International Journal of Plant & Soil Science

Volume 38, Issue 8, Page 796-805, 2026; Article no.IJPSS.164385
ISSN: 2320-7035

Temporal Dynamics of Soluble Carbon Pools in Surface Rice Soils under Alternating Oxic-anoxic Conditions in the Eastern Himalayan Terai Agro-ecological Region

Abhishek Sen [a++*], Dibyendu Mukhopadhyay [a#], Abhas Kumar Sinha [a#], Ganesh Chandra Banik [a†], Amrit Tamang [a‡], Partha Sarathi Patra [b‡], Manoj Kanti Debnath [c‡] and Rajib Das [d##]

[a] *Department of Soil Science and Agricultural Chemistry, Uttar Banga Krishi Viswavidyalaya, Pundibari, Coochbehar, West Bengal, India.*
[b] *Department of Agronomy, Uttar Banga Krishi Viswavidyalaya, Pundibari, Coochbehar, West Bengal, India.*
[c] *Department of Statistics, Uttar Banga Krishi Viswavidyalaya, Pundibari, Coochbehar, West Bengal, India.*
[d] *KVK, Khowai, Tripura, India.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijpss/2026/v38i86260

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/164385

Original Research Article

Received: 06/06/2026
Accepted: 11/08/2026
Published: 12/08/2026

[++] *PhD Research Scholars;* [#] *Professor;* [†] *Associate Professor;* [‡] *Assistant Professor;* [^] *Senior Scientist;* [##] *SMS, (Agricultural Extension);*
**Corresponding author: E-mail: connectabhishek1@gmail.com;*

Cite as: *Sen, A., Mukhopadhyay, D., Sinha, A. K., Banik, G. C., Tamang, A., Patra, P. S., ... Das, R. (2026). Temporal Dynamics of Soluble Carbon Pools in Surface Rice Soils under Alternating Oxic-anoxic Conditions in the Eastern Himalayan Terai Agro-ecological Region. International Journal of Plant & Soil Science, 38(8), 796–805. https://doi.org/10.9734/ijpss/2026/v38i86260*

Abstract

Flooding and drainage impose on lowland rice soils a distinctive alternation of anoxic and oxic conditions that is widely believed to govern the residence time of soil organic carbon. Yet the short-term, within-season expression of this control on surface soil has rarely been examined under controlled conditions that isolate texture and organic matter supply from the confounding variability of the field. A pot experiment was conducted with surface (0-20 cm) soils of three textural classes: loam, sandy clay loam and sandy loam drawn from rice croplands of the Terai agro-ecological region of West Bengal, India. Eighteen pots were arranged in a two-factor scheme combining soil texture (three levels) with the presence or absence of farmyard manure applied at a rate equivalent to 10 t ha^{-1}, and a rice crop (cv. Bongabandhu) was raised to maturity under the flooding and drainage regime characteristic of lowland rice culture. The soils of every pot were sampled at weekly intervals over eight weeks, a period spanning an initial aerobic, drained phase (weeks 1-2) and a subsequent anaerobic, flooded phase (weeks 3-8), and the water-soluble and hot-water-soluble carbon fractions were determined on each occasion. Water-soluble carbon fluctuated within a comparatively narrow band of about 52-58 mg kg^{-1} of total organic carbon. In contrast, HWSC showed a sharper decline on the transition to anoxia, especially in the unamended pots. Total soluble carbon, ranging between roughly 105 and 115 mg kg-1 of total organic carbon, was raised by manure addition chiefly in the early, aerobic weeks and the amended and unamended pots converged as the season advanced. A repeated-measures analysis of variance detected a significant effect of week ($p = 0.002$) and a significant week-by-texture interaction ($p = 0.006$), but no significant main effect of texture and no significant net difference between the aerobic and anaerobic phase means ($p = 0.96$). These findings indicate that the soluble carbon pool of surface rice soil is a genuinely dynamic but texturally buffered fraction, whose short-term, texture-dependent trajectory rather than its season-long average carries the imprint of redox alternation and of fresh organic matter addition.

Keywords: Soil organic carbon; paddy soil redox dynamics; water soluble carbon; hot water soluble carbon; organic amendment; soil texture.

1. Introduction

Soil holds a larger stock of organic carbon than the atmosphere and the world's living vegetation combined. Even proportionally small changes in this stock are capable of producing globally significant fluxes of carbon dioxide (Lal, 2004). Beyond its role in the global carbon cycle, organic carbon underpins soil structure, water relations, nutrient supply and biological activity, so that its maintenance is central to both climate mitigation and the sustainability of crop production (Schmidt et al., 2011). It has also been shown that iron and aluminium-associated organic carbon can contribute substantially to SOC stabilisation, with mineral–organic associations and microbial community characteristics jointly influencing the persistence of soil carbon in paddy systems (Hou et al., 2025). Lowland rice soils occupy a distinctive place in this discussion, because the puddling, flooding and periodic drainage practised in rice culture subject the soil to a regime of alternating anaerobic and aerobic conditions that has no counterpart in upland agriculture, and this alternation is now recognised as an important, if still incompletely understood, regulator of carbon turnover in paddy environments (Kögel-Knabner et al., 2010). Recent evidence has reinforced the importance of water regime in controlling paddy-soil carbon dynamics. Prolonged flooding can modify the relationship between paddy-soil organic carbon sequestration and climatic factors, highlighting the distinctive role of anaerobic conditions in regulating carbon storage in rice soils (Dai et al., 2024). Recent work in subtropical paddy soils further indicates that microbial metabolic capacity can constrain the accrual of mineral-associated organic carbon, reinforcing the close coupling between microbial processing and carbon stabilisation in these systems (Li et al., 2024).

Submergence of a rice soil sets in motion a sequence of biogeochemical changes that bear directly on the fate of soil carbon. As oxygen is exhausted by microbial respiration, the soil becomes progressively reduced, and dissolution of iron oxides releases organic compounds that were previously bound to mineral surfaces; on subsequent drainage, the re-oxidation and re-precipitation of iron generate fresh reactive surfaces capable of sorbing and protecting organic matter afresh (Kögel-Knabner et al., 2010). At a finer scale, anaerobic microsites that persist even within nominally aerated soil have been shown to spare certain classes of organic compounds from decomposition, so that a shift from anoxic to oxic conditions can expose previously protected carbon to markedly accelerated mineralisation (Keiluweit et al., 2017). Because rice soils cycle repeatedly between these two states within a single cropping season, the residence time of their carbon is not a fixed property of the soil but a dynamic quantity that depends on the phase of the redox cycle at the moment of observation (Sahrawat, 2004).

The temporal behaviour of soil carbon under this regime is further complicated by the addition of fresh organic matter, a routine practice in rice-based cropping systems. Organic amendments can supply readily available substrate that stimulates microbial activity and priming of native soil carbon, while at the same time providing the precursors from which microbial necromass and, ultimately, more stable mineral-associated carbon are formed (Cotrufo et al., 2013; Angst et al., 2021). The balance between these opposing tendencies, and the speed with which it is established, is expected to depend on soil texture, since the abundance of reactive mineral surface governs the capacity of a soil to retain freshly produced soluble and microbial carbon (Cotrufo & Lavallee, 2022; Georgiou et al., 2022). The water-soluble and hot-water-soluble carbon fractions, though a small proportion of total organic carbon, are particularly sensitive indicators of these short-term transformations and have long been used to detect early responses of soil carbon to management and to changing environmental conditions (Ghani et al., 2003). Long-term application of rice straw, green manure and pig manure was shown to increase SOC, particulate organic carbon (POC) and mineral-associated organic carbon (MAOC), while changes in microbial carbon-use efficiency, microbial biomass and microbial necromass were closely associated with SOC accumulation (Ye et al., 2025). Long-term organic amendments in paddy soil have also been associated with greater soil organic carbon, principally through particulate organic matter accumulation, while dissolved organic nutrients were linked with carbon stabilisation pathways in mineral-associated fractions (Bian et al., 2024). Field studies in rice-based systems likewise report increases in soil organic carbon following farmyard-manure inputs and green-manure incorporation, supporting the manuscript's emphasis on fresh organic matter as a relevant control on soil carbon dynamics (Ravi et al., 2025; Hlaing et al., 2025). Recent evidence also shows that nutrient availability can regulate microbial growth, carbon-use efficiency and respiration in paddy soils, further indicating that management-mediated microbial metabolism contributes to organic carbon turnover (Sun et al., 2025).

Most of the evidence for redox control over paddy soil carbon has come from single-time-point field comparisons or from long-term experiments that report the cumulative outcome of many seasons of flooding and drainage, and comparatively little controlled, weekly-resolved evidence exists on how the soluble carbon pools of surface rice soil actually behave, week by week, as a season progresses from an aerobic to an anaerobic phase, and on how this behaviour is modified jointly by soil texture and by the addition of fresh organic matter. Addressing this gap requires an experimental system in which the redox regime, the texture and the organic-matter supply can be observed under standardised conditions and at a temporal resolution fine enough to capture the transition itself. The present study was therefore designed with the specific objective of examining the dynamics of soluble soil carbon pools under alternating oxic and anoxic conditions in surface rice soil, by means of a controlled pot experiment in which soils of contrasting texture were cropped to rice with and without the addition of fresh organic matter and monitored at weekly intervals through the cropping season.

2. Materials and Methods

2.1 Study Area and Soil Collection

The soil used in the experiment was collected from rice croplands of the eastern Himalayan Terai agro-ecological region, within the Cooch Behar and Alipurduar districts of West Bengal, India. The region is built on deep alluvium deposited by rivers descending from the eastern Himalaya and experiences a humid to perhumid climate with a hot, wet monsoon and heavy, well-distributed rainfall; under this freely leaching regime carbonates do not accumulate, so that the inorganic carbon content of the soils is negligible and the total carbon content can, for practical purposes, be equated with the organic carbon content (Deb et al., 2016). The croplands sampled were under a uniform, double-rice cropping system managed in a broadly comparable manner, so that differences among the soils could be attributed to texture rather than to differences in land management.

Three textural classes, namely loam, sandy clay loam and sandy loam, were identified within this landscape with reference to a regional soil resources map and were subsequently confirmed by laboratory particle-size analysis.

For the purpose of the present pot experiment, surface soil from the 0-20 cm layer was collected from the locations representing each of the three textural classes, in a quantity sufficient to fill the experimental pots, and was transferred to the pots in as undisturbed a condition as practicable so that the field bulk density and structural condition of each soil were approximately reproduced in the experimental units.

2.2 Experimental Design and Treatments

The experiment was established as a two-factor factorial, with soil texture (loam, sandy clay loam, sandy loam) as the first factor and the addition of fresh organic matter (present or absent) as the second. Six pots were prepared for each textural class, giving eighteen pots in all; within each textural class three pots received the organic amendment and three did not, so that each texture-by-treatment combination was represented by three replicate pots.

2.3 Pot Preparation and Crop Husbandry

Each pot measured 30 × 30 × 34 cm internally and was filled with 20 kg of soil, packed to approximate the field bulk density of the corresponding textural class. The beds and pots were prepared between 20 and 22 May. Rice (cv. Bongabandhu, total duration approximately 135 days from seed to seed and 85-90 days from transplanting) was raised in a nursery sown on 13 May and transplanted into the pots on 16 June at a spacing of 20 cm between rows and 15 cm between plants. Thereafter, the pots were maintained under the standard agronomic practices of the Terai region, including the flooding and drainage regime typical of lowland rice, and the crop was grown to maturity, so that the soils experienced the characteristic sequence of submergence and drainage of a rice-growing season.

2.4 Fertiliser and Organic Matter Application

All pots received mineral fertiliser at the regionally recommended dose of 100 kg N, 50 kg P and 50 kg K ha-1 (equivalent to about 1.95 g N, 2.79 g P and 0.75 g K per pot), applied through urea, single superphosphate and muriate of potash. The nine pots assigned to the organic-matter treatment additionally received farmyard manure at a rate equivalent to 10 t ha-1 (about 89.28 g per pot), applied on 13 June, before transplanting; the remaining nine pots received the mineral fertiliser alone, so that the contrast between the two sets of pots isolated the effect of fresh organic-matter addition.

2.5 Sampling Schedule and Analytical Methods

The basic physico-chemical properties of each soil, namely reaction (pH), bulk density and total organic carbon, were determined once, at the outset of the experiment, on the fraction passing a 2 mm sieve, pH being measured potentiometrically in a soil-water suspension (Jackson, 1967) and total carbon by dry combustion in a Vario EL III elemental analyser (Elementar, Germany), with the inorganic carbon fraction confirmed to be negligible by the dilute-acid method. Bulk density was determined by the core method (Blake & Hartge, 1986). Thereafter, the soil of every pot was sampled at weekly intervals for eight consecutive weeks, spanning an initial aerobic, drained phase (weeks 1 and 2) and a subsequent anaerobic, flooded phase (weeks 3 to 8), and the WSC and HWSC fractions were determined on each weekly sample and expressed relative to the total organic carbon of the soil. Microbial biomass carbon was determined, where reported, by the chloroform fumigation-extraction method, with the biomass carbon calculated from the flush of carbon released on fumigation using an extraction-efficiency factor of 0.41 (Vance et al., 1987; Voroney & Paul, 1984).

2.6 Statistical Analysis

The weekly total soluble carbon of the eighteen pots was analysed by a repeated-measures (mixed model) analysis of variance, with soil texture as the between-subjects factor and week as the within-subjects factor. The individual pot was treated as the subject, and the magnitude of each effect was expressed by the partial eta-squared statistic (η^2_p). The contrast between the aerobic phase (weeks 1-2) and the anaerobic phase (weeks 3-8) was additionally tested by a paired comparison of pot means between the two phases, using Cohen's d as the accompanying measure of effect size.

3. Results and Discussion

3.1 Initial Properties of the Pot Soils

The three textural classes used to fill the experimental pots differed appreciably in their initial characteristics (Table 1). The sandy clay loam soil carried the highest initial organic carbon stock (14.05 Mg ha^{-1}), while the loam and sandy loam soils carried somewhat less (10.93 and 11.76 Mg ha-1, respectively). The sandy loam soil was distinctly the most acid of the three (pH 4.96), and the sandy clay loam was the densest (bulk density 1.21 Mg m^{-3}). These initial contrasts provided the textural background against which the effects of organic-matter addition and of the oxic-anoxic cycle were subsequently assessed.

Table 1. Initial properties of the surface (0-20 cm) soils used in the pot experiment

Textural class	pH	Bulk density (Mg m^{-3})	Total organic C (Mg ha^{-1})	Microbial biomass C (Mg ha^{-1})
Loam	5.79	1.144	10.93	0.0549
Sandy clay loam	5.73	1.206	14.05	0.0508
Sandy loam	4.96	1.157	11.76	0.0659

3.2 Weekly Dynamics of Water-soluble Carbon

The weekly water-soluble carbon, expressed relative to total organic carbon, fluctuated within a comparatively narrow band throughout the season, generally between about 52 and 58 mg kg-1 (Table 2). These fluctuations were nonetheless systematically related to the prevailing redox phase and to the organic-matter treatment. Values tended to be higher and more variable during the aerobic weeks, and the onset of the anaerobic phase was generally accompanied by a modest decline and stabilisation of water-soluble carbon, consistent with a slowing of decomposition and a reduced release of soluble carbon under anoxic conditions (Sahrawat, 2004; Kögel-Knabner et al., 2010). Addition of farmyard manure raised water-soluble carbon in most weeks and textural classes, an effect that was clearest immediately after application, when labile manure-derived substrate was most abundant, an effect that narrowed progressively as this substrate was consumed, a pattern consistent with the transient stimulation, and subsequent depletion, of the soluble pool that typically follows fresh organic matter addition (Cotrufo et al., 2013; Ghosh et al., 2012). Among the textural classes, the sandy loam and loam soils tended to carry marginally higher water-soluble carbon than the sandy clay loam, which may reflect the stronger retention of soluble carbon on the more abundant reactive mineral surfaces of the clay-richer soil.

Table 2. Weekly water soluble carbon (mg kg^{-1} TOC) under the three textural classes with (+OM) and without (-OM) organic matter addition (weeks 1-2, aerobic; weeks 3-8, anaerobic)

Soil (treatment)	W1	W2	W3	W4	W5	W6	W7	W8
Loam (-OM)	57.7	53.7	55.3	54.3	54.4	54.3	54.3	55.1
Loam (+OM)	57.7	56.4	54.5	53.9	52.4	53.9	53.9	52.4
Sandy clay loam (-OM)	53.3	53.5	58.5	57.6	56.0	56.2	55.3	55.1
Sandy clay loam (+OM)	55.3	54.9	56.8	56.4	54.7	56.4	56.2	55.1
Sandy loam (-OM)	57.7	56.8	55.7	56.2	54.3	56.2	56.0	55.9
Sandy loam (+OM)	57.7	57.5	58.4	57.7	55.3	57.7	57.7	55.8

3.3 Weekly Dynamics of Hot-Water-Soluble Carbon

Hot-water-soluble carbon, which represents a larger and more weakly bound pool than that obtained by cold-water extraction, showed a clearer response to the redox transition than the water-soluble fraction (Table 3). In several treatments, hot-water-soluble carbon fell appreciably on the shift from the aerobic to the anaerobic phase, declining from values of roughly 56-58 mg kg-1 in the first weeks to around 50-52 mg kg-1 in the later, flooded weeks, a pattern consistent with a reduced production of weakly bound, microbially derived soluble carbon once decomposition is suppressed by flooding (Ghani et al., 2003; Kögel-Knabner et al., 2010). As with the water-soluble fraction, organic-matter addition tended to raise hot-water-soluble carbon, particularly in the early weeks, and amended pots generally sustained somewhat higher values through the anaerobic phase than unamended pots. The persistence of this difference into the later weeks, in contrast with the more transient effect observed for the water-soluble fraction suggests that the organic amendment contributed to a slightly larger and more durable pool of microbially processed soluble carbon, in keeping with the recognised role of fresh organic inputs in supplying the precursors of microbial products (Cotrufo et al., 2013; Angst et al., 2021).

Table 3. Weekly hot-water-soluble carbon (mg kg^{-1} TOC) under the three textural classes with (+OM) and without (-OM) organic matter addition

Soil (treatment)	W1	W2	W3	W4	W5	W6	W7	W8
Loam (-OM)	57.6	51.8	57.2	56.8	57.2	56.7	57.2	56.8
Loam (+OM)	56.8	55.2	59.5	57.1	58.0	57.2	58.0	57.2
Sandy clay loam (-OM)	56.8	51.6	50.9	51.2	51.4	51.2	51.4	50.9
Sandy clay loam (+OM)	57.6	52.2	56.0	55.3	56.0	54.6	56.0	55.7
Sandy loam (-OM)	56.6	54.1	50.8	50.7	50.8	50.8	50.8	50.9
Sandy loam (+OM)	56.6	51.3	57.6	56.4	57.6	55.8	57.6	56.2

3.4 Total Soluble Carbon and the Aerobic-Anaerobic Contrast

The total soluble carbon, the sum of the water-soluble and hot-water-soluble fractions, ranged broadly between about 105 and 115 mg kg^{-1} of total organic carbon and declined, in most treatment combinations, on the transition from the aerobic to the anaerobic phase, the decline typically amounting to a few percentage points (Table 4). Averaged over the two phases (Table 5), the aerobic period carried a higher total soluble carbon than the anaerobic period in the majority of the texture-by-treatment combinations, confirming a general tendency for the onset of anoxia to reduce the pool of biologically available soluble carbon. The response was not, however, uniform: the sandy loam soil without organic-matter addition showed the largest aerobic-to-anaerobic decline (6.1 mg kg^{-1}), whereas the corresponding amended pots of the same texture showed a small increase, and the sandy clay loam soils showed contrasting directions of change depending on the organic-matter treatment. This heterogeneity indicates that soil texture and organic-matter addition jointly modulate the magnitude, and at times even the direction, of the redox effect on total soluble carbon.

Table 4. Weekly total soluble carbon (WSC + HWSC, mg kg^{-1} TOC) under the three textural classes with (+OM) and without (-OM) organic matter addition

Soil (treatment)	W1	W2	W3	W4	W5	W6	W7	W8
Loam (-OM)	115.3	105.5	112.5	111.1	111.6	110.9	111.5	112.0
Loam (+OM)	114.5	111.6	114.0	110.9	110.4	111.1	111.9	109.6
Sandy clay loam (-OM)	110.2	105.1	109.4	108.7	107.4	107.4	106.8	106.0
Sandy clay loam (+OM)	112.9	107.1	112.8	111.6	110.6	110.9	112.2	110.8
Sandy loam (-OM)	114.3	110.9	106.5	106.9	105.1	107.0	106.8	106.8
Sandy loam (+OM)	114.3	108.8	116.0	114.1	112.9	113.5	115.3	112.0

Table 5. Mean total soluble carbon (mg kg^{-1} TOC) during the aerobic (weeks 1-2) and anaerobic (weeks 3-8) phases, with and without organic matter addition

Soil (treatment)	Aerobic mean	Anaerobic mean	Difference
Loam (-OM)	110.4	111.6	-1.2
Loam (+OM)	113.1	111.3	1.7
Sandy clay loam (-OM)	107.6	107.6	0.0
Sandy clay loam (+OM)	110.0	111.5	-1.5
Sandy loam (-OM)	112.6	106.5	6.1
Sandy loam (+OM)	111.5	114.0	-2.5

3.5 Effect of Organic Matter Addition through the Season

Expressing the organic-matter effect as the difference between amended and unamended pots of each texture (Table 6) sharpens this picture. In the aerobic weeks, the amendment raised total soluble carbon appreciably in all three textural classes, the increase being largest immediately after application, when the labile substrate of the manure was most abundant. As the season progressed and the soils turned anaerobic, the difference between amended and unamended pots generally narrowed, and in the loam soil it even reversed sign, indicating that the readily soluble carbon supplied by the manure was progressively consumed and that amended and unamended soils converged towards a common, redox-controlled level of soluble carbon. This behaviour is consistent with the initial, rapid availability of fresh, easily decomposable manure substrate to the soil microbial community, followed by its assimilation or mineralisation as decomposition proceeds (Cotrufo et al., 2013; Ghosh et al., 2012). That soluble carbon remained slightly elevated under organic-matter addition even into the anaerobic phase in some textural classes suggests that part of the added carbon was converted into relatively stable, microbially processed compounds rather than lost entirely to mineralisation, in keeping with the recognised contribution of fresh organic inputs to microbially derived and ultimately more persistent, soil carbon (Cotrufo et al., 2013; Angst et al., 2021; Sokol & Bradford, 2019).

Table 6. Effect of organic-matter addition on total soluble carbon (mg kg^{-1} TOC): difference between amended (+OM) and unamended (-OM) pots, by textural class, in the aerobic and anaerobic phases

Textural class	Aerobic phase (+OM - -OM)	Anaerobic phase (+OM - -OM)
Loam	2.67	-0.27
Sandy clay loam	2.35	3.90
Sandy loam	-1.05	7.47

3.6 Repeated-Measures Analysis of the Temporal Dynamics

A repeated-measures (mixed model) analysis of variance of the weekly total soluble carbon of the eighteen pots, with texture as the between-subjects factor and week as the within-subjects factor, confirmed the patterns described above (Table 7). Week was a significant within-subjects source of variation ($F = 3.61$, $p = 0.002$, $\eta^2_p = 0.194$), confirming that soluble carbon changed significantly through the season, and the week-by-texture interaction was also significant ($F = 2.40$, $p = 0.006$, $\eta^2_p = 0.243$), indicating that the temporal pattern of soluble carbon differed among the textural classes. The main effect of texture, in contrast, was not significant ($F = 1.11$, $p = 0.355$), so that the textural classes did not differ in their season-long average soluble carbon even though they followed distinct temporal trajectories. A paired comparison of the aerobic- and anaerobic-phase means across all pots showed the two phases to be almost identical (110.4 against 110.4 mg kg^{-1} TOC) and the difference to be far from significant (paired $t = -0.05$, $p = 0.96$, Cohen's $d = 0.02$).

Table 7. Repeated measures (mixed model) analysis of variance of weekly total soluble carbon: texture (between subjects), week (within subjects) and their interaction (18 pots × 8 weeks)

Source	F	p-value	η^2_p
Texture	1.11	0.355	0.129
Week	3.61	0.002	0.194
Texture × Week	2.40	0.006	0.243

This statistical picture refines the qualitative interpretation offered above. The soluble carbon pool is a genuinely dynamic fraction that responds significantly to time, and its temporal trajectory depends on soil texture, yet its season-long average appears to be buffered against the redox transition, plausibly by the much larger and more stable carbon stock of the bulk soil and, in amended pots, by the continued supply of carbon from the growing crop. That the net phase contrast was non-significant while the week and week-by-texture effects were highly significant indicates that the temporal dynamics of soluble carbon in these soils are driven by short-term, texture-dependent fluctuations rather than by a simple, monotonic response to the imposition of anoxia. The significant week-by-texture interaction, in particular, provides experimental, weekly-resolved evidence that clay-richer and coarser-textured soils follow measurably different temporal courses of soluble carbon turnover, consistent with the differing capacities of their mineral fractions to retain and release soluble carbon (Ghani et al., 2003; Cotrufo et al., 2013; Georgiou et al., 2022).

Taken together, these results indicate that the shift from aerobic to anaerobic conditions consistently reduces the pool of biologically available soluble carbon in surface rice soil, in agreement with earlier evidence that anoxic conditions slow organic matter mineralisation and favour carbon preservation in paddy soils (Sahrawat, 2004; Kögel-Knabner et al., 2010; Keiluweit et al., 2017), while the addition of fresh organic matter raises soluble carbon under both redox regimes without eliminating this decline, so that redox status remains the dominant short-term regulator of soluble carbon availability. The controlled, weekly-resolved design used here allowed these texture, treatment and time-dependent interactions to be resolved in a way that a single field sampling could not, complementing field-based, cumulative evidence on paddy soil carbon with a direct, within-season view of the underlying temporal process (Mandal et al., 2007). Certain limitations should nevertheless be borne in mind: although the pots were packed to field bulk density and the crop was grown under recommended agronomic practice, the pot system could not fully reproduce the hydrological and root-soil interactions of the open field, and the soluble carbon fractions represent only a small, highly dynamic part of the total organic carbon, buffered by a much larger and more stable reservoir. The observed effects of redox phase and organic-matter addition should therefore be judged mainly by their consistency and direction rather than by their absolute magnitude, and some caution is warranted in extrapolating the quantitative responses obtained here to unconfined field conditions (Cotrufo & Lavallee, 2022).

4. Conclusion

The pot experiment demonstrated that the soluble carbon pools of surface rice soil respond measurably, week by week, to the alternation of oxic and anoxic conditions that characterises lowland rice culture, and that this response is shaped jointly by soil texture and by the addition of fresh organic matter. Water-soluble carbon fluctuated within a comparatively narrow range through the season, whereas hot-water-soluble carbon showed a clearer decline on the transition from the aerobic to the anaerobic phase, particularly where no organic amendment had been applied. Farmyard manure addition raised total soluble carbon chiefly in the early, aerobic weeks, with the amended and unamended pots converging as the season advanced and the readily available substrate was consumed. The repeated-measures analysis confirmed that time, and its interaction with soil texture, were the dominant sources of variation in total soluble carbon, whereas the overall aerobic versus anaerobic contrast, and the main effect of texture, were not significant when averaged over the season. Water-soluble carbon fluctuated within a comparatively narrow band of about 52-58 mg kg^{-1} of total organic carbon. In contrast, HWSC showed a sharper decline on the transition to anoxia, especially in the unamended pots. Total soluble carbon, ranging between roughly 105 and 115 mg kg-1 of total organic carbon, was raised by manure addition chiefly in the early, aerobic weeks and the amended and unamended pots converged as the season advanced. A repeated-measures analysis of variance detected a significant effect of week ($p = 0.002$) and a significant week-by-texture interaction ($p = 0.006$), but no significant main effect of texture and no significant net difference between the aerobic and anaerobic phase means ($p = 0.96$). These findings suggest that the soluble carbon pool of surface rice soil is best understood as a texturally differentiated, short-term dynamic fraction, buffered at the season scale by the larger and more stable soil carbon stock, and that its management implications lie less in the net seasonal balance than in the timing and texture-dependence of its response to flooding, drainage and organic matter supply. Future work extending this weekly monitoring to microbial biomass carbon, soil respiration and the operationally fractionated carbon pools, and comparing pot-based observations with field measurements over multiple seasons, would help to establish how far the short-term dynamics identified here translate into longer-term differences in carbon accumulation among differently textured rice soils.

5. Limitations

The pot experiment provided controlled weekly observations but could not fully reproduce the hydrological and root-soil interactions of open-field conditions. The eight-week monitoring period captured an aerobic-to-anaerobic transition within one cropping cycle, so the results describe short-term dynamics rather than long-term carbon accumulation. Moreover, WSC and HWSC represent small, highly dynamic fractions of total organic carbon and are buffered by a larger, more stable carbon reservoir. Accordingly, quantitative extrapolation of the observed responses to unconfined field conditions and longer time scales should be made cautiously.

Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement and reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgement of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

References

Angst, G., Mueller, K. E., Nierop, K. G. J., & Simpson, M. J. (2021). Plant- or microbial-derived? A review on the molecular composition of stabilized soil organic matter. *Soil Biology and Biochemistry, 156*, 108189. https://doi.org/10.1016/j.soilbio.2021.108189

Bian, Q., Zhao, L., Cheng, K., Jiang, Y., Li, D., Xie, Z., Sun, B., & Wang, X. (2024). Divergent accumulation of microbe- and plant-derived carbon in different soil organic matter fractions in paddy soils under long-term organic amendments. *Agriculture, Ecosystems & Environment, 366*, 108934. https://doi.org/10.1016/j.agee.2024.108934

Blake, G. R., & Hartge, K. H. (1986). Bulk density. In A. Klute (Ed.), *Methods of soil analysis: Part 1. Physical and mineralogical methods* (2nd ed., pp. 363–375). American Society of Agronomy and Soil Science Society of America. https://doi.org/10.2136/sssabookser5.1.2ed.c13

Cotrufo, M. F., & Lavallee, J. M. (2022). Soil organic matter formation, persistence, and functioning: A synthesis of current understanding to inform its conservation and regeneration. *Advances in Agronomy, 172*, 1–66. https://doi.org/10.1016/bs.agron.2021.11.002

Cotrufo, M. F., Wallenstein, M. D., Boot, C. M., Denef, K., & Paul, E. (2013). The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: Do labile plant inputs form stable soil organic matter? *Global Change Biology, 19*(4), 988–995. https://doi.org/10.1111/gcb.12113

Dai, Z., Zhou, F., Zhang, S., Pan, Z., & Wang, Z. (2024). Long-term flooding mitigates the linkage between paddy soil organic carbon sink and climate factors. *ACS Earth and Space Chemistry, 8*(7), 1495–1504. https://doi.org/10.1021/acsearthspacechem.4c00122

Deb, S., Chakraborty, S., Weindorf, D. C., Murmu, A., Banik, P., Debnath, M. K., & Choudhury, A. (2016). Dynamics of organic carbon in deep soils under rice and non-rice cropping systems. *Geoderma Regional, 7*(4), 388–394. https://doi.org/10.1016/j.geodrs.2016.11.004

Georgiou, K., Jackson, R. B., Vindušková, O., Abramoff, R. Z., Ahlström, A., Feng, W., Harden, J. W., Pellegrini, A. F. A., Polley, H. W., Soong, J. L., Riley, W. J., & Torn, M. S. (2022). Global stocks and capacity of mineral-associated soil organic carbon. *Nature Communications, 13*, 3797. https://doi.org/10.1038/s41467-022-31540-9

Ghani, A., Dexter, M., & Perrott, K. W. (2003). Hot-water extractable carbon in soils: A sensitive measurement for determining impacts of fertilisation, grazing and cultivation. *Soil Biology and Biochemistry, 35*(9), 1231–1243. https://doi.org/10.1016/S0038-0717(03)00186-X

Ghosh, S., Wilson, B., Ghoshal, S., Senapati, N., & Mandal, B. (2012). Organic amendments influence soil quality and carbon sequestration in the Indo-Gangetic plains of India. *Agriculture, Ecosystems & Environment, 156*, 134–141. https://doi.org/10.1016/j.agee.2012.05.009

Hlaing, T., Moe, K., Kyaw, E. H., Ngwe, K., Hlaing, M. M., & Oo, H. H. (2025). Green manuring enhances nitrogen use efficiency of rice and soil nutrient contents of paddy soil. *Asian Research Journal of Current Science, 7*(1), 288–300. https://doi.org/10.56557/arjocs/2025/v7i1151

Hou, N., Yin, X., Wang, W., Huang, X., Fang, Y., Vancov, T., Sardans, J., Tariq, A., Zeng, F., Wiesmeier, M., & Peñuelas, J. (2025). Soil carbon stabilization associated with iron-aluminum complexes and microbial communities in paddy. *Environmental Research, 285*, 122601. https://doi.org/10.1016/j.envres.2025.122601

Jackson, M. L. (1967). *Soil chemical analysis*. Prentice-Hall of India Pvt. Ltd.

Keiluweit, M., Wanzek, T., Kleber, M., Nico, P., & Fendorf, S. (2017). Anaerobic microsites have an unaccounted role in soil carbon stabilization. *Nature Communications, 8*, 1771. https://doi.org/10.1038/s41467-017-01406-6

Kögel-Knabner, I., Amelung, W., Cao, Z., Fiedler, S., Frenzel, P., Jahn, R., Kalbitz, K., Kölbl, A., & Schloter, M. (2010). Biogeochemistry of paddy soils. *Geoderma, 157*, 1–14. https://doi.org/10.1016/j.geoderma.2010.03.009

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science, 304*(5677), 1623–1627. https://doi.org/10.1126/science.1097396

Li, Z., Duan, X., Guo, X., Gao, W., Li, Y., Zhou, P., Zhu, Q., O'Donnell, A. G., Dai, K., & Wu, J. (2024). Microbial metabolic capacity regulates the accrual of mineral-associated organic carbon in subtropical paddy soils. *Soil Biology and Biochemistry, 195*, 109457. https://doi.org/10.1016/j.soilbio.2024.109457

Mandal, B., Majumder, B., Bandyopadhyay, P. K., Hazra, G. C., Gangopadhyay, A., Samantaray, R. N., Mishra, A. K., Chaudhury, J., Saha, M. N., & Kundu, S. (2007). The potential of cropping systems and soil amendments for carbon sequestration in soils under long-term experiments in subtropical India. *Global Change Biology, 13*(2), 357–369. https://doi.org/10.1111/j.1365-2486.2006.01309.x

Ravi, P., Venu Reddy, Ch., Raju, B., Krishna Chaitanya, A., & Wanjari, R. H. (2025). Critical carbon inputs to maintain soil organic carbon stocks under long-term rice-rice cropping system in semi-arid southern India. *Journal of Scientific Research and Reports, 31*(10), 27–35. https://doi.org/10.9734/jsrr/2025/v31i103546

Sahrawat, K. L. (2004). Organic matter accumulation in submerged soils. *Advances in Agronomy, 81*, 169–201. https://doi.org/10.1016/S0065-2113(03)81004-0

Schmidt, M. W. I., Torn, M. S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I. A., Kleber, M., Kögel-Knabner, I., Lehmann, J., Manning, D. A. C., Nannipieri, P., Rasse, D. P., Weiner, S., & Trumbore, S. E. (2011). Persistence of soil organic matter as an ecosystem property. *Nature, 478*, 49–56. https://doi.org/10.1038/nature10386

Sokol, N. W., & Bradford, M. A. (2019). Microbial formation of stable soil carbon is more efficient from belowground than aboveground input. *Nature Geoscience, 12*, 46–53. https://doi.org/10.1038/s41561-018-0258-6

Sun, H., Wang, L., Kumar, A., Auwal, M., Van Zwieten, L., Ge, T., Fu, Y., & Kuzyakov, Y. (2025). Nutrient availability mediates organic carbon turnover in paddy soils through regulating microbial metabolism. *Geoderma, 458*, 117313. https://doi.org/10.1016/j.geoderma.2025.117313

Vance, E. D., Brookes, P. C., & Jenkinson, D. S. (1987). An extraction method for measuring soil microbial biomass C. *Soil Biology and Biochemistry, 19*, 703–707. https://doi.org/10.1016/0038-0717(87)90052-6

Voroney, R. P., & Paul, E. A. (1984). Determination of kC and kN in situ for calibration of the chloroform fumigation-incubation method. *Soil Biology and Biochemistry, 16*, 9–14. https://doi.org/10.1016/0038-0717(84)90117-2

Ye, J., Chen, Z., Ma, J., Ma, J., Zou, P., Sun, W., Wang, F., Yu, Q., & Wang, Q. (2025). The effect of long-term organic amendments on soil organic carbon accumulation via regulating microbial traits in a paddy soil. *Agriculture, 15*(21), 2308. https://doi.org/10.3390/agriculture15212308

Peer-review history:
The peer review history for this paper can be accessed here:
https://pr.sdiarticle5.com/review-history/164385