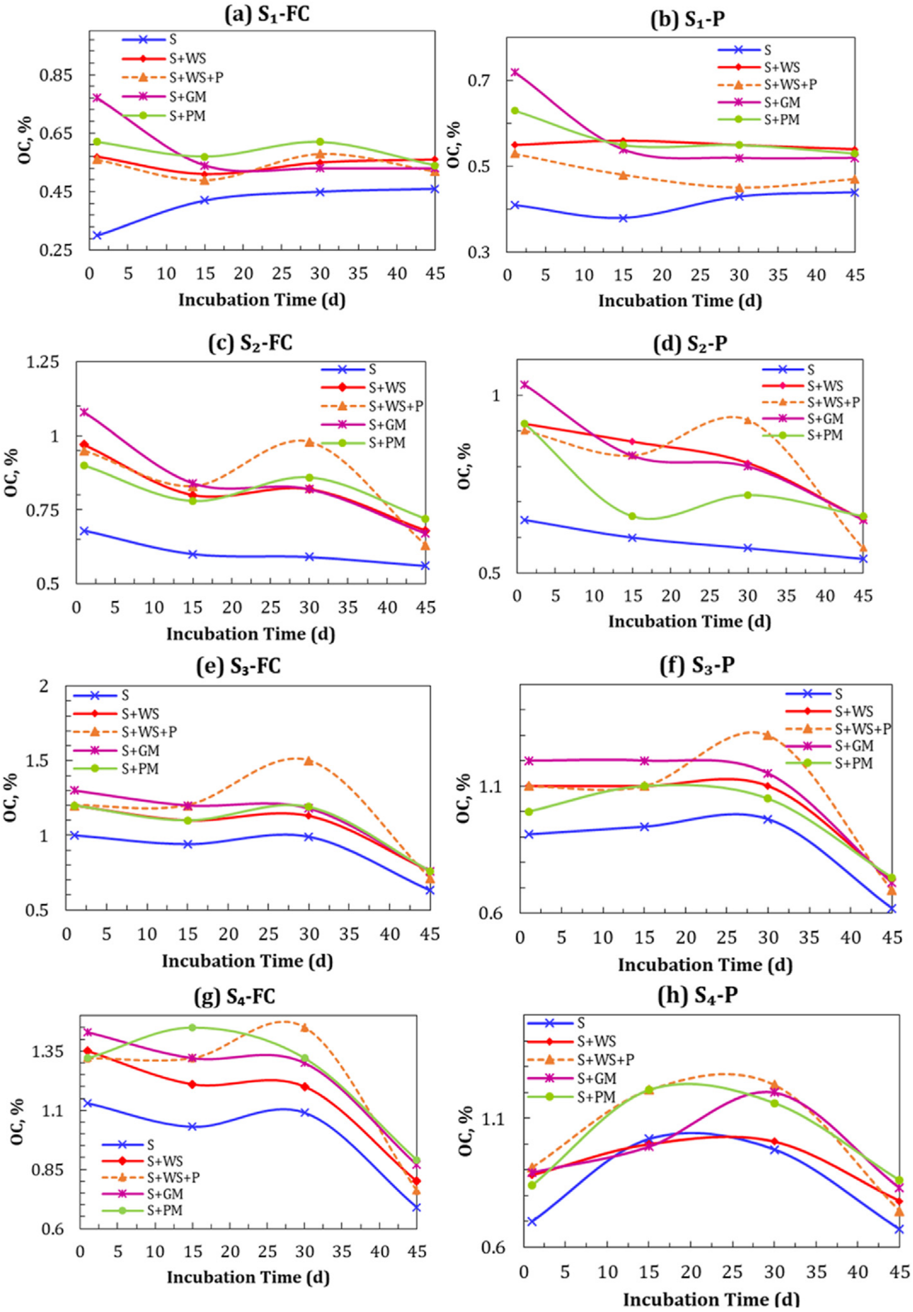

Fig. 9. (a–h). Soil organic carbon (%) at field capacity (FC) and ponding (P) moisture levels.

After 45 d of incubation, SOC content (initial SOC + added carbon) in different organic matter treatments declined by 0.22–0.29, 0.26–0.35, 0.43–0.48, and 0.46–0.58% in S_1, S_2, S_3, and S_4, respectively. This decline followed the SOC content. Similar results were observed under the ponding moisture regime, except that organic carbon after one day was higher under ponding than FC in S_1 only whereas in other soils it was lower. The OC content under P moisture decreased with increasing incubation time. It may be concluded that in soil having low to medium OC content, it increased while in other soils it decreased upon incubation. The finding that the addition of organic materials increases the OC content in the soils (Fig. 9.) depending upon their carbon saturation levels is also corroborated by previous studies (Gentile et al., 2011; Rasmussen et al., 1980; Stewart et al., 2009).

Irrespective of the organic matter treatment and moisture level there was a gradual decline in $CaCO_3$ content with time (Fig. 10.). However, after 45 d of incubation without the addition of organics, the $CaCO_3$ content of soils declined to 0.61–1.54% and 0.73–1.85% at FC and P moisture conditions, respectively. At the 45th d stage of incubation of the organic materials, $CaCO_3$ was 22.2, 18.9, 23.2, and 21.7% of its initial status (2.7, 7.9, 5.6, and 4.6%) S_1, S_2, S_3, and S_4, respectively at FC. The higher $CaCO_3$ content at the P (both in treated and untreated soils) may be attributed to its lower contribution towards CO_2 as compared to FC moisture conditions.

It was observed that organic matter addition further leads to the depletion of $CaCO_3$ over control soils. The extent of depletion of

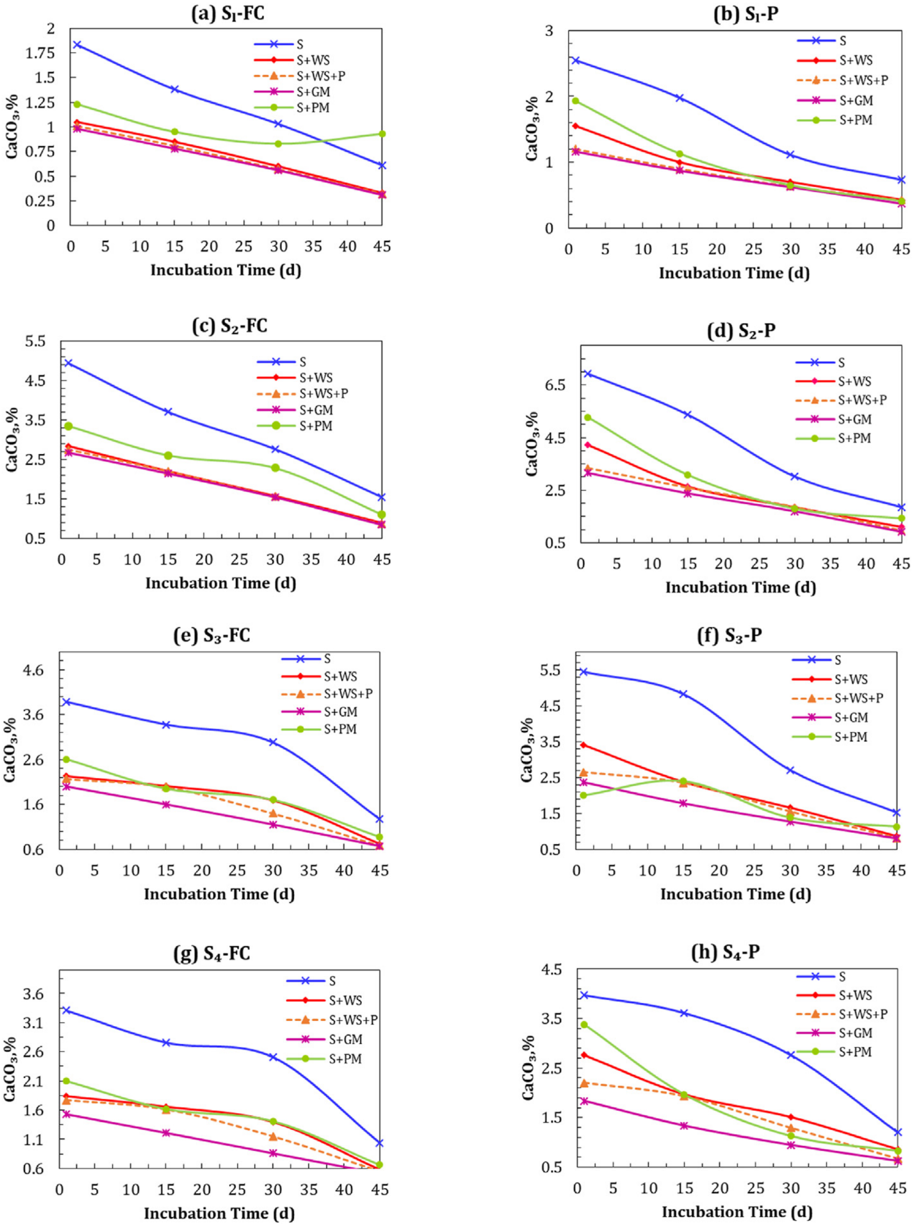

Fig. 10. (a–h). The $CaCO_3$ (%) in soils S_1, S_2, S_3, and S_4 at field capacity (FC) and ponding (P).

$CaCO_3$ followed the order of CO_2-C evolution from mineralizing organic residues. The $CaCO_3$ depletion was maximum in GM-treated soils followed by WS + P, WS, and PM-treated soils. The difference in $CaCO_3$ depletion among organics narrowed down with increasing incubation time. The CO_2 evolved by decomposing organics neutralizes $CaCO_3$ in residue-treated soils (Hyatt et al., 1958).

4. Conclusion

The carbon mineralization potential of soils varied with the native SOC, moisture content, and other soil properties. When the residues of WS, GM, and PM in amounts of similar net carbon were added to each soil under similar temperature and moisture conditions the mineralized and organic carbon build-ups also varied depending upon the soil and residue characteristics. Although the optimum moisture for carbon mineralization is 40–50% of FC, the FC moisture was chosen from the carbon build-up point of view. A higher carbon build-up was observed under ponding than in FC. We conclude that adding 0.5% organic carbon by WS, GM, and P will result in carbon build-up of a similar 0.1% in S_1 both at FC and P moisture levels in 45 d. While PM added the highest carbon (0.2 and 0.1% at FC and P, respectively) in S_2. In S_3 all residues raised the carbon level to 0.13% at both moisture levels. Whereas, the highest OC build-up (of 0.2% via PM) and the variation were observed in S_4 or Typic Halustalf. The residues added more carbon in higher OC soils compared to lower OC and were almost similar at both moisture levels. The FC and P soil conditions may be taken as representative of surface and sub-surface soil conditions in terms of anaerobic microbial activity. From the foregoing results, it may be concluded that the total amount of CO_2-C evolved followed the natural OC content of the soils. The amount of CO_2-C evolved from added organics, however, varied with plant biochemistry and soil characteristics. This research is one of the most comprehensive additions to the existing literature on the kinetics of carbon mineralization from crop residues of varied characteristics in soils from diverse origins under different environmental conditions. Thus this information may help tackle climate change and enhance the soil quality and crop yields in developing countries.

Declaration of competing interest

"Authors declare no significant competing financial, professional, or personal interests that might have influenced the performance or presentation of the work described in this manuscript."

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