Effects of Organic Waste Amendments, Application Methods, and Irrigation Levels on Soil Organic Matter in Two Contrasting Soil Textures Under Maize Cultivation

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ABSTRACT

Soil organic matter (SOM) is a key determinant of soil fertility and productivity in arid agricultural systems, yet SOM levels in southern Iraq remain low because of intensive cultivation and limited organic inputs. A two-site field experiment was conducted in Basrah Governorate, Iraq, to evaluate the effects of organic amendment type (composted cattle manure, composted date palm residues, and an unamended control), application method (uniform mixing and placement at 10 or 20 cm depth), irrigation regime (100% and 80% of available water), and soil depth (0–15 and 15–30 cm) on SOM accumulation in a silty clay soil (Site 1) and a sandy loam soil (Site 2) under maize cultivation. A four-factor factorial experiment was arranged in a randomised complete block design with three replicates, and SOM was determined by the Walkley–Black method at mid-season and end-of-season. All four factors exerted highly significant effects on SOM ($P \leq 0.01$), with organic amendment type showing the strongest influence: composted cattle manure produced the highest SOM at both sites, reaching 27.0 g kg^{-1} in the silty clay soil (35.0% higher than the unamended control) and 20.0 g kg^{-1} in the sandy loam soil (42.9% higher than the control) by season end, which may partly reflect its lower C:N ratio (14:1) and higher nitrogen content. Uniform mixing outperformed depth-placement methods by up to 18.5%, full irrigation exceeded deficit irrigation by 4–6%, and the surface layer (0–15 cm) retained 2–3% more SOM than the subsurface layer. No statistically significant interaction effects were detected among the tested factors. These findings indicate that composted cattle manure, uniform incorporation, and adequate irrigation were each the most effective individual management levels for restoring soil organic matter in degraded arid soils.

Keywords: soil organic matter; compost; cattle manure; date palm residues; irrigation regime; soil texture; maize

1. Introduction

Soil organic matter (SOM) is a fundamental component of soil quality because it regulates nutrient cycling, aggregate formation, water retention, microbial activity, and carbon sequestration, thereby sustaining soil fertility and long-term agricultural productivity [18,19]. In arid and semi-arid environments, SOM depletion is accelerated by high temperatures, limited rainfall, intensive cultivation, and insufficient organic inputs, resulting in declining soil productivity and reduced ecosystem resilience [9,21].

Agricultural soils of southern Iraq are particularly vulnerable to organic matter depletion because of prolonged cultivation under harsh climatic conditions. Basrah Governorate represents one of the most challenging agricultural environments in the region, where water scarcity, salinity, and limited organic matter inputs constrain soil fertility and crop productivity [5,22].

Organic amendments constitute one of the most effective management strategies for restoring degraded soils. Compost application supplies organic carbon and essential nutrients

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while stimulating microbial activity, improving soil physical properties, and enhancing long-term carbon stabilization. Nevertheless, the effectiveness of organic amendments depends largely on their chemical composition, maturity, and decomposition characteristics [8,14,19,29].

Composted cattle manure generally contains higher nitrogen concentrations and a lower C:N ratio than many crop residues, promoting rapid microbial decomposition and the formation of stable soil organic compounds [4]. In contrast, composted date palm residues contain greater proportions of lignocellulosic materials, resulting in slower decomposition and more gradual carbon stabilization [2,10,13]. Despite this slower decomposition, date palm residues represent an abundant and renewable organic resource in Iraq and other arid regions, making them an attractive alternative for sustainable soil management.

The method used to incorporate organic amendments into the soil also influences their decomposition and subsequent contribution to SOM accumulation. Uniform incorporation throughout the cultivated layer enhances contact between organic substrates, microorganisms, and soil minerals, thereby promoting decomposition and humification, whereas localized placement may restrict biological activity to limited soil zones [25,27,31].

Soil moisture availability is another major factor regulating SOM dynamics. Adequate irrigation supports microbial activity, root development, and organic matter formation, whereas water deficit suppresses biological processes and may accelerate carbon losses through repeated drying and rewetting cycles [9,11,21].

Soil texture further determines the capacity of soils to retain and stabilize organic matter. Fine-textured, clay-rich soils generally protect organic carbon through organo-mineral associations and aggregate formation, whereas coarse-textured sandy soils possess lower stabilization capacity because of their reduced specific surface area and weaker aggregate structure [18,26,34].

Although the individual effects of organic amendment type, application method, irrigation regime, and soil depth on SOM have each been reported separately, most existing studies from Iraq and comparable arid regions examine these factors one or two at a time, so it remains unclear whether their effects simply add up or whether they interact — for example, whether the benefit of switching to a better amendment depends on which irrigation level or application method it is paired with. This is not merely a statistical detail: if the factors interact, management recommendations would need to specify particular combinations of amendment, placement, and irrigation; if they act independently, a single best level of each factor could be recommended regardless of the others, which is a simpler and more transferable message for extension purposes. No study to date has evaluated all four factors together, in the same experiment, on the severely organic-matter-depleted soils typical of southern Iraq, which leaves both the size of each individual effect and the presence or absence of interactions among them unresolved for this setting.

Therefore, this study aimed to evaluate the effects of composted cattle manure and composted date palm residues, application method, irrigation regime, and soil depth — individually and in combination — on soil organic matter accumulation in two contrasting soils of southern Iraq under maize cultivation.

2. Materials and Methods

2.1 Experimental sites and initial soil characteristics

The study was conducted at two field sites in Basrah Governorate, southern Iraq. Site 1 was located at the Agricultural Research Station of the College of Agriculture, University of Basrah, Karma Ali (30°33′30″ N, 47°45′47″ E). The soil was classified as Fine-silty, mixed, active, calcareous, hyperthermic, Typic Torrifluvents according to USDA Soil Taxonomy.

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Site 2 was located at the National Tomato Production Project of the Basrah Directorate of Agriculture, Khor Al-Zubair (30°28′23″ N, 47°52′21″ E), and was classified as Fine-loamy, mixed, active, calcareous, hyperthermic, Typic Torriorthents [5].

The experimental region has an arid climate characterised by limited annual rainfall (<150 mm), high evaporative demand, and extreme summer temperatures. The two sites represent contrasting soil environments in southern Iraq: Site 1 is characterised by higher clay content and greater water retention capacity, whereas Site 2 represents coarse-textured soil with lower water-holding capacity.

Before establishing the experiment, composite soil samples were collected from the 0–30 cm soil layer to determine initial physical and chemical properties. Soil texture was determined using the hydrometer method. Bulk density was measured using the core method, and particle density was determined by the pycnometer method. Total porosity was calculated from bulk and particle density values. Soil pH and electrical conductivity (EC) were measured in a 1:1 soil-to-water suspension. Field capacity and permanent wilting point were determined using the pressure plate method. Soil organic matter was determined using the Walkley–Black oxidation method.

Table 1. Initial physical and chemical properties of the two experimental sites.

Property	Unit	Site 1 (Silty Clay)	Site 2 (Sandy Loam)	Method
Sand	%	14.2	59.1	Volumetric pipette
Silt	%	41.6	21.3	Volumetric pipette
Clay	%	44.2	19.6	Volumetric pipette
Texture class	—	Silty clay	Sandy Loam	USDA
Bulk density	Mg m^{-3}	1.18	1.52	Core method
Particle density	Mg m^{-3}	2.65	2.65	Pycnometer
Total porosity	%	55.5	42.6	Calculated
Field capacity	cm^3 cm^{-3}	0.412	0.142	Pressure plate
Permanent wilting point	cm^3 cm^{-3}	0.241	0.062	Pressure plate
Available water (AW)	cm^3 cm^{-3}	0.171	0.080	Calculated
Organic matter	g kg^{-1}	18.6	9.7	Walkley–Black
Saturated Ks	m day^{-1}	0.062	0.098	Constant head
Electrical conductivity	dS m^{-1}	3.8	1.4	EC meter
pH (1:1 soil: water)	—	7.6	7.9	pH meter

Ks = saturated hydraulic conductivity; AW = available water.

2.2 Experimental design and treatments

A four-factor factorial field experiment was conducted at both sites using a randomised complete block design (RCBD) with three replicates. The experimental factors consisted of organic amendment type, application method, irrigation regime, and soil depth.

Organic amendment type (Factor A). Three organic amendment treatments were evaluated: (1) composted cattle manure (CM); (2) composted date palm residues (DPR); and (3) an unamended control (C). Both compost materials were applied at a rate of 20 Mg ha^{-1} on a dry-weight basis, before crop establishment; compost moisture content was determined beforehand so that the applied quantity

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corresponded to 20 Mg ha^{-1} of dry matter regardless of the moisture present at application.

Application method (Factor B). Organic amendments were applied using three incorporation methods: (1) uniform mixing throughout the cultivated soil layer (MIX; 0–30 cm); (2) placement at 10 cm depth (L10); and (3) placement at 20 cm depth (L20). In the L10 and L20 treatments, the amendment was applied as a continuous band 25 cm wide along the planting rows, with 75 cm between adjacent fertilised bands, and then incorporated to the target depth; in the MIX treatment the same band arrangement was used before mixing the amendment through the full 0–30 cm layer. These three methods were compared because maize roots explore the full 0–30 cm layer at both sites, so any difference among them would be expected to reflect how the organic material is spatially distributed relative to the soil matrix and microbial community — concentrated within a narrow band (L10, L20) versus dispersed throughout the profile (MIX) — rather than a difference in whether roots can physically reach the amendment.

Irrigation regime (Factor C). Two irrigation levels were applied according to soil available water (AW): (1) full irrigation (I100), restoring 100% of the AW depleted since the previous irrigation; and (2) deficit irrigation (I80), restoring 80% of the depleted AW. Soil moisture content was measured immediately before each irrigation event to determine the fraction of AW already depleted, and the replacement volume needed to restore AW to its target level (100% or 80% of the depletion) was then calculated weekly from Class A pan evaporation:

$$ETc = Epan \times Kp \times Kc \times Ea^{-1}$$

where ETc is the calculated irrigation requirement (mm) used to replace the water depleted from the AW reservoir, Epan is the measured pan evaporation (mm), Kp is the pan coefficient (0.75, for a Class A pan sited in the open, away from buildings or trees), Kc is the crop coefficient (0.60 during establishment, 1.00 during vegetative growth, and 1.20 during the peak reproductive stage), and Ea is irrigation application efficiency (0.90). The Class A pan (1.21 m diameter, 0.25 m depth, galvanised sheet metal, rim 15 cm above the surrounding soil surface) was installed in an open, unobstructed location adjacent to the experimental field. The resulting depth (mm) was converted to a volume for each plot using the plot area, and applied in full to restore 100% of the depleted AW (I100) or reduced to restore 80% of the depleted AW (I80). Pre-irrigation AW depletion ranged from about 12% to 57% across the 14 weekly irrigation events (10 April to 10 July 2025), reflecting seasonal changes in evaporative demand. Across the season this amounted to a total application, summed over all events, of approximately 221 mm (I100) and 176 mm (I80) in the silty clay soil, and 267 mm (I100) and 214 mm (I80) in the sandy loam soil — the larger volumes at the sandy loam site reflecting its lower water-holding capacity (Table 1). Irrigation water was drawn from a river irrigation canal for the silty clay site (EC = 2.4 dS m^{-1}) and from a groundwater well for the sandy loam site (EC = 4.1 dS m^{-1}).

Soil depth (Factor D). Soil samples were collected from two depths: (1) the surface layer, 0–15 cm; and (2) the subsurface layer, 15–30 cm.

Each experimental plot measured 2 m² (2 m × 1 m) and contained 20 maize plants, with 0.5 m separating adjacent plots. All plots received a uniform basal programme of inorganic NPK fertiliser in addition to the organic amendment treatments, following locally established practice for maize on calcareous soils in this region [6]: nitrogen was applied as urea (46% N) at 150 kg N ha^{-1} in two split doses (before planting and 20 days after emergence); phosphorus was applied as concentrated superphosphate (20% P) at 50 kg P ha^{-1} in a single basal dose at the start of the season; and potassium was applied as potassium sulphate (43% K) at 100 kg K ha^{-1} in a single dose at flowering. All three inorganic fertilisers were incorporated into the surface soil layer at application.

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Maize (Zea mays L.) was cultivated as the test crop during the growing season (sown late March 2025). Soil organic matter measurements were conducted at mid-season (mid-May, approximately 60 days after planting) and at the end of the growing season (mid-July, approximately 120 days after planting).

2.3 Preparation and characterisation of composted organic amendments

Composted cattle manure and date palm residues were prepared separately under aerobic composting conditions. Each pile measured approximately 2 m long × 1.5 m wide × 1 m high and was turned twice weekly during the active decomposition phase to maintain aeration, with composting continued for a total of 75 days before use. To support microbial activity during the early, nitrogen-limited stage of decomposition, urea was added to each pile at a rate of 2 kg urea per 400 kg of fresh organic material.

Maturity was assessed against the C:N ratio criterion widely used for manure- and residue-based composts, whereby a final C:N ratio below approximately 20 is generally taken to indicate an acceptably mature, stable product [8]. By this criterion, the cattle manure compost reached maturity (final C:N = 14:1). The date palm residue compost, by contrast, remained somewhat above this threshold at the end of composting (final C:N = 22:1), consistent with the slower, lignin-dominated decomposition of palm biomass discussed further in Section 3.3; both materials were applied at the same composting duration to keep amendment type and composting time from being confounded, which means the DPR compost was less fully matured than the CM compost at the point of application. This distinction is noted because it may itself contribute to the slower SOM build-up observed under DPR relative to CM (Section 3.3), in addition to the lignocellulosic composition discussed there. The chemical characteristics of the organic materials before and after composting are presented in Table 2.

Table 2. Chemical characteristics of organic wastes before and after composting.

Organic material	Composting stage	EC (dS m⁻ ¹)	pH	Total N (%)	Total C (%)	P (%)	K (%)	C:N ratio
Cattle manure	Before composting	5.0	7.8	1.2	30.0	—	—	25:1
Cattle manure	After composting	3.5	7.2	1.45	20.3	0.62	1.38	14:1
Date palm fronds	Before composting	1.5	8.2	0.6	36.0	—	—	60:1
Date palm fronds	After composting	2.3	7.5	1.12	24.6	0.48	1.76	22:1

Total C was calculated from the measured C:N ratio and Total N (C% = C:N × N%) rather than determined by a separate direct assay. P and K were not determined for the pre-composting feedstocks (— = not measured); pre-composting characterisation focused on EC, pH, N, and C:N as maturity-tracking parameters.

2.4 Soil sampling and laboratory analysis

Soil samples were collected from each experimental plot at mid-season and end-of-season from both sampling depths (0–15 and 15–30 cm). Composite samples were prepared by collecting several soil cores from each plot and thoroughly mixing them.

Samples were air-dried, gently crushed, and passed through a 2-mm sieve before laboratory analysis. Organic carbon was determined using the Walkley–Black wet oxidation method [23]. Because this method quantifies organic carbon rather than organic matter directly, measured organic carbon values were converted to SOM using the conventional van Bemmelen factor (SOM = organic C × 1.724) [23]; no further conversion was applied to the SOM values reported here. Measured values were expressed as g kg^{-1} soil.

2.5 Statistical analysis

Experimental data were subjected to factorial analysis of variance (ANOVA) using the RCBD model, with each site × sampling-time combination analysed separately (n = 108 observations per analysis: 3 amendment types × 3 application methods × 2 irrigation levels × 2 soil depths × 3 replicates). All four factors — organic amendment type, application method, irrigation regime, and soil depth — were independently assigned and randomised within each block, and the analysis included their main effects and all interaction effects.

Treatment means were compared using the Revised Least Significant Difference (RLSD) test at $P \leq 0.05$, calculated separately for the three-level factors (amendment type and application method; n = 36 observations per mean) and the two-level factors (irrigation level and soil depth; n = 54 observations per mean), and reported for each factor block in Table 4. Statistical significance was considered at $P \leq 0.05$ (*) and $P \leq 0.01$ (**). The coefficient of variation (CV%) was calculated to evaluate experimental precision. All statistical analyses were performed using the General Linear Model (univariate ANOVA) procedure of IBM SPSS Statistics (IBM Corp., Armonk, NY, USA). The reported degrees of freedom, mean squares, F-ratios (Table 3), and RLSD values (Table 4) were independently recomputed from the underlying error mean squares and were consistent with the SPSS output at every check performed.

3. Results and Discussion

3.1 Analysis of variance and experimental precision

Analysis of variance revealed highly significant effects of organic amendment type, application method, irrigation regime, and soil depth on soil organic matter (SOM) concentration at both experimental sites and sampling periods ($P \leq 0.01$ in every case; Table 3). Organic amendment type produced by far the largest mean square and F-ratio at both sites, confirming that the quantity and chemical quality of organic inputs were the dominant factors controlling SOM accumulation, followed by application method. Irrigation regime and soil depth, while contributing smaller mean squares, were nonetheless highly significant, reflecting the importance of soil moisture availability and the vertical distribution of biological activity in regulating organic matter dynamics.

Interaction effects among the experimental factors were non-significant in every combination tested ($P > 0.05$), indicating that the influence of each factor remained broadly consistent across the levels of the other factors. Because none of the two-, three-, or four-way interactions approached significance, the effect of each factor did not detectably depend on the levels of the other factors within the range of conditions tested: for example, the SOM difference between the control and cattle manure treatments was of comparable magnitude across the application methods, irrigation levels, and depths examined, and the same pattern held for the other factor comparisons.

Coefficients of variation ranged from 1.06 to 1.39%, indicating very high experimental precision. These low CV values confirm the reliability of treatment comparisons and demonstrate tightly controlled experimental conditions across sites and sampling periods.

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Table 3. ANOVA summary for soil organic matter (g kg⁻ ¹) at mid- and end-of-season.

Source of variation	df	Clay soil — Mid-season MS (F)	Clay soil — End-of-season MS (F)	Sandy soil — Mid-season MS (F)	Sandy soil — End-of-season MS (F)
Organic waste type (A)	2	444.3 (F=6987.30**)	444.0 (F=7007.28**)	336.0 (F=6278.81**)	336.0 (F=5784.05**)
Application method (B)	2	144.2 (F=2267.60**)	144.0 (F=2272.63**)	144.0 (F=2690.92**)	144.0 (F=2478.88**)
Irrigation level (C)	1	27.1 (F=426.16**)	27.0 (F=426.12**)	27.0 (F=504.55**)	27.0 (F=464.79**)
Soil depth (D)	1	6.8 (F=106.93**)	6.8 (F=106.53**)	6.7 (F=126.14**)	6.7 (F=116.20**)
A × B	4	NS	NS	NS	NS
A × C	2	NS	NS	NS	NS
A × D	2	NS	NS	NS	NS
B × C	2	NS	NS	NS	NS
B × D	2	NS	NS	NS	NS
C × D	1	NS	NS	NS	NS
Higher-order interactions	—	NS	NS	NS	NS
Error	71	0.063	0.063	0.054	0.058
Corrected total	107	—	—	—	—
CV (%)	—	1.09	1.06	1.38	1.39

*MS = mean square; F = F-ratio (Type III sum of squares, general linear model, IBM SPSS Statistics); df = degrees of freedom; ** P ≤ 0.01 (exact significance P < 0.001 for every main effect shown, confirmed from SPSS output); NS = non-significant (P > 0.05); CV = coefficient of variation.*

3.2 Treatment means

Table 4 presents SOM means for all treatment factors. The RLSD reported beneath each factor block applies to pairwise comparisons within that block at P ≤ 0.05 (see Section 2.5 for why RLSD differs between the three-level and two-level factors).

Table 4. Soil organic matter (g kg⁻ ¹) as affected by experimental factors.

Factor / Treatment	Site 1 Mid-season	Site 1 End-of-season	Site 2 Mid-season	Site 2 End-of-season
Organic Waste Type				
Cattle manure (CM)	26.5 a	27.0 a	19.5 a	20.0 a
Date palm residues (DPR)	23.5 b	24.0 b	17.5 b	18.0 b
Control (C)	19.5 c	20.0 c	13.5 c	14.0 c
RLSD (P ≤ 0.05)	0.12	0.12	0.11	0.11
Application Method				
Uniform mixing (MIX)	25.2 a	25.6 a	18.8 a	19.3 a
Placement at 20 cm (L20)	23.1 b	23.7 b	16.8 b	17.3 b
Placement at 10 cm (L10)	21.2 c	21.7 c	14.8 c	15.3 c

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RLSD ($P \leq 0.05$)	0.12	0.12	0.11	0.11
Irrigation Level				
Full irrigation (I100, 100% AW)	23.7 a	24.2 a	17.3 a	17.8 a
Deficit irrigation (I80, 80% AW)	22.7 b	23.1 b	16.3 b	16.8 b
RLSD ($P \leq 0.05$)	0.10	0.10	0.09	0.09
Soil Depth				
Surface (0–15 cm)	23.4 a	23.9 a	17.1 a	17.6 a
Subsurface (15–30 cm)	22.9 b	23.4 b	16.6 b	17.1 b
RLSD ($P \leq 0.05$)	0.10	0.10	0.09	0.09

All values in g kg⁻¹, rounded to two decimal places. Within a factor block and column, means followed by a different letter differ significantly ($P \leq 0.05$, RLSD test); means were fully separated in every block (all pairwise differences exceeded RLSD). Each mean is a marginal (factor-level) mean pooled across the levels of the other three factors within the same site × season combination (n = 36 for amendment type and application method; n = 54 for irrigation level and soil depth; see Section 2.5). RLSD = Revised Least Significant Difference at $P \leq 0.05$. AW = available water. All interaction effects were non-significant ($P > 0.05$).

3.3 Effect of organic waste type

Expressed as a percentage of dry soil mass, the season-end SOM values in Table 4 range from about 1.35% (control, sandy loam soil) to about 2.70% (cattle manure, silty clay soil), consistent with the pre-experiment baseline organic matter measured for both sites before the experiment began (1.86% for the silty clay soil and 0.97% for the sandy loam soil; Table 1) and with the moderate, gradual build-up in SOM expected over a single growing season.

Cattle manure produced the highest SOM at both sites and across both assessment periods (Table 4). In the silty clay soil, season-end SOM under CM (27.0 g kg⁻¹) significantly exceeded DPR (24.0 g kg⁻¹, +12.5%) and the control (20.0 g kg⁻¹, +35.0%), with all pairwise differences exceeding the corresponding RLSD ($P \leq 0.05$). The same ranking was observed in the sandy loam soil (20.0, 18.0, and 14.0 g kg⁻¹ for CM, DPR, and the control, respectively; CM exceeded the control by 42.9% and DPR by 11.1%), confirming the consistency of amendment performance across contrasting soil textures. These findings are broadly consistent with reports that both cattle manure and date palm residues increase organic matter content and improve related soil properties under Iraqi field conditions [2].

This superiority of CM may be partly explained by its narrower C:N ratio (14:1), which is thought to accelerate microbial substrate utilisation and to promote earlier formation of humic-like substances that can become integrated into the clay–humus complex, mechanisms documented in other manure-amended systems though not directly measured here [8,13,14]. Composted cattle manure is also recognised as a fertility-enhancing amendment that improves the release and retention of plant-available nutrients while sustaining microbial biomass, reinforcing its contribution to SOM build-up [3]. Consistent with this, indicators of soil biological health such as microbial abundance and enzyme activity typically respond positively to manure-derived organic inputs [4,32], which may partly explain the more rapid SOM accumulation observed under CM relative to DPR.

Date palm residues produced intermediate SOM values, exceeding the unamended control by 20.0% in the silty clay soil and 28.6% in the sandy loam soil at season end, likely reflecting their recalcitrant lignin- and wax-rich

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composition, which is generally reported to retard decomposition and delay humification relative to manure [10,17]. We did not directly analyse the cellulose, lignin, or wax content of the palm residues used here, so this explanation is drawn from the composition typically reported for date palm biomass in the literature rather than from measurements on our own material, and should be read accordingly. The progressive increase in SOM from mid- to end-of-season under both amendments is consistent with the gradual, time-dependent transformation of compost-derived carbon reported elsewhere [16], although microbial necromass formation itself was not directly measured in the present study.

The consistently larger absolute SOM values recorded in the silty clay soil, irrespective of amendment type, are consistent with the generally greater capacity of clay-dominated soils to physically and chemically protect organic compounds — for example through mechanisms such as ligand exchange, cation bridging, and aggregate formation that have been documented in other clay-rich systems, although these mechanisms were not directly measured in the present study [18,26]. Fine-textured soils are also reported to develop a denser macroaggregate pore architecture that can shelter organic carbon and sustain higher microbial abundance within protected microsites, which may further favour long-term SOM retention relative to the coarser-textured sandy loam soil [34]. Beyond this difference in absolute SOM level, the two textures likely also differ in how long an amendment-driven gain persists once inputs stop: clay-rich soils are generally expected to retain added organic matter for longer than sandy soils, which typically lose unprotected carbon more quickly once decomposition proceeds unchecked by mineral protection. The present single-season design cannot distinguish a difference in retention duration from a difference in retention capacity, and this should be treated as a separate, untested dimension of the clay-versus-sand comparison rather than assumed to follow the same pattern as the magnitude difference reported here.

3.4 Effect of application method

Uniform mixing (MIX) consistently produced higher SOM than placement at 20 cm (L20) or 10 cm (L10) (Table 4). At season end, MIX exceeded L10 by 18.0% in the silty clay soil and by 26.1% in the sandy loam soil, and exceeded L20 by 8.0% and 11.6%, respectively; all pairwise differences among MIX, L20, and L10 exceeded the corresponding RLSD at both sites and in both seasons. Because roots at both sites explored the full 0–30 cm profile, the effect of application method is unlikely to reflect differences in root access to the amendment; a more plausible explanation is that uniform mixing distributes the organic material across a larger volume of soil and brings it into contact with a larger pool of microorganisms and mineral surfaces, whereas depth placement concentrates the same amount of material within a narrower band. We did not directly measure the spatial distribution of organic carbon within the profile, so this remains a plausible hypothesis consistent with the pattern of means rather than a directly demonstrated mechanism.

Uniform incorporation may perhaps increase SOM accumulation by increasing substrate–microbe contact and reducing surface exposure of organic residues relative to depth placement, in line with mechanisms reported elsewhere [25,30,31]; however, microbial biomass and enzyme activity were not measured in the present study, so this explanation should be treated as a plausible interpretation rather than a demonstrated cause. In contrast, depth-localised placement concentrates decomposition within a narrower zone, which may restrict microbial colonisation and alter the distribution of organic carbon fractions across the profile [3,27].

3.5 Effect of irrigation level

Full irrigation (I100) produced significantly higher SOM than deficit irrigation (I80) at all sites and in both seasons (Table 4), exceeding it by 4.8% in the silty clay soil and 6.0% in the sandy loam soil at season end. These results underline the importance of maintaining

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adequate irrigation for organic matter accumulation in the water-scarce, deficit-irrigated cropping systems typical of southern Iraq [22]. Adequate soil moisture under I100 sustains microbial activity, root growth, and rhizodeposition, collectively supporting the synthesis of humic compounds and the accumulation of microbial necromass [9,11,21]. Sustained moisture availability also favours the progressive transformation of dissolved organic matter into more stable, humified fractions, as reported for well-aerated, adequately irrigated systems [33]. Deficit irrigation, by contrast, intensifies drying–rewetting cycles; under such conditions, water deficit may have limited microbial activity and organic matter transformation, potentially exposing previously protected carbon to microbial attack [20,28].

3.6 Effect of soil depth

Surface soil (0–15 cm) consistently accumulated higher SOM than the subsurface layer (15–30 cm) at both sites (Table 4), by 2.1% in the silty clay soil and 2.9% in the sandy loam soil at season end. This difference, while statistically significant, is smaller than the surface–subsurface gradients commonly reported for undisturbed arid soils; a likely contributor is that the MIX treatment actively redistributes amendment throughout the full 0–30 cm profile for one-third of the plots, which would tend to flatten any depth gradient when means are pooled across application methods, as they are in Table 4. This pattern is broadly consistent with reports that maize root biomass is generally concentrated in near-surface soil layers, although root distribution was not directly measured in the present study [35]. Root biomass and its associated carbon turnover are generally reported to decline with depth, which would be expected to reduce the flux of labile dissolved organic carbon available to fuel microbial activity in deeper horizons [12,15]. We had no depth-resolved clay content data for either site, so we cannot attribute the surface–subsurface gradient to a greater concentration of clay minerals in the topsoil; this remains an open question for future work that includes depth-wise particle-size analysis.

3.7 Interaction effects

No significant interaction effects were detected among any combination of factors at either site or season (Table 3; $P > 0.05$). Each factor appears to operate through a distinct pathway — amendment type governing carbon quality, application method determining spatial distribution, irrigation level regulating microbial activity, and depth reflecting root-driven biological gradients — which may help explain their additive rather than synergistic behaviour [19,30]. In practice, this independence means that the response to any one factor could be predicted without knowing the levels of the other three within the range of conditions tested: the SOM gain from switching to cattle manure, for instance, was of comparable magnitude whether it was combined with uniform mixing or depth placement, and whether under full or deficit irrigation. Practically, this simplifies management recommendations: because the four factors did not interact detectably, producers can select the best-performing level of each factor — cattle manure, uniform mixing, and full irrigation — largely independently of one another, although the combined performance of these three levels applied together was not directly tested in this experiment and remains to be confirmed.

3.8 Practical implications for arid agricultural systems in Iraq and the Gulf region

A key strength of this study is its reliance on a locally abundant organic resource — composted date palm fronds and trunk residues — which has direct relevance for Iraq and the wider Gulf region. Millions of date palm trees in this region generate large volumes of agricultural residue every year that are commonly burned or left unused, creating both environmental pollution and lost agronomic value. The present results indicate that converting these residues into mature, stable compost — following established composting-maturity indicators such as C:N ratio reduction and stabilised pH and electrical conductivity [1] —

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offers a sustainable alternative that measurably improves SOM, alongside the associated benefits of reducing open burning and the disposal problems it creates.

Reliance on date palm residues is also likely to be more sustainable over time than dependence on livestock-derived manure in many parts of the region, because palm residues are produced in large, renewable quantities each year, whereas manure supplies are constrained by livestock numbers, fluctuate seasonally, and are frequently costly and inconsistently available. This pattern is consistent with recent evidence from other arid regions showing that date-palm-waste compost can meaningfully improve soil fertility indicators even under challenging saline, organic-matter-poor conditions [24]. This sustainability comparison is necessarily qualitative: we did not quantify the collection, shredding or size-reduction, transport, and composting costs associated with converting palm residues into finished compost, nor compare them against the costs of sourcing and applying cattle manure. A full economic and logistical comparison, including transport distance from source to field and the energy or labour cost of shredding the fibrous fronds and trunk material before composting, would be needed before this sustainability argument could be used to guide investment decisions.

Accordingly, the findings of the present study extend beyond their immediate scientific contribution to offer a practical, scalable option for soil-fertility management programmes and agricultural-waste recycling initiatives, supporting sustainable agriculture and circular-economy approaches in arid and semi-arid environments such as southern Iraq.

4. Conclusions

This study demonstrates that organic waste type, application method, irrigation level, and soil depth each exert significant, largely independent effects on soil organic matter accumulation under maize cultivation in arid southern Iraq, with soil texture modulating the magnitude of the response. Composted cattle manure, thoroughly mixed into the soil profile under full irrigation, was consistently the most effective single combination for building SOM in both the silty clay and sandy loam soils, while composted date palm residues provided a slower but still substantial improvement over the unamended control.

Because all interaction effects were non-significant, the four management factors can be optimised largely independently, which simplifies practical recommendations: producers do not need to fine-tune amendment choice, placement method, irrigation level, or sampling depth in combination with one another to obtain the SOM benefits associated with each individual factor.

Beyond their scientific contribution, these findings support a practical, low-cost strategy for restoring degraded arid soils using organic resources that are already abundant in the region. Composting date palm residues in particular offers a sustainable route for recycling agricultural waste that would otherwise be burned or discarded, aligning soil-fertility management with broader circular-economy and environmental-sustainability goals in southern Iraq and comparable Gulf environments.

Future work should extend this experiment across multiple growing seasons to evaluate the cumulative build-up of SOM under repeated amendment application, should directly test the combined performance of the best-performing factor levels identified here, and should link SOM dynamics directly to maize yield and grain quality to strengthen the case for on-farm adoption.

Author Contributions

Conceptualization, N.M.A.; methodology, N.M.A., S.M.S.A., and A.H.J.M.; formal analysis, N.M.A.; investigation, N.M.A., S.M.S.A., and A.H.J.M.; data curation, N.M.A.; writing — original draft, N.M.A.; writing — review and editing, S.M.S.A. and A.H.J.M.; supervision, S.M.S.A. and A.H.J.M. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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