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Improving soil carbon in semiarid agroecosystems: reclaimed water and mulch effects in cactus-sorghum intercropping

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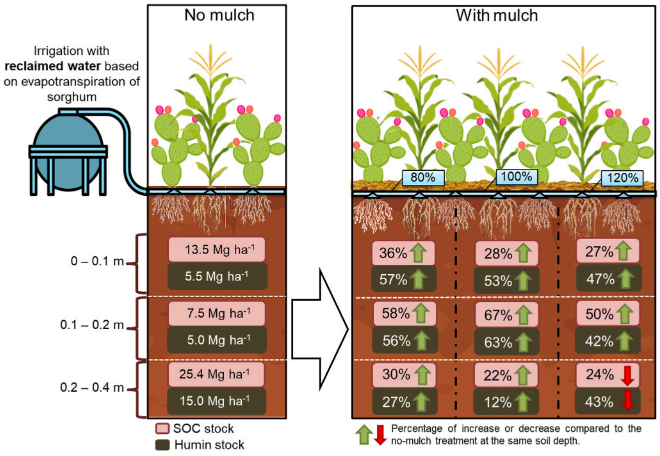
HIGHLIGHTS

- Reclaimed water increases soil carbon stocks in the semiarid region.
- Mulch and reclaimed water synergistically increase C accumulation in SOM pools.
- The combination of reclaimed water and mulch improves forage sorghum yield.
- Irrigation at 80–100 % ETc boosted humic C stocks in tropical semiarid soils.

GRAPHICAL ABSTRACT



Abbreviations: (SOC), Soil organic carbon; (SOM), Soil Organic Matter; (C), Carbon; (ETc), Crop evapotranspiration; (HWEO-C), hot water-extractable carbon; (POX-C), potassium permanganate-oxidizable carbon; (POC), particulate organic carbon; (HS), humic substances; (HU), humin; (FA), fulvic acid; (HA), humic acid; (NV), native vegetation; (80WM), 80 % ETc with mulch; (100WM), 100 % ETc with mulch; (ETo), reference evapotranspiration; (Kp), class-A pan coefficient; (Kc), crop coefficient.

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ABSTRACT

In semiarid regions, soil organic carbon (SOC) stocks and soil organic matter (SOM) pools are often low due to limited biomass input and inadequate management. This study evaluated SOC stocks and SOM fractions in a forage cactus–sorghum intercropping system irrigated with treated sewage water under diverse mulch in the northeastern Brazilian semiarid. The experiment followed a randomized split-plot block design with four replicates. Main plots included four irrigation levels (0, 80, 100, and 120 % of sorghum evapotranspiration (ETc)), and split plots comprised two mulch treatments: no mulch (NM) and mulch (WM) with 8 Mg ha^{-1} of sabi grass, spiny burrgrass, and goosegrass. Soil samples were collected at 0–0.10, 0.10–0.20, and 0.20–0.40 m depths in three sorghum cuts to determine labile SOM fractions: hot water-extractable C (HWEO-C), potassium permanganate-oxidizable C (POX-C), and particulate organic C (POC). In addition, SOC stocks and humic substances (HS), including humin (HU), fulvic acid (FA), and humic acid (HA), were determined at the end of the experiment. Intercropping system productivity was also evaluated. The highest SOC, POC, POX-C, and HWEO-C stocks occurred in 80WM and 100WM treatments, especially in HS, with HU as the dominant component. SOC in the HU fraction exceeded that in native vegetation soils, with threefold increases at 0–0.10 m and six-to sevenfold increases in deeper layers. Soils without irrigation, regardless of mulch, exhibited lower C storage, underscoring the importance of water management. Combining reclaimed water irrigation and mulching enhanced SOC accumulation, particularly in stable humic fractions, boosted carbon sequestration and crop productivity, and fostered sustainable, climate-resilient agriculture in semiarid tropical regions.

1. Introduction

The Caatinga is a unique Brazilian biome, spanning approximately 734,000 km^2, and is classified as a tropical dry forest, and considered as one of the largest semiarid regions in the world (Fernandes et al., 2020). It is predominantly located in northeastern Brazil, a region marked by high population density and rich biodiversity (Londe et al., 2023). The climate is characterized by high temperatures, with annual averages between 25 °C and 30 °C, and low mean annual rainfall, typically below 800 mm, although it can reach up to 1000 mm in peripheral areas. Rainfall is irregular and often intense, while potential evapotranspiration ranges from 1500 to 2000 mm per year, leading to a persistent water deficit that defines the semiarid nature of the region (Torres et al., 2017).

The Caatinga exhibits one of the lowest soil organic carbon (SOC) stocks among Brazilian biomes, estimated at 4.8 PgC (petagram = 10^{15} g), compared to the Atlantic Forest (11.5 PgC), Cerrado (17.1 PgC), and the Amazon Rainforest (36.1 PgC) (Gomes et al., 2019). The low SOC stock, combined with the widespread use of traditional farming practices, has contributed to a significant decline in soil C stocks of 50 % or more (Lacerda et al., 2023; Menezes et al., 2021; Tomaz et al., 2024). Therefore, the implementation of strategies that promote C sequestration and storage in semiarid environments is essential to advance sustainable agricultural systems. Thus, it is also critical to assess C dynamics across different soil organic matter (SOM) fractions and to understand how specific management practices influence C distribution within these fractions.

The use of reclaimed water or treated wastewater for irrigation, combined with soil mulching, has shown promise in this regard, particularly in intercropping systems involving economically and socially important crops such as forage cactus (*Opuntia stricta*) and sorghum (*Sorghum sudanense*). These species exhibit complementary root architectures that contribute to C input in both surface and subsurface soil layers. *Opuntia* species have a high root density concentrated within the top 0–0.5 m (Santana et al., 2024), with root biomass production of up to 136 g per plant, contributing approximately 0.4 g of C to the soil (Dubeux Junior et al., 2013). In contrast, sorghum develops a large, deep root system capable of exuding root-derived C at depths exceeding 2 m (Lamb et al., 2022). This intercropping strategy enhances biomass production, improves C inputs, and optimizes nutrient, water, and light use efficiency, along with the synergistic effects among species (Chimonyo et al., 2018; Jardim et al., 2021; Lima et al., 2018).

The use of reclaimed water for supplementary irrigation in agriculture provides multiple benefits for regions facing extreme climatic conditions, including increased nutrient availability for crops, reduced production costs, increased protection of aquatic ecosystems, and enhanced SOM content through higher biomass production (Adrover et al., 2017). Mulching further contributes to controlling hydric erosion in semiarid environments (Lima et al., 2020) and promotes C sequestration in soils (Silva et al., 2019). Specifically, mulching increases particulate organic carbon (POC) stocks, especially in sandy loam soils, where POC plays a critical role in SOC storage (Nisar and Benbi, 2024). This effect is linked to improved macroaggregate stability and enhanced root development (De Oliveira Ferreira et al., 2018; Six et al., 2004).

Use of drip irrigation can accelerate the transformation of POC, enhance decomposition processes, and influence labile SOM fractions such as oxidizable C (POX-C) and hot water-extractable C (HWEO-C) (Liu et al., 2024; Núñez et al., 2022). The integration of drip irrigation with mulching and no tillage (NT) improves soil structure and facilitates C sequestration in soils of semiarid regions, particularly those vulnerable to salinization and degradation (Garcia-Franco et al., 2021). Results from some short-term studies indicate that combining irrigation and mulching increases SOC content, especially in the 0–0.05 m soil layer (Chatterjee et al., 2018). However, cultivation and irrigation may also increase exposure of labile fractions to microbial processes, such as POX-C and POC, and thus accelerate SOM oxidation (Mandal et al., 2020). Moreover, more soluble fractions such as HWEO-C can be percolated by irrigation water and leached out of the root zone (Núñez et al., 2022).

Assessing the effects of irrigation with reclaimed water and mulching on SOM pools and C sequestration is crucial for advancing the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger and Sustainable Agriculture), SDG 6 (Clean Water and Sanitation), and SDG 13 (Climate Action) (United Nations, 2015). Thus, the present study is based on the hypothesis that combining reclaimed water irrigation with mulching (8 Mg ha^{-1}) in forage cactus–sorghum intercropping systems enhances soil C storage. Therefore, the specific objective of the study is to evaluate the effects of different levels of irrigation by reclaimed water and with and without mulching on SOC stocks and the distribution of SOM pools in forage cactus–sorghum intercropping systems in the Brazilian semiarid region.

2. Methods

The study was conducted at the Mutuca Hydroagricultural Reuse Unit in Pesqueira, Pernambuco, Brazil (8°16′50.94″S, 36°34′17.63″W; elevation: 654 m). The site lies within the Borborema Plateau geoenvironmental unit, characterized by high massifs, hills, rugged terrain, and deep, narrow valleys, with vegetation dominated by sub-deciduous and deciduous forests (CPRM- Serviço Geológico do Brasil, 2005). The climate is classified as hot semiarid (Köppen), with a mean annual temperature of 26 °C, relative humidity of 73 %, and average annual precipitation of 670 mm, mostly received between May and August.

The soil is classified as Planosol Eutric (IUSS Working Group WRB, 2022). The 3,614 m^2 experimental area has been used for research since 2009. Initial soil preparation included disking, followed by the use of animal manure. Previous crops included rainfed and irrigated cotton (*Gossypium hirsutum*, cultivar BRS Safira) with reclaimed water, and managed with weed control and insecticide applications for aphids. In 2015, moringa *(Moringa oleifera)* was established under drip irrigation with reclaimed water and fertilized with bovine manure. Forage sorghum (*Sorghum bicolor*) was cultivated in 2018 and 2019 under similar irrigation and mulching practices, using coconut husk and ground moringa as mulch materials.

2.1. Experimental design and management system of the study area

The experiment was laid out according to the randomized block design in a split-plot with four replicates. Treatments consisted of four irrigation regimes (0 %, 80 %, 100 %, and 120 % of sorghum crop evapotranspiration) combined with two mulch levels: with mulch (WM, 8 Mg ha^{-1}) and without mulch (NM, 0 Mg ha^{-1}), resulting in eight treatments (0NM, 80NM, 100NM, 120NM, 0WM, 80WM, 100WM, 120WM) in an intercropping system of forage cactus and sorghum.

Each block contained four plots (of 15 m^2 area), each with four rows of cactus spaced 1.0 m between rows and 0.2 m between plants, and four rows of sorghum seeded 0.5 m from cactus rows in 0.5 m deep furrows. Plots 0NM and 0WM were left uncultivated (Fig. 1).

Forage cactus was planted first, followed by sorghum seeded 11 months later, after which irrigation commenced. Mulch, composed of grasses (*Urochloa mosambicensis*, *Cenchrus echinatus, Eleusine indica*), was applied three times (total of 24 Mg ha^{-1}, corresponding to a C input of 9.9 Mg ha^{-1}): initially at 7 months after planting of cactus (September 2021), at the time of seeding sorghum (April 2022), and one month after the first sorghum harvest (August 2022).

Sorghum was thinned for uniformity and grown in three 60- to 90-day cycles: first cut in July 2022, second 60 days later, and third 60 days after the second cut. Forage cactus was harvested 18 months after planting (Fig. 1).

Irrigation was via a drip system, managed based on daily evaporation from a Class A Pan. ETc was calculated using sorghum crop coefficients (Kc) for different growth stages: establishment (0.4), vegetative (1.1), flowering (1.0), and maturity (0.7) (Costa et al., 2017). Reference evapotranspiration (ETo) and the class-A pan coefficient (Kp) were calculated from pan evaporation, and irrigation was applied every two days. Reclaimed water comprised domestic effluent of 150 households (~3000 L Day^{-1}), treated via screening, sand filtration, an Upflow Anaerobic Sludge Blanket (UASB) reactor with anaerobic filter, and polishing lagoon (Tomaz et al., 2025). Applied irrigation depths per sorghum cut were: First cut: 80 % = 26.7 mm; 100 % = 33.1 mm; 120 % = 39.7 mm; Second cut: 80 % = 77.7 mm; 100 % = 97.1 mm; 120 % = 116.5 mm; Third cut: 80 % = 63.98 mm; 100 % = 79.97 mm; 120 % = 95.96 mm.

2.2. Sampling and characteristics of treated wastewater

Soil samples were collected from 0 to 0.10, 0.10–0.20, and 0.20–0.40 m depths for chemical and physical analyses (Table S1). Sorghum productivity was assessed after each harvest by collecting plants from each subplot, drying them at 65 °C, and determining dry matter content. Forage cactus was harvested 18 months after planting. Concurrently with sorghum harvests, soil samples were collected from the same depths between cactus and sorghum rows to evaluate SOC levels across different carbon pools (POC, POX-C, and HWEO-C). Analyses of SOC and humic substances (humic acid (HA), fulvic acid (FA) and humin (HU)), were performed only at the end of the experiment. Additionally, soil samples were also obtained under native vegetation for the corresponding depths for comparison.

Total organic carbon contents in reclaimed water and mulch material were determined as 24.8 mg L^{-1} and 404.7 g kg^{-1} C, respectively. Thus, inputs of C from reclaimed water and mulch during the experimental period were calculated (Tables S2 and S3). Total phosphorus in reclaimed water was determined following the method of Parron et al. (2011), while concentrations of metals and metalloids (As, Ba, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, Pb, Se, Zn) were measured via ICP-OES according to USEPA (1992) (Table S2).

2.3. Total soil C stock

The SOC contents were determined at the end of the experiment by the method of Yeomans and Bremner (1988). The SOC stocks were calculated using the soil equivalent mass method (Ellert and Bettany, 1995). SOC stocks of soil C pools were also obtained by the same method as outlined in Eq. (1):

$$\text{SOC stock (Mg ha}^{-1}\text{)} = \text{SOC (kg ha}^{-1}\text{)} * \text{soil bulk density (Mg m}^{-3}\text{)} * \text{layer volume (m}^{3}\text{)} \qquad \text{Eq.1}$$

where, SOC = soil organic carbon.

2.4. Particulate organic carbon and mineral-associated organic carbon

Particulate organic carbon was determined by the method of Cambardella and Elliott (1992). A 20 g soil sample was dispersed in a 5 g L^{-1} sodium hexametaphosphate solution and shaken for 16 h on a horizontal shaker. The suspension was then passed through a 53 μm sieve, and the retained material was oven-dried at 65 °C. The C content of the dried fraction was determined by the wet oxidation method of Yeomans and Bremner (1988).

2.5. Hot water extracted carbon and potassium permanganate oxidized carbon

The HWEO-C was determined according to the methodology adapted from Ghani et al. (2003), where C measurement was done by the method of Yeomans and Bremner (1988). The POX-C was determined using a spectrophotometer, following the method of Blair et al. (1995) and modified by Shang and Tiessen (1997).

2.6. Carbon of the HU, HA, and FA fractions

Extraction of humic substances was performed by using 1 g of air-dried soil and 10 mL of 0.1 mol L^{-1} NaOH. The suspension was shaken for 1 h on a vertical shaker, allowed to rest for 24 h, and then centrifuged for 20 min. The resulting alkaline extract, containing humic acid and fulvic acid, was acidified to pH 2.0 using 20 % H_2SO_4 to precipitate the HA fraction. After resting for 18 h, the solution was centrifuged for 5 min. The supernatant, representing the FA fraction, was collected into 50 mL flasks. The HA precipitate was redissolved in 30 mL of 0.1 mol L^{-1} NaOH.

Carbon contents in HA and FA were determined by wet digestion. The residual material, corresponding to the humin fraction, was oven-dried at 45 °C, and its C content was quantified by acid digestion using $K_2Cr_2O_7$, following the procedures of Teixeira et al. (2017) and Yeomans and Bremner (1988).

2.7. Data analysis

SOC stocks and C pool data were tested for normality using the Shapiro–Wilk test, confirming a normal distribution. Subsequently, analysis of variance (ANOVA) was conducted using the F-test in SISVAR 5.0 software (Ferreira, 2010), with a significance level of 5 %. When

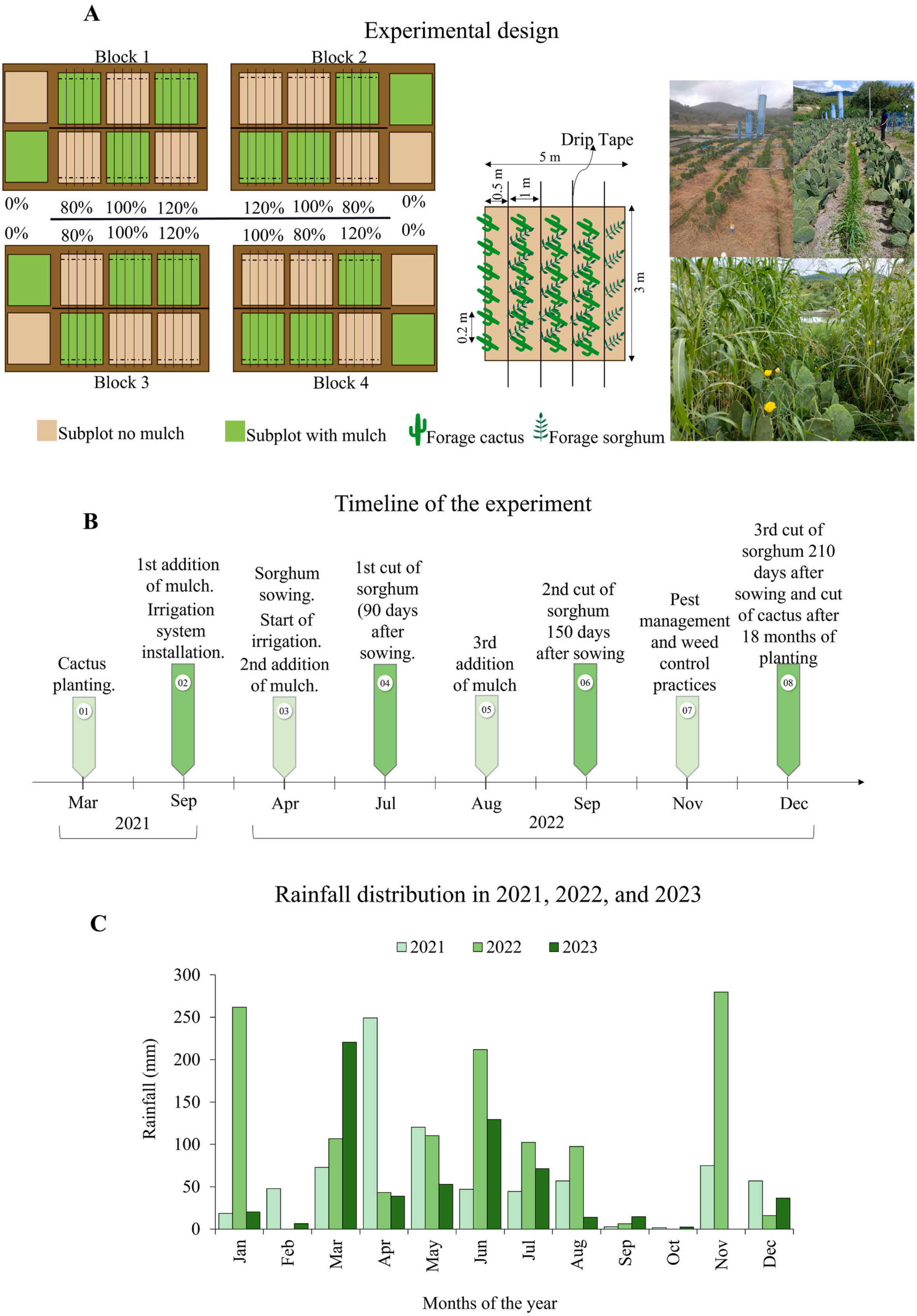

Fig. 1. (A) Experimental design in split plots with four irrigation depths with reclaimed water in the plots (0, 80, 100 and 120 % of the sorghum ETc) and two mulch rates in the subplots (0 and 8 Mg ha^{-1}) in a consortium of forage cactus and sorghum; (B) Timeline of the experiment; (C) Rainfall distribution in 2021, 2022, and 2023.

significant differences were detected, means were compared using Tukey's test at the 5 % level. In addition, data from the final soil sampling and the last sorghum harvest were compared with those from native vegetation, also using Tukey's test ($p < 0.05$). Pearson correlation analysis was performed in R software using data from the final sampling to assess relationships between SOC, carbon pools, and crop productivity at each depth.

3. Results

3.1. SOC stocks

SOC stocks were generally higher under mulched than without mulch treatments (WM), especially for 80WM and 100WM. At 0–0.10 m, irrigation with 80 % ETc and 8 Mg ha^{-1} mulch caused a significant individual effect ($p < 0.05$). At 0.10–0.20 m and 0.20–0.40 m, SOC stock increased by 2 % and 38 % for 80WM, and by 42 % and 19 % for 100WM, respectively, compared to that under NM (Fig. 2A). Further, SOC stock was positively correlated with C pools at 0–0.10 m with POX-

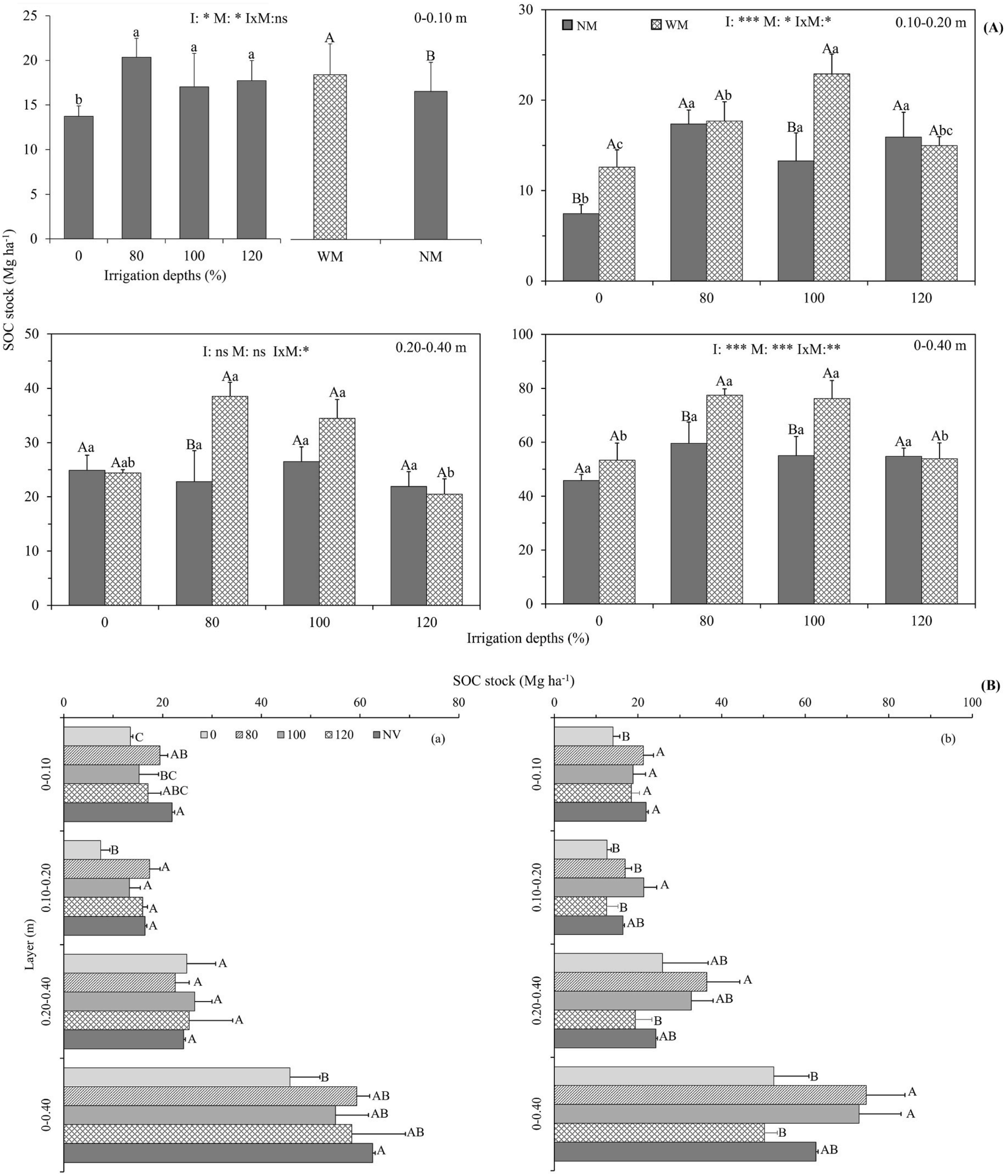

Fig. 2. SOC stock under different irrigation depths with reclaimed water (0, 80, 100, and 120 % of sorghum ETc), with different mulch rates (0 and 8 Mg ha^{-1}) (A); and SOC stocks compared with native vegetation (B): (a) No mulch; (b) With mulch. Capital letters indicate the effect of mulch, and lower-case letters indicate the effect of irrigation depths by Tukey's test at 5 % significance. Significance is indicated by the symbols *, **, ***, and ns when P < 0.05, 0.01, 0.001, or not significant. I = irrigation; M = mulch; I x M = interaction of irrigation with mulch.

C, HU, and FA; at 0.10–0.20 m with POC, POX-C, HU, HA, and FA; and at 0.20–0.40 m with POC, POX-C, HU, and HA (Fig. 5, Table S4).

In the 0–0.40 m layer, SOC stocks increased by 8–26 % in 0WM, 80WM, and 100WM compared to those under NM. Interestingly, soil under 120NM exhibited 7 % higher SOC stock than soils under WM treatments (Fig. 2A). Although SOC stock under any treatment significantly exceeded that under native vegetation, SOC stock under 100WM was 28 % more at 0.10–0.20 m, and that under 80WM and 100WM was 33 % and 26 % more at the 0.20–0.40 m layer, respectively (Fig. 2B).

3.2. *SOC stock in the labile pools*

POC stocks increased significantly with mulch, especially in the 0–0.10 m layer in the first cut (+37 %) and under 80 % ETc (up to 32 %) (Fig. 3). In the 0.10–0.20 m layer, only 80 % ETc showed an effect, while at 0.20–0.40 m, POC stock in WM treatments was more than that under NM by 39–60 %, except in the 120NM treatment. In the second cut, POC stock under 100 WM treatment was 33 % more for the 0–0.10 m layer, and mulching increased POC by 8 % for the 0.10–0.20 m layer. In the third cut, the irrigation level of 80 % ETc improved POC in the surface layer, and under 80WM and 100WM treatments were more at depth (by 47–100 % at 0.10–0.20 m; and by 32–47 % at 0.20–0.40 m). In the third cut, POC stocks under none of the treatments exceeded those in the soil under NV (Table 1). However, POC stock was positively correlated with SOC and other C fractions, especially in the layer below 0.10 m depth (Fig. 5, Table S4).

The POX-C stock peaked in 80WM treatment during the first and third cuts for 0–0.10 m depth (Fig. 3). For the 0.10–0.20 m depth, soil under 0WM, 100WM, and 120WM had variable significance across different cuts. At 0.20–0.40 m depth, the soil under 80WM had the highest POX-C stock. Furthermore, POX-C stock correlated positively with SOC, POC, HU, and HA, but negatively with HWEO-C and FA in subsoil layers (Fig. 5, Table S4).

HWEO-C was enhanced by mulch and 80 % ETc, with gains up to 71 % in WM treatments at 0–0.10 m and 56 % under 80 % ETc (Fig. 3). Treatment effects were also observed in subsoil layers across cuts. HWEO-C showed mixed correlations: positive with POX-C, POC, and HU at 0.10–0.20 m; negative with HA at 0–0.10 m and with POX-C and HA at 0.20–0.40 m depth (Fig. 5, Table S4).

3.3. *SOC stock in the stable reservoir*

At 0–0.10 m depth, HU stocks were significantly higher in 80WM and 100WM compared to 0WM and 120WM treatments, with increases ranging from 12 % to 41 % ($p < 0.05$) (Table 2). HU stocks in soil under these treatments also exceeded those under their NM counterparts by 11 % and 13 %, respectively. At 0.10–0.20 m, soil under 100WM treatment had the highest HU stock, which was 15–55 % more than that in soil under other irrigation regimes. Specifically, the HU stock in soil under 80WM and 100WM was more than that in soil under 80NM and 100NM treatments by 13 % and 27 %, respectively. At 0.20–0.40 m depth, soil under 80WM had significantly more HU stock than that in all NM treatments for the same depths, with increases of 2.1-, 1.2-, and 2.4-fold, and 47 % higher than that under 80NM treatment (Table 2). Furthermore, HU was positively correlated with other SOC fractions for all depths, especially for the subsurface layer (Fig. 5).

For HA, at 0–0.10 m depth, soil under 80WM and 100WM exceeded that in soil under NM treatments by 39 % and 11 %, respectively. At 0.10–0.20 m depth, HA in soil under 80WM and 100WM recorded increases of 79 % and 46 %, respectively. The highest HA stock was observed at 0.20–0.40 m depth in soil under 100WM (5.3 Mg ha^{-1}) treatment, which is significantly higher than that in all other treatments (Table 2).

FA also responded to mulching treatment at 0–0.10 m depth, with soil under 0WM, 80WM, 100WM, and 120WM showing increases of 60 %, 18 %, 39 %, and 50 % to that in soil under NM. At 0.10–0.20 m depth, soil under 100WM recorded the highest FA levels, surpassing those in other WM treatments by 23–32 %. At 0.20–0.40 m depth, however, FA was significantly higher in soil under 80NM and 120NM treatments, with increases of 26 % and 46 % compared with that in soil under WM treatment (Table 2).

Compared to soil under native vegetation, HU stocks were consistently higher across all layers. At 0–0.10 m depth, HU stock in soil under NM treatments ranged from 3.0- to 3.6-fold higher, and that under WM treatments from 2.4- to 4.1-fold higher compared to that in soil under NV (Table 3). At 0.10–0.20 m depth, increases ranged from 1.9 to 3.4 (NM) and 2.0–4.6 (WM), while at 0.20–0.40 m depth, HU stocks reached 4.8–6.8 (NM) and 3.4–8.2 times (WM) those of soil under NV. For HA and FA, none of the treatments exceeded the values in soil under NV (Table 3).

3.4. *Crop productivity*

For forage cactus, 100WM and 120WM treatments showed significantly higher DM yields, with increases of 9 % and 35 %, respectively, compared to those with 100NM and 120NM treatments ($p < 0.05$) (Fig. 4). However, the DM produced under 80WM and 100WM outperformed that under 120WM. For sorghum, in the first cut, DM production under 80WM, 100WM, and 120WM was 47 %, 18 %, and 49 % more, respectively, than that under their NM counterparts. In the second cut, DM production under 80WM and 120WM increased by 35 % and 42 % compared to that under NM treatments, with 80WM surpassing that under 100WM and 120WM treatments by 22 % and 15 %, respectively (Fig. 4).

In the third cut, all mulched treatments (WM) showed significant DM gains compared with those under NM, ranging from 24 % to 37 %, with 100WM being the most productive, and 48 % and 30 % higher than that under 80WM and 120WM, respectively (Fig. 4). Productivity of both crops was positively correlated with SOC stocks and SOM fractions, especially at 0.10–0.20 m depth, with stronger associations found for POX-C, POC, HU, and HA (Fig. 5).

4. Discussion

4.1. *SOC stocks*

This study demonstrated the significant effect of combining reclaimed domestic wastewater irrigation with mulching on SOC stocks and C pools in a tropical semiarid region. These improvements were evident in both surface (0–0.10 and 0.10–0.20 m) and subsurface (0.20–0.40 m) layers. Notably, total SOC stocks and the HU fraction exceeded those found under native vegetation, highlighting the potential of these management practices to restore and enhance soil C stocks in degraded soils of semiarid ecoregions. Land use change is known to strongly reduce SOC stock compared to that under NV (Lacerda et al., 2023; Sánchez–González et al., 2017), but the results presented indicate that irrigation and mulching can counteract such losses, even exceeding the SOC stocks of NV.

Higher SOC stocks observed at 0.20–0.40 m depth likely result from the downward translocation of C fractions, including HWEO-C, HA, and FA, combined with increased rhizodeposition from the deep-rooting forage sorghum. The sandy soil texture facilitates vertical C movement, and the greater C deficit in deeper layers favors its accumulation at depth (de Oliveira Ferreira et al., 2021; Sá et al., 2022).

The positive correlations between total SOC and its pools reaffirm their critical role in C sequestration in soils of a semiarid climate. The highest SOC stocks observed in treatments irrigated with 80 and 100 % of crop evapotranspiration combined with 8 Mg ha^{-1} of mulch likely result from the synergistic effects of optimal irrigation and mulch application, which promoted residue decomposition while preserving SOC. Additionally, the lack of soil tillage after establishing these practices enhanced soil aggregation by forming macroaggregates, physically

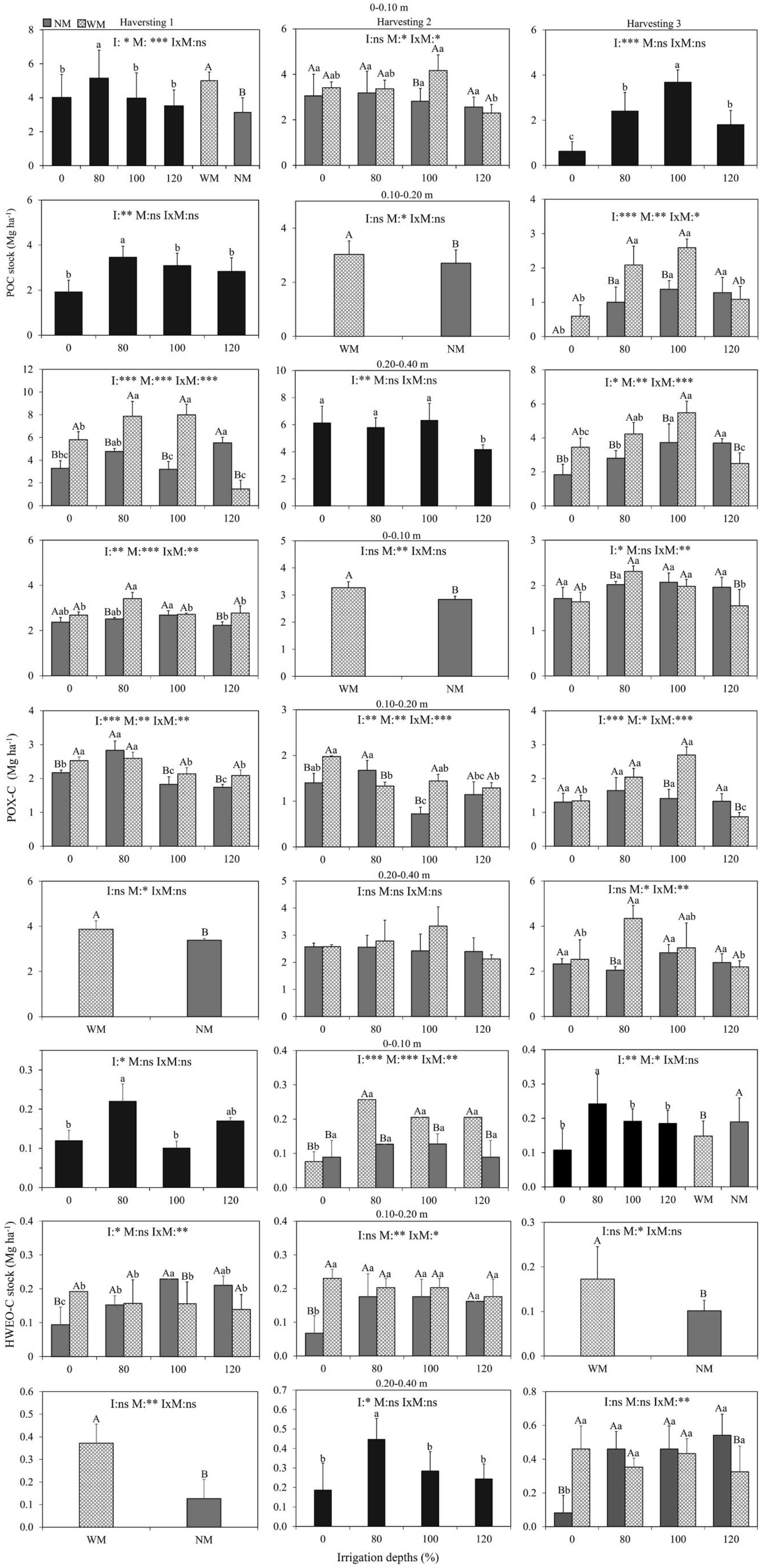

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Fig. 3. POC, POX-C, and HWEO-C stocks under different irrigation depths with reclaimed water (0, 80, 100, and 120 % of sorghum ETc), with 0 and 8 Mg ha^{-1} of mulch and three cuts of the sorghum crop. Capital letters indicate the effect of mulch, and lower-case letters indicate the effect of irrigation depths by Tukey's test at 5 % significance. Significance is indicated by the symbols *, **, ***, and ns when P < 0.05, 0.01, 0.001, or not significant. I = Irrigation depths; M = mulch; WM with mulch and NM = no mulch; I x M = interaction between irrigation and mulch.

Table 1
POC, POX-C and HWEO-C stocks (Mg ha^{-1}) under different irrigation depths with reclaimed water (0, 80, 100 and 120 % of sorghum ETc) with different soil mulch rates compared to native vegetation (NV).

Layers	Mulch	Irrigation depths (%)				
(m)		0	80	100	120	NV
POC stock (Mg ha^{-1})						
0–0.10	NM	$0.4^{\pm0.3}$D	$2.3^{\pm0.9}$C	$3.6^{\pm0.6}$B	$1.5^{\pm0.4}$CD	$5.9^{\pm0.3}$A
0.10–0.20		$0.0^{\pm0.0}$C	$1.0^{\pm0.4}$BC	$1.7^{\pm0.8}$B	$1.3^{\pm0.4}$B	$3.6^{\pm0.2}$A
0.20–0.40		$1.8^{\pm0.6}$C	$2.8^{\pm0.8}$BC	$4.0^{\pm1.3}$B	$3.7^{\pm0.3}$B	$6.6^{\pm0.3A}$
0–0.10	WM	$0.9^{\pm0.4}$D	$2.8^{\pm1.0}$BC	$3.8^{\pm0.6}$B	$1.8^{\pm1.0}$CD	$5.9^{\pm0.3}$A
0.10–0.20		$0.6^{\pm0.03}$C	$2.1^{\pm0.5}$B	$2.6^{\pm0.3}$B	$1.1^{\pm0.4}$C	$3.6^{\pm0.2}$A
0.20–0.40		$3.5^{\pm0.5}$CD	$4.2^{\pm0.7}$BC	$5.2^{\pm1.0}$AB	$2.5^{\pm0.6}$D	$6.6^{\pm0.3}$A
POX-C stock (Mg ha^{-1}))						
0–0.10	NM	$1.7^{\pm0.3B}$	$2.0^{\pm0.1}$B	$2.1^{\pm0.2}$B	$2.0^{\pm0.2}$B	$3.2^{\pm0.3}$A
0.10–0.20		$1.3^{\pm0.3}$B	$1.6^{\pm0.4}$B	$1.4^{\pm0.3}$B	$1.3^{\pm0.2}$B	$3.0^{\pm0.3}$A
0.20–0.40		$2.3^{\pm0.2}$B	$2.1^{\pm0.2}$B	$2.8^{\pm0.4}$B	$2.4^{\pm0.4}$B	$5.3^{\pm0.7}$A
0–0.10	WM	$1.6^{\pm0.2}$C	$2.3^{\pm0.1B}$	$2.0^{\pm0.2}$BC	$1.5^{\pm0.4}$C	$3.2^{\pm0.3}$A
0.10–0.20		$1.3^{\pm0.2}$D	$2.0^{\pm0.3}$C	$2.7^{\pm0.2}$B	$0.9^{\pm0.1E}$	$3.0^{\pm0.3}$A
0.20–0.40		$2.5^{\pm0.9BC}$	$4.3^{\pm0.6\ AB}$	$3.0^{\pm1.1BC}$	$2.2^{\pm0.3BC}$	$5.3^{\pm0.7}$A
HWEO-C stock (Mg ha^{-1}))						
0–0.10	NM	$0.13^{\pm0.09}$C	$0.31^{\pm0.07}$AB	$0.19^{\pm0.05}$BC	$0.19^{\pm0.03}$BC	$0.42^{\pm0.03}$A
0.10–0.20		$0.08^{\pm0.03}$B	$0.08^{\pm0.03}$B	$0.12^{\pm0.05}$B	$0.12^{\pm0.05}$B	$0.28^{\pm0.01}$A
0.20–0.40		$0.08^{\pm0.10}$C	$0.46^{\pm0.10}$AB	$0.46^{\pm0.14}$AB	$0.54^{\pm0.13}$A	$0.25^{\pm0.02}$B
0–0.10	WM	$0.09^{\pm0.03}$C	$0.18^{\pm0.03}$B	$0.19^{\pm0.03}$B	$0.18^{\pm0.05}$B	$0.42^{\pm0.03}$A
0.10–0.20		$0.09^{\pm0.03A}$	$0.27^{\pm0.18}$A	$0.16^{\pm0.00}$A	$0.16^{\pm0.00}$A	$0.28^{\pm0.01}$A
0.20–0.40		$0.46^{\pm0.09}$ns	$0.35^{\pm0.25}$ ns	$0.43^{\pm0.11}$ ns	$0.32^{\pm0.20}$ ns	$0.25^{\pm0.02}$ ns

Letters indicate differences between treatments by Tukey's test at 5 % significance. $^{\pm}$Standard deviation of the mean. NM = no mulch (0 Mg ha^{-1}); WM = with mulch (8 Mg ha^{-1}). The comparisons made here were only with data from the last soil collection, equivalent to the last sorghum cut.

protecting SOC (Tomaz et al., 2024). The intercropping system of forage cactus and sorghum further contributed to SOC through root exudation and increased root density in both surface and subsurface layers, and improved microbial activity, contributing to SOC stock via extracellular polysaccharides production, enzymes, and fungal mycelium production (Chatterjee et al., 2018; Kumar et al., 2024; Lacerda et al., 2023; Liu et al., 2021).

Long-term irrigation with reclaimed water may have a cumulative effect on SOC stocks due to its high content of organic compounds, which favor the formation of organic matter fractions such as HU (Liang et al., 2014; Liu et al., 2021; Weldewahid et al., 2023). Specifically, reclaimed water contributed significantly to SOC inputs, supplying 42.2, 52.8, and 63.5 kg C ha^{-1} for the 80, 100, and 120 % irrigation depths, respectively, across sorghum cycles. Although there was an input via reclaimed water, the mulch contributed even more, with a C input of 9 Mg ha^{-1} during the experimental period. This sustainable carbon input offers a viable strategy to enhance soil C storage in soils of the Brazilian semiarid ecosystem, a region characterized by water scarcity and harsh climate.

Deficit irrigation not only helps maintain SOC stocks but also promotes water savings via drip irrigation (Soni et al., 2021). In the present study, treatments with 80 and 100 % ETc combined with mulch increased SOC stocks by 30 % compared to soils under native vegetation, highlighting the potential of these management practices to restore and even enhance soil carbon stocks in degraded semiarid soils (Chatterjee et al., 2018; Kumar et al., 2024; Zong et al., 2023).

Soils in the Caatinga biome naturally have low SOC accumulation due to climatic factors, high temperatures, irregular rainfall, high evapotranspiration, and the predominance of deciduous vegetation, which limits biomass input and accelerates decomposition of organic matter (Monroe et al., 2021). Thus, mulch application combined with reclaimed water irrigation in the cactus-sorghum intercropping system enhances SOC stocks and carbon pools.

Treatments without irrigation, regardless of mulch application, were characterized by lower SOC levels, probably due to reduced inputs of organic matter and absence of crop root biomass. Furthermore, limited soil moisture storage combined with high temperatures decreases SOC sequestration in semiarid regions by restricting the formation and stabilization of soil organic compounds (Chen et al., 2023; Zhou et al., 2023). These results suggest that the input of biomass alone is not sufficient to provide C storage in semiarid environments if the water regime is inadequate to promote its decomposition and cycling in the system. Therefore, management strategies for sustainable soil use should focus not only on soil but also on water conservation and management in the root zone. In contrast, the 120NM treatment presented a higher stock (7 %) than the 120WM, however, it was not significant, indicating a temporary effect of the accumulation of coverage on the SOC stock.

4.2. Changes in labile and stable SOC reservoirs following the use of reclaimed water combined with soil mulch

Labile SOC fractions (*i.e.*, POC, POX-C, HWEO-C) have high turnover rates and play key roles in the cycling of plant nutrients, stabilization of soil structure, and early detection of management-induced changes in soil functions (Liang et al., 2014). The data presented herein confirm that irrigation with reclaimed water combined with mulch significantly increased POC and POX-C levels compared to non-irrigated treatments. Treatments with 8 Mg ha^{-1} mulch showed higher POC values, which were associated with improved soil structure and increased macroaggregate formation (Nisar and Benbi, 2024; Zong et al., 2023). Mulch

Table 2

Carbon stock (Mg ha^{-1}) of humin (HU), humic acid (HA) and fulvic acid (FA) fractions under different irrigation depths with reclaimed water with soil mulch.

Depth (m)	Mulch	Irrigation depths (%) 0	80	100	120
HU (Mg ha^{-1}))					
0–0.10	NM	$9.1^{\pm 0.6}$Ab	$11.3^{\pm 1.3}$Ba	$10.4^{\pm 0.6}$Bab	$9.0^{\pm 0.5}$Bb
0.10–0.20		$5.5^{\pm 0.4}$Bc	$9.9^{\pm 1.3}$Ba	$7.9^{\pm 0.4}$Bb	$8.9^{\pm 0.8}$Aab
0.20–0.40		$15.0^{\pm 1.0}$Aa	$12.0^{\pm 0.4}$Bb	$16.3^{\pm 0.8}$Aa	$14.1^{\pm 0.6}$Aab
0–0.10	WM	$7.4^{\pm 0.5}$Bc	$12.7^{\pm 0.9}$Aa	$11.6^{\pm 0.9}$Aab	$10.3^{\pm 0.7}$Ab
0.10–0.20		$6.0^{\pm 0.5}$Ad	$11.4^{\pm 1.2}$Ab	$13.5^{\pm 0.7}$Aa	$8.6^{\pm 0.4}$Ac
0.20–0.40		$9.8^{\pm 1.2}$Bc	$20.6^{\pm 0.8}$Aa	$17.0^{\pm 0.7}$Ab	$8.6^{\pm 2.7}$Bc
HA (Mg ha^{-1}))					
0–0.10	NM	$1.4^{\pm 0.3}$Aab	$1.1^{\pm 0.2}$Bb	$1.4^{\pm 0.1}$Ab	$1.8^{\pm 0.2}$Aa
0.10–0.20		$0.6^{\pm 0.1}$Bc	$1.7^{\pm 0.2}$Aa	$1.3^{\pm 0.5}$Bab	$1.0^{\pm 0.2}$Abc
0.20–0.40		$1.4^{\pm 1.1}$Ab	$1.1^{\pm 0.4}$Ab	$2.8^{\pm 1.1}$Ba	$0.2^{\pm 0.2}$Bb
0–0.10	WM	$1.2^{\pm 0.1}$Ab	$1.8^{\pm 0.3}$Aa	$1.5^{\pm 0.3}$Aab	$1.4^{\pm 0.3}$Bab
0.10–0.20		$2.9^{\pm 0.3}$Aa	$1.3^{\pm 0.2}$Bb	$2.4^{\pm 0.3}$Aa	$0.0^{\pm 0.0}$Bc
0.20–0.40		$1.9^{\pm 0.4}$Ab	$1.5^{\pm 0.5}$Ab	$5.3^{\pm 1.0}$Aa	$2.1^{\pm 0.1}$Ab
FA (Mg ha^{-1}))					
0–0.10^{ns}	NM	$1.0^{\pm 0.1}$	$4.0^{\pm 0.4}$***	$2.5^{\pm 0.2}$***	$2.3^{\pm 0.5}$***
0.10–0.20		$2.4^{\pm 0.1}$Aa	$2.3^{\pm 0.4}$Aa	$1.4^{\pm 0.2}$Bb	$2.3^{\pm 0.1}$Aa
0.20–0.40		$1.7^{\pm 1.1}$Ac	$4.7^{\pm 0.2}$Aab	$3.5^{\pm 0.7}$Ab	$4.9^{\pm 0.4}$Aa
0–0.10^{ns}	WM	$2.6^{\pm 0.1}$*	$4.9^{\pm 0.9}$*	$4.1^{\pm 0.6}$*	$4.6^{\pm 0.5}$*
0.10–0.20		$2.5^{\pm 0.4}$Ab	$2.3^{\pm 0.1}$Ab	$3.3^{\pm 0.2}$Aa	$2.2^{\pm 0.0}$Ab
0.20–0.40		$1.8^{\pm 0.4}$Ac	$3.5^{\pm 0.6}$Bab	$4.3^{\pm 0.4}$Aa	$2.6^{\pm 0.4}$Bbc

Lowercase letters indicate differences between the depth and uppercase letters indicate differences between the soil mulch rates. According to the Tukey test at 5 % significance. *** significant effect for 80, 100 e 120 % irrigation depth; *significant effect for the soil mulch rate of 8 Mg ha^{-1}; ns = no significance to interaction; $^{\pm}$Standard deviation of the mean. NM = no mulch (0 Mg ha^{-1}); WM = with mulch (8 Mg ha^{-1}).

enhances aggregate stability and inputs of root-derived C, and thus, promotes POC accumulation through physical protection (De Oliveira Ferreira et al., 2018; Six et al., 2004). It also stimulates microbial activity, accelerates residue decomposition, and promotes its incorporation into the POC pool (Tomaz et al., 2025).

The sorption of partially decomposed or oxidized residues onto mineral surfaces accelerates the formation of stable C (Briedis et al., 2012; Virk et al., 2021). Drip irrigation may facilitate the transformation of POC into stable C forms, especially in sandy soils, where POC serves as a key pathway for SOC stabilization (Nisar and Benbi, 2024). In the present study, strong correlations between POC, POX-C, and HU, particularly at depth, suggest a synergistic role of these fractions in long-term SOC sequestration. Conversely, the absence of mulch may disrupt soil structure, reduce aggregate protection, and increase carbon losses through erosion and oxidation (Virk et al., 2021). Despite the increase in POC in the treatments with coverage, it was observed that they were not sufficient to overcome the NV.

POX-C, though also labile, has a faster turnover than POC and consists of highly oxidizable compounds that are sensitive to land use and land use change. The lower POX-C values compared to those in soil under NV suggest accelerated mineralization by supplemental irrigation. While mulch offers some protection, irrigation enhances microbial activity and increases POX-C decomposition (Mandal et al., 2020). POC, strongly associated with mineral fractions, is less prone to rapid loss. Mulch biomass also supports microaggregate formation and thus, enhances POC stability (De Oliveira Ferreira et al., 2018). The decline in POX-C may also relate to increased non-labile fractions and the high C: N ratio of mulch materials, which contain high lignin and cellulose content (Chatterjee et al., 2018).

The data presented herein show that HWEO-C levels were highest in the subsoil layers, likely due to leaching processes triggered by irrigation and the high temperatures typical of semiarid ecoregions. The downward movement of soluble carbon and its subsequent binding to mineral surfaces promotes the formation of stable organo-mineral complexes, which constitute a major pathway for carbon storage in deeper soil horizons (Núñez et al., 2022). The observed negative correlation between HWEO-C and HA suggests that humic acids may act as precursors to this labile carbon fraction. Reclaimed water, rich in dissolved organic

Table 3

Carbon stock (Mg ha^{-1}) of humin (HU), humic acid (HA) and fulvic acid (FA) fractions under different irrigation depths with reclaimed water (0, 80, 100 and 120 % of sorghum ETc) with different soil mulch rates compared to native vegetation (NV).

Depth (m)	Mulch	Irrigation depths (%) 0	80	100	120	NV
HU (Mg ha^{-1}))						
0–0.10	NM	$9.1^{\pm 0.6}$B	$11.3^{\pm 1.3}$A	$10.4^{\pm 0.6}$AB	$9.0^{\pm 0.5}$B	$3.1^{\pm 0.4}$C
0.10–0.20		$5.5^{\pm 0.4}$C	$9.9^{\pm 1.3}$A	$7.9^{\pm 0.4}$B	$8.9^{\pm 0.8}$AB	$2.9^{\pm 0.8}$D
0.20–0.40		$15.0^{\pm 1.0}$AB	$12.0^{\pm 0.4}$C	$16.3^{\pm 0.8}$A	$14.1^{\pm 0.6}$B	$2.5^{\pm 0.4}$D
0–0.10	WM	$7.4^{\pm 0.5}$C	$12.7^{\pm 0.9}$A	$11.6^{\pm 0.9}$AB	$10.3^{\pm 0.7}$B	$3.1^{\pm 0.4}$D
0.10–0.20		$6.0^{\pm 0.5}$D	$11.4^{\pm 1.2}$B	$13.5^{\pm 0.7}$A	$8.6^{\pm 0.4}$C	$2.9^{\pm 0.8}$E
0.20–0.40		$9.8^{\pm 1.2}$C	$20.6^{\pm 0.8}$A	$17.0^{\pm 0.7}$B	$8.6^{\pm 2.7}$C	$2.5^{\pm 0.4}$D
HA (Mg ha^{-1}))						
0–0.10	NM	$1.4^{\pm 0.3}$BC	$1.1^{\pm 0.2}$C	$1.4^{\pm 0.1}$BC	$1.8^{\pm 0.2}$B	$5.8^{\pm 0.4}$A
0.10–0.20		$0.6^{\pm 0.1}$C	$1.7^{\pm 0.2}$B	$1.3^{\pm 0.5}$BC	$1.0^{\pm 0.2}$BC	$4.5^{\pm 0.6}$A
0.20–0.40		$1.4^{\pm 1.1}$C	$1.1^{\pm 0.4}$C	$2.8^{\pm 1.1}$B	$0.2^{\pm 0.2}$C	$4.5^{\pm 0.1}$A
0–0.10	WM	$1.2^{\pm 0.1}$B	$1.8^{\pm 0.3}$B	$1.5^{\pm 0.3}$B	$1.4^{\pm 0.3}$B	$5.8^{\pm 0.4}$A
0.10–0.20		$2.9^{\pm 0.3}$B	$1.3^{\pm 0.2}$C	$2.4^{\pm 0.3}$B	$0.0^{\pm 0.0}$D	$4.5^{\pm 0.6}$A
0.20–0.40		$1.9^{\pm 0.4}$B	$1.5^{\pm 0.5}$B	$5.3^{\pm 1.0}$A	$2.1^{\pm 0.1}$B	$4.5^{\pm 0.1}$A
FA (Mg ha^{-1}))						
0–0.10	NM	$1.0^{\pm 0.1}$D	$4.0^{\pm 0.4}$B	$2.5^{\pm 0.2}$C	$2.3^{\pm 0.5}$CD	$5.9^{\pm 1.3}$A
0.10–0.20		$2.4^{\pm 0.1}$B	$2.3^{\pm 0.4}$B	$1.4^{\pm 0.2}$C	$2.3^{\pm 0.1}$B	$5.4^{\pm 0.8}$A
0.20–0.40		$1.7^{\pm 1.1}$B	$4.7^{\pm 0.2}$A	$3.5^{\pm 0.7}$A	$4.9^{\pm 0.4}$A	$4.1^{\pm 0.3}$A
0–0.10	WM	$2.6^{\pm 0.1}$C	$4.9^{\pm 0.9}$AB	$4.1^{\pm 0.6}$BC	$4.6^{\pm 0.5}$AB	$5.9^{\pm 1.3}$A
0.10–0.20		$2.5^{\pm 0.4}$BC	$2.3^{\pm 0.1}$BC	$3.3^{\pm 0.2}$B	$2.2^{\pm 0.0}$C	$5.4^{\pm 0.8}$A
0.20–0.40		$1.8^{\pm 0.4}$C	$3.5^{\pm 0.6}$AB	$4.3^{\pm 0.4}$A	$2.6^{\pm 0.4}$BC	$4.1^{\pm 0.3}$A

Letters indicate differences between treatments by Tukey's test at 5 % significance. $^{\pm}$Standard deviation of the mean. NM = no mulch (0 Mg ha^{-1}); WM = with mulch (8 Mg ha^{-1}).

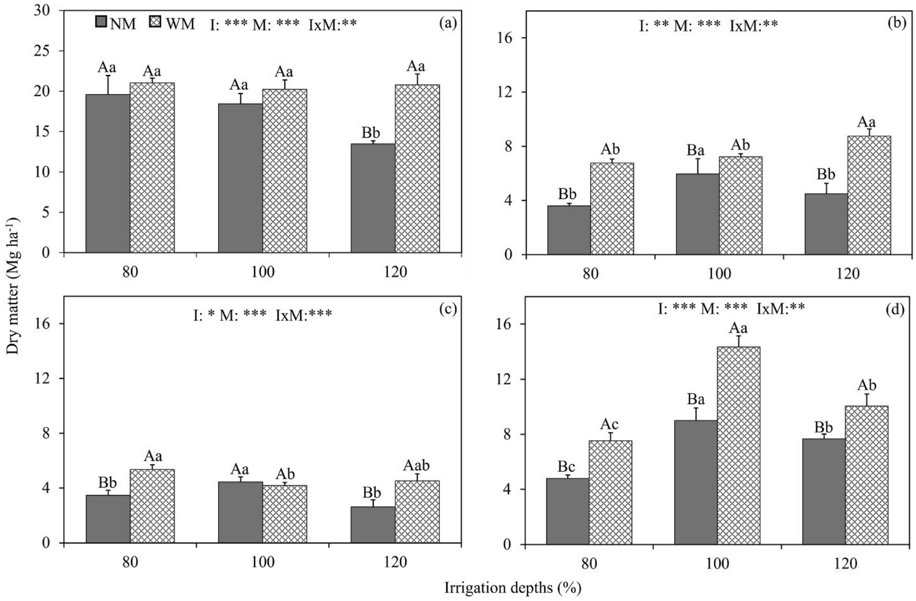


Fig. 4. Dry matter of forage cactus (a); and dry matter of sorghum under different irrigation depths in three harvesting seasons: (b)-after 90 days of sowing, (c)-after 150 days of sowing, (d)-after 210 days of sowing. Capital letters indicate the effect of mulch, and lower-case letters indicate the effect of irrigation depths by Tukey's test at 5 % significance. Significance is indicated by the symbols *, **, ***, and ns when $P < 0.05$, 0.01, 0.001 or not significant. I= Irrigation depths; M = mulch: WM = with mulch and NM = no mulch; I x M = interaction between irrigation and mulch.

carbon, stimulates microbial activity and the release of carbohydrates, enzymes, and other compounds that contribute to HWEO-C formation. Additionally, root exudates and cell lysates from crops further enhance the accumulation of this fraction, favoring carbon stabilization in subsoil layers (Ghani et al., 2003).

Among humic substances, the humin (HU) fraction accounted for the highest SOC stocks, particularly under the 80 % irrigation treatment combined with 8 Mg ha^{-1} of mulch, across all soil depths. This consistent dominance of HU suggests its greater persistence, as it is commonly associated with mineral complexes (Almeida et al., 2021; Rosset et al., 2024). In contrast, HU stocks were significantly lower in soil under NV, while treatments with 80WM and 100WM showed 76 % and 73 % higher HU-C stocks, respectively. These findings confirm that the long-term application of reclaimed water and mulch promotes the accumulation of this more stable C fraction (Tiwari et al., 2023).

Fulvic acid (FA) stocks generally exceeded those of humic acid (HA), except under NV conditions, where FA and HA contents were similar and higher than those observed in the experimental treatments. Irrigation likely accelerated mulch decomposition, thereby increasing FA levels. Due to its greater mobility and short-term contribution to SOC (Lira Junior et al., 2020), FA responds rapidly to biomass inputs and root activity. The root systems of cactus and sorghum further contributed to C incorporation into multiple SOC pools (Jaouadi et al., 2019).

Semiarid conditions and cultivation-induced oxidation accelerate SOM mineralization and reduction in HA stocks (Ben Mbarek et al., 2024). Nonetheless, higher HA concentrations have been reported in soil under conservation systems (Datta et al., 2022). Despite lower HA levels than FA, irrigation and mulch may have supported its formation, particularly at 100 % irrigation. HA improves soil fertility, nutrient retention, and aggregation, especially in Ca^{2+}-rich soils, thereby enhancing water dynamics and porosity (Datta et al., 2022; Tiwari et al., 2023). However, HA and FA are less stable and more prone to leaching or decomposition, processes that may reduce their stocks over time (Rosset et al., 2024).

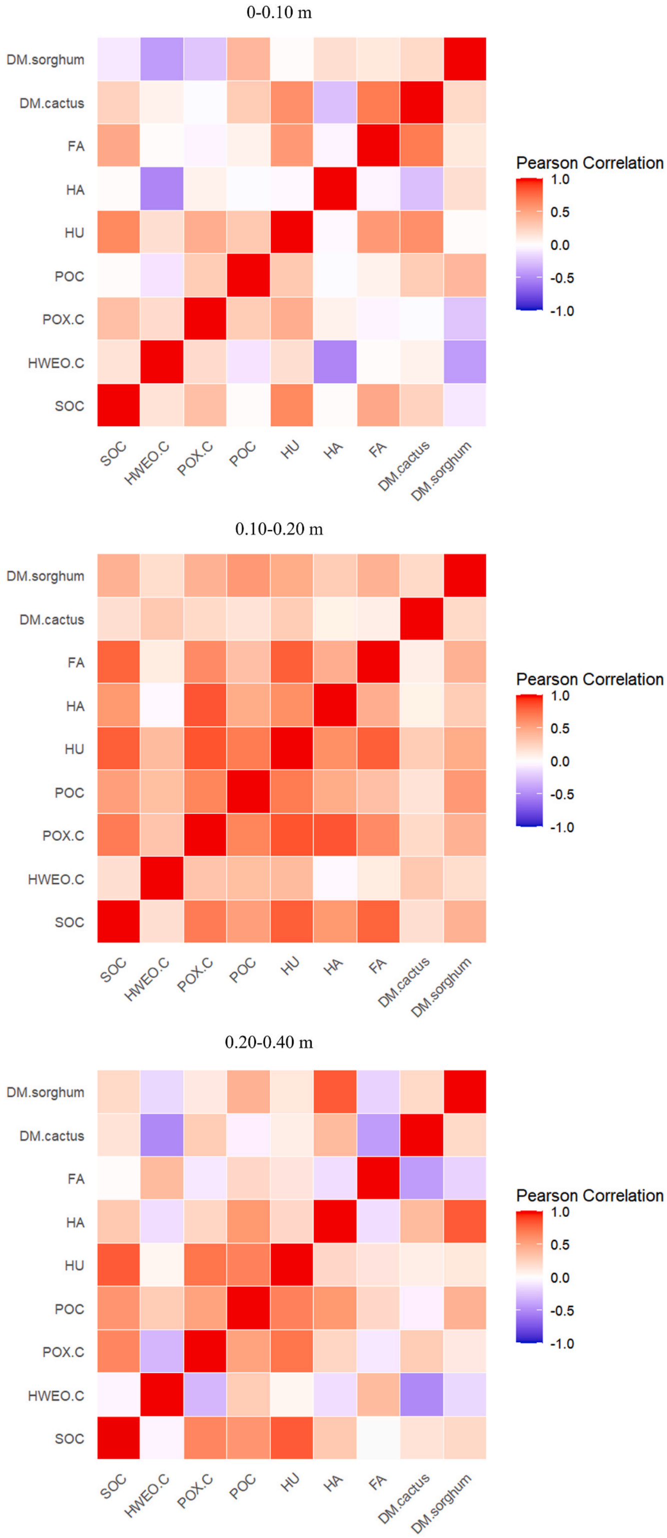
Therefore, the results indicate that an increase in C storage in response to the mulching and irrigation systems was observed across a range of fractions, from operationally defined labile pools to more chemically recalcitrant forms. Although chemical fractionation methods have declined in popularity in recent years due to their limited capacity to explain SOM persistence, they remain useful for assessing the effects of specific treatments on carbon stabilization. The observed increase in subsoil C stocks under irrigation represents a particularly favorable outcome, considering that enhancing subsoil carbon is one of the key challenges in modern agriculture. The data presented herein show that integrated management using reclaimed water and mulch can be an effective strategy to increase SOC storage across multiple pools, improve key indicators of soil functionality, and enhance the carbon sequestration potential of soils in semiarid agroecosystems.

4.3. *Crop productivity after the use of reclaimed water associated with soil mulching*

The combination of mulch and reclaimed water irrigation enhanced the productivity of both cactus and forage sorghum, as indicated by the increased shoot biomass production. This practice is especially recommended for semiarid regions with high erosion risks, as it improves water-use efficiency, reduces evaporation, and stabilizes soil temperature, factors that collectively promote higher agronomic yields (Carvalho et al., 2021; Souza et al., 2023).

Sorghum productivity varied across cuts, with the highest yields observed under 120, 80, and 100 % ETc with 8 Mg ha^{-1} mulch in the first, second, and third cuts, respectively. This trend in productivity indicates a positive effect of reclaimed water irrigation combined with mulching on agronomic yield. Carvalho et al. (2021) also reported increased sorghum yield under 140 % ETc with reclaimed water, and a 24 % gain with mulch in the Brazilian semiarid ecosystem. In contrast, Araújo et al. (2023) found no effect of mulching in cactus–millet intercropping, probably due to rapid mulch decomposition from high temperatures (~26.9 °C) and availability of continuous moisture from irrigation and rainfall.

Regarding the forage cactus, the use of mulches favored productivity, and it was observed that the treatments with 100 and 120 % of 8 Mg ha^{-1} of mulch were more efficient than those with 0 Mg ha^{-1} of mulch. Lemos et al. (2021) reported that irrigating the forage cactus (*Opuntia tuna L.* Mill) with reclaimed water is viable in terms of productivity, yielding three times more labile biomass than growing cactus under


0-0.10 m

0.10-0.20 m

0.20-0.40 m

Fig. 5. Matrices of correlation and Pearson correlation coefficients among soil carbon stocks and dry matter of forage cactus and sorghum variables at layers of 0–0.10, 0.10–0.20 and 0.20–0.40 m.

rainfed conditions. In terms of dry matter, productivity was observed at around 70 Mg ha^{-1} per year under irrigation with reclaimed water compared with 44 Mg ha^{-1} per year under rainfed conditions (Lemos et al., 2021).

Intercropping between forage cactus (CAM photosynthesis) and sorghum (C4 photosynthesis) likely enhanced productivity by enabling complementary water use and reducing water loss (Souza et al., 2023). Jardim et al. (2021) reported that this intercropping system yielded 47 % and 3.5 times fresher and drier biomass, respectively, than cactus monoculture in the semiarid region. Additionally, this practice improves soil C input by increasing nutrient, water, and light use efficiency (Chimonyo et al., 2018; Diniz et al., 2017; Lima et al., 2018; Salvador et al., 2024). In this study, sorghum productivity was positively influenced by SOC stocks, especially subsurface fractions such as POX-C, POC, HU, and HA.

Despite the current safety and agronomic benefits of the treated wastewater source, its long-term use requires continuous monitoring due to the potential accumulation of contaminants and salts in the soil, which may eventually be taken up by crops (Liang et al., 2022; Lu et al., 2021; Yerli et al., 2025).

5. Conclusion

The combined application of reclaimed water irrigation and surface mulching (8 Mg ha^{-1}) significantly enhanced soil organic carbon stocks and the more stable pools of soil organic matter, particularly the humin fraction, favoring a higher C persistence in the environment. The highest SOC stocks were observed under irrigation at 80 % and 100 % of sorghum crop evapotranspiration (ETc) combined with mulching.

Labile carbon pools exhibited dynamic responses throughout the sorghum harvests, with treatments receiving 80 % and 100 % ETc plus mulch showing pronounced increases. On the other hand, treatments without irrigation had lower C storage regardless of the application of mulch, emphasizing the importance of water management for improving C sequestration in semiarid areas.

The integration of mulching with reclaimed water irrigation also increased the productivity of the cactus-sorghum intercropping system. For forage cactus, the greatest biomass yields occurred under 100 % and 120 % ETc irrigation with mulch, whereas sorghum productivity varied over the growing cycles, with peak yields recorded at 120 %, 80 %, and 100 % ETc, respectively, all in conjunction with mulch application.

Therefore, mulching at 8 Mg ha^{-1} combined with reclaimed water irrigation at 80 % and 100 % of ETc represents an effective, sustainable management strategy to enhance soil carbon sequestration and increase forage productivity in tropical semiarid agricultural systems. This practice offers a low-cost, easily adoptable technology with high potential for implementation by local farmers, contributing to both soil health and climate change mitigation objectives.

CRediT authorship contribution statement

Aline Roma Tomaz: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Rattan Lal:** Writing – review & editing. **William Ramos da Silva:** Software, Methodology, Data curation. **Thiago Massao Inagaki:** Writing – review & editing. **Aline dos Santos Correia:** Methodology, Formal analysis. **Felipe José Cury Fracetto:** Writing – review & editing. **Giselle Gomes Monteiro Fracetto:** Writing – review & editing. **Clever Briedis:** Writing – review & editing. **Débora Marcondes Bastos Pereira Milori:** Writing – review & editing, Funding acquisition. **Abelardo Antônio de Assunção Montenegro:** Writing – review & editing, Funding acquisition. **Ademir de Oliveira Ferreira:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2026.147687.

Data availability

Data will be made available on request.

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