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The concept of bio-economic mulching in droughty tropical agroecosystems and its trans-season effects on soil hydro-thermal regime and okra performance

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ABSTRACT

Mulching is an effective soil-water conservation technique in high-evaporative-demand tropical climates. Because of the drawbacks in bulk application of organic mulches, we introduce the concept of bio-economic mulching (BEM), a one-time low-rate application of organic mulch to improve soil productivity while sustaining economic viability. The study evaluated the effects of BEM (dry-grass mulching at 0, 2, 4, and 6 t ha^{-1}) on soil hydrothermal properties of sandy-loam Ultisols using okra growth during 4–9 weeks after sowing in successive rainy-to-dry/partially rainfed season (PRS) and rainy/completely rainfed season (CRS). During the PRS, soil volumetric moisture content (θ) increased (10.02%–25.50%), but soil temperature decreased (37.67–26.67°C) as BEM rate increased. A similar θ trend (8.71%–18.37%) occurred during the CRS. Soil thermal conductivity (0.78 to 4.88 W m^{-1} K^{-1}), thermal diffusivity (3.95 × 10^{-7} to 35.97 × 10^{-7} m^2 s^{-1}), and heat flux (15.00 to 85.56 W m^{-2}) generally decreased as θ increased with BEM application rate particularly during the PRS; the reverse prevailed for volumetric heat capacity (1.33 × 10^6 to 2.25 × 10^6 J m^{-3} K^{-1}). Okra plant height differed (BEM-6 > BEM-4 > BEM-2/BEM-0) in the PRS, but BEM-6 and BEM-4 gave the tallest and shortest plants, respectively in the CRS. Fruit yield was 1.8- and 9.5-fold higher in BEM-6 than BEM-4 in PRS and CRS, respectively. Mulch treatment-induced temporal variations in soil θ influenced okra performance indices of plant height (r^2 = 0.85) and total fresh fruit yield (r^2 = 0.69). In droughty tropical environments, BEM implementation at 6 t ha^{-1} could engender soil hydrothermal regime favoring vegetable production beyond the ‘drier’ first season and even more pronouncedly in the second season.

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1. INTRODUCTION

Farmers in the derived savannah of southeastern Nigeria face soil drought because of high temperatures and rainfall variability (Obalum et al., 2012). This region's predominant wet and dry seasons define crop cropping seasons and delineate climatic influences on crop growth and soil hydrothermal properties. Soil moisture rapidly depletes in the absence of rain, resulting in poor establishment and growth of winter– and dry–season crops (Atugwu et al., 2023; Ngangom et al., 2020). The coarse-textured soils of the tropics are also structurally fragile because of their long weathering history, related low silt content, low organic matter content, increased frequency of heavy rainfall, and high terminal heat (Igwe & Obalum, 2013). Mulching is among the soil and agronomic management practices towards achieving sustainable agriculture in tropical fragile agroecosystems (Igwe & Obalum, 2023). As a result, surface mulching has received a lot of attention as one of the finest soil management techniques under rainfed conditions for increasing crop output, conserving soil moisture content, controlling temperature, and maintaining soil health (Critchley et al., 2023; Kodzwa et al., 2020). Obalum et al. (2017) reported that mulching the soil surface improved the yield of fluted pumpkins in southern Nigeria. The use of grass and legume mulches during dry and wet seasons,

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respectively, maximized okra (*Abelmoschus esculentus* (L.) Moench) growth and yields (Adekiya et al., 2017) and increased soil moisture content (Li et al., 2020). Soil moisture content is a critical component that shapes the complex network of ecological interactions and processes in the soil (Wang et al., 2019). Increases in soil moisture would generally lead to increases in volumetric heat capacity. Such increases would generally lead to increases in the thermal conductivity of the soil (Alnefaie & Abu-Hamdeh, 2020; Malek et al., 2021).

Therefore, the moisture content of the soil as modified by surface mulching is very important in soil hydrothermal processes. Soil hydrothermal properties refer to processes that explain the soil's ability and efficiency to store and transfer water and heat. These properties include thermal conductivity, thermal diffusivity, heat flux, and volumetric heat capacity. However, the effects of surface mulching on these soil properties vary because of the exchange of heat between the air, soil, and layers of mulches; such that mulch properties, soil properties, and the prevailing climatic conditions determine the transport of heat and water through soil profiles (Kader, 2020). The temperature of the soil is one of the key elements that significantly impact soil heat storage, soil heat and water fluxes, nutrient transportation, and transformation (Novák & Hlaváčiková, 2019), and overall crop growth and productivity. Fluctuations in temperature, therefore, adversely affect the production of vegetables especially okra, as several of the plant's physiological, biochemical, and metabolic activities are temperature-dependent (Das et al., 2020).

Nonetheless, despite the numerous positive impacts, the biodegradability of organic mulches could temporarily lower soil mineral nitrogen levels (Bandopadhyay et al., 2023). This is because the microorganisms responsible for breaking down the organic mulch rely on immobilized mineral nitrogen and the release of natural phytotoxins during the decomposition process, which could potentially hinder the growth of crops. Though grass mulching promotes the activities of earthworms (Obalum & Obi, 2010), the reverse effect is possible beyond soil-cooling application rate. Similarly, surface mulching can lead to increases in the population of both beneficial soil microbes and those that can contaminate the soil (Kader, 2020). Abbate et al. (2023) alluded that biodegradable mulch can alter soil's interaction with microbial communities. Moreover, surface mulch generally lowers soil temperature (Osakwe et al., 2023), but under certain conditions can raise it by trapping the energy of the sun thereby heating the soil and air underneath. This suggests that mulches when used in bulk quantities can trap excess heat and bake plants and can also provide habitable places for pests to thrive. Bulk application of mulches can thus lead to pest outbreaks, rotting of the plant's roots, and other unfavorable conditions (Kader, 2020). Also, excessively high application rates of mulch can lead to extreme results of soil erosion (Rahma et al., 2017).

Various organic mulches, including composts, wood chips, grasses, straws, and leaves, offer diverse resource use options, but this study opted for dry grasses. In tropical agriculture, surface mulch of assorted dry grasses is often applied at rather unrealistically high rates in excess of 15 t ha^{-1} (Ezenne et al., 2019; Obi et al., 2024). The rate can even be much higher especially when the main target is to preserve added organic matter against rapid mineralization before the next cropping season (Onah et al., 2023). In their review of optimal mulch rate, Li et al. (2021) suggested about 6 t ha^{-1} as a reference application rate for organic mulching. For efficient soil erosion control, Fan et al. (2023) suggested a straw mulch rate of 3-4 t ha^{-1} and 6-8 t ha^{-1} for wood-based mulch. Soil moisture increased with the increasing rate of mulch up to 5.56 t ha^{-1}, and thus 6 t ha^{-1} could be appropriate for soil moisture conservation (Li et al., 2020).

In this paper, therefore, we introduce the agronomic term 'bio-economic mulching (BEM)'. This concept entails surface application of organic mulch at low rates to improve soil hydrothermal regime towards enhancing crop yields and biodiversity without compromising environmental quality. Specifically, BEM deploys dry grasses and advocates minimal harm to ecological biodiversity with judicious use of as small quantities as possible in soil and water conservation in crop production, considering the expense due to their bulk application. While previous studies often focused on isolated or specific aspects (Adekiya et al., 2017; Obalum et al., 2017), the novel approach of this research holistically explores the interconnected influence of BEM on soil moisture, thermal properties, and crop growth to contribute to the existing body of knowledge in agroecology and sustainable farming practices. The success of common soil moisture conservation techniques is influenced by socioeconomic context, soil type, and prevailing climatic conditions, among other factors (Jabran et al., 2015). In proposing BEM for drought-prone soils, an extra component is double cropping in two successive seasons, with an emphasis on vegetable crops. This concept is trifocal in that it could concurrently address the ecological, agronomic, and economic problems associated with organic mulching in agriculture; by resolving the issues surrounding the limited availability of organic materials and the logistics involved in their use as surface mulch (Fig. 1).

The present study aimed to find out the effects of the implementation of low rates of organic mulch on hydrothermal properties of droughty tropical soils and to evaluate these effects on the productivity of vegetable crops represented here by okra. Because of the expected greater effectiveness of surface mulch when freshly applied under conditions of limited climatic supply and high evaporative demand, we hypothesized that the soil and agronomic benefits of BEM rates would be more realizable in the partially rainfed than the subsequent completely rainfed season.

2. MATERIAL AND METHODS

2.1. Study area

The experiment was carried out at the University of Nigeria Teaching and Research Farm (6^{0} 52'N, 7^{0} 24'E; 447 m asl) in Nsukka in southeastern Nigeria. The climate is tropical and humid, with clear wet and dry seasons. On average, 1600 mm of rain falls each year. The average minimum temperature during the year is 21°C. The maximum temperature can reach but rarely exceeds 35°C during the year's hottest months. The rainy season usually lasts from April to October, with a short dry spell around July/August popularly known as "August Break." Relative humidity ranges between 80% and 60%.

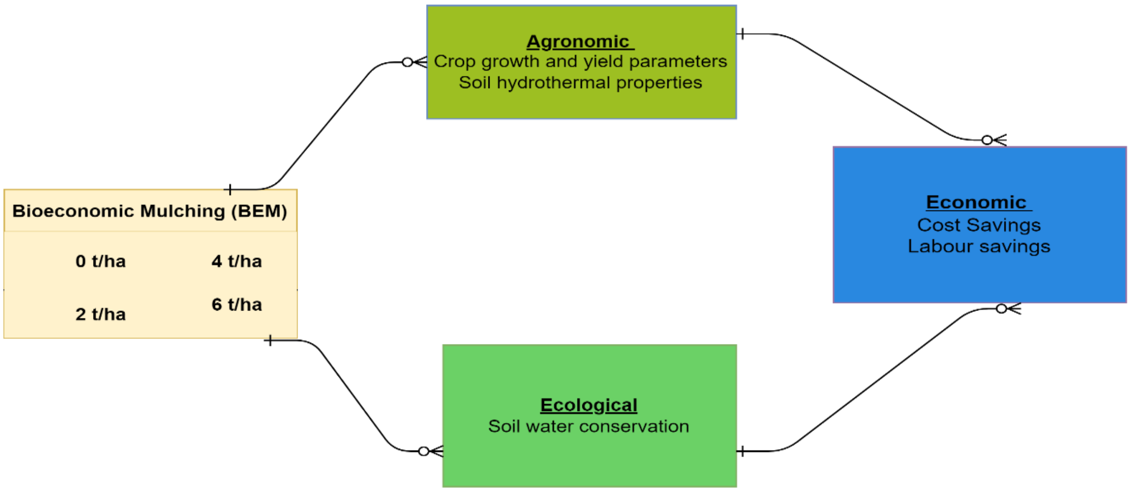

Figure 1. Trifocal concept of bioeconomic mulching

The harmattan period, characterized by a dusty trade wind often with temperatures dropping below the minimum value and relative humidity dropping to around 55%, falls within the dry season (usually during December/January). In most months of the year, potential evapotranspiration is higher than rainfall amounts, and the annual total amount may also be higher for the former than the latter.

The soil of the study location is derived from false-bedded sandstone. The soil is mostly of coarse loamy texture classified as Ultisols, based on the USDA Soil Taxonomy (Soil Survey Staff, 2022), and Ferric Acrisols based on the FAO's World Reference Base for soil resources (IUSS Working Group WRB, 2022). It is generally low in organic matter and has a granular surface structure rendering it excessively 'porous' and well-drained (Obalum et al., 2012; Obalum & Obi, 2014). This hydraulic attribute also predisposes soils of this location to excessive evapotranspiration relative to rainfall, rendering them generally droughty. The prevailing vegetation depicts the location as a typified derived savannah.

2.2. Rainfall and temperature conditions in the two seasons of the study

The study was executed in two successive cropping seasons with contrasting weather (mainly rainfall and temperature) conditions. The first cropping season lasted ca. 12 weeks, from 12 September 2016 to 4 December 2016. It, therefore, began during the wet season and extended into the season with less rain. Being that it was initially sustained by rainfall and later without rain, this first cropping season was designated partially rainfed season (PRS). The second cropping season also lasted approximately 12 weeks, from 17 April 2017 to 6 July 2017. Being that it came fully in the subsequent rainy season and was sustained by rainfall from the beginning till the end, this second cropping season was designated completely rainfed season (CRS).

The data on rainfall and atmospheric temperature at the experimental site during the study, shown in Figures 2a and 3a, respectively, were obtained from a nearby meteorological station of the University of Nigeria Nsukka as recorded by the Department of Crop Science. The total rainfall amount in the PRS was 255.53 mm, whereas that in the CRS was 657.59 mm. Atmospheric temperature reached its bottom (17.86°C) and peak (32.29°C) at 5 and 12 weeks after sowing (WAS), respectively in the PRS, whereas it reached its bottom (20.25°C) and peak (32.43°C) at 2 and 12 WAS, respectively in the CRS. The mean values of these minimum and maximum temperatures were, however, similar in both seasons.

2.3. Some properties of the pre-study soil

The physical and some physico-chemical properties of the soil at the beginning of the experiment are given in Table 1. The soil is sandy clay loam texture. The soil pH indicated that the soil was very strongly acidic. Soil organic matter content was low; so too was the soil content of total nitrogen and cation exchange capacity of the soil. Available phosphorus, however, showed a rather high value. The generally low values of these soil fertility indices are typical of the coarse-textured soils in the study area.

2.4. Experimental design and field establishment

The field trial was carried out using a randomized completely block design (RCBD) involving five blocks, each having four soil mulch treatments, giving 20 plots. Treatments were surface application of organic mulch at 6, 4, 2, and 0 t ha^{-1}, referred to as bio-economic mulching, BEM. These rates were designated BEM-6, BEM-4, BEM-2, and BEM-0 (control),

Table 1. Soil properties of the experimental site before growing of okra during the rainy-to-dry cropping season designated the partially rainfed season (PRS)

Soil properties	Mean
Sand (g kg^{-1})	697
Silt (g kg^{-1})	40
Clay (g kg^{-1})	263
pH-H_2O	4.65
pH-KCl	4.30
Soil organic matter (g kg^{-1})	18.80
Total Nitrogen (g kg^{-1})	0.70
Available Phosphorus (mg kg^{-1})	41.50
Cation exchange capacity (cmol kg^{-1})	5.00

respectively. The mulch material in the present study was dry grasses comprising mostly guinea grass (*Panicum maximum*).

The experimental site was manually cleared and demarcated into 20 treatment plots each of size 2.36 m × 1.80 m (4.25 m^2) at the end of August 2016. The demarcation was done by raised bunds after which the treatment plots were prepared by tilling to ca. 20 cm depth and pulverized into seedbeds using an African hoe. The treatment plots were spaced 1 m apart and the blocks were 1.5 m. The dry-grass mulch was applied at rates equivalent to the chosen BEM rates just before sowing the seeds of the test crop, okra (*Abelmoschus esculentus* (L.) Moench).

Seeds of Madison spineless variety of hybrid okra were sown on 12 September 2016 in partially rainfed season. The seeds were sown in shallow (2–3 cm) depths following Onah et al. (2023) who also worked with this okra variety. The field was established at a plant spacing of 60 cm × 45 cm, giving 16 stands of okra plants per plot. The rain seceded by the end of October, such that rains sustained okra in this partially rainfed season (PRS) in the first six weeks (first half) of its growth phase. The crop was sustained in the remaining six weeks (second half) of the growth phase with manual watering, whereby every okra stand received 300 ml daily for the first two weeks and at two-day intervals subsequently till the end of this second half being 4 December 2016.

The rain returned at the beginning of April 2017, and the field trial was repeated in the ensuing completely rainfed season (CRS). In line with the concept of the proposed BEM, however, the plots were not re-tilled, but surface mulch was not re-applied before seeding; only manual weeding was done. Seeding was done on 17 April 2017 in this season, and the experiment terminated after crop senescence on 6 July 2017. Notably, there was a time lag of 4.5 months between the end of the PRS and the start of the CRS.

Seedling emergence occurred 6–10 days after sowing in both cropping seasons. During the field experiment, the plots were kept weed-free by removing weeds by hand picking as frequently as they were noticed. Mineral fertilizer being NPK 15:15:15 was applied by top-dressing at a rate of 150 kg ha^{-1}, roughly 3.5 WAS in both cropping seasons.

2.5. Field data collection

Monitoring of soil moisture content and soil temperature was started at 4 WAS and was continued at weekly intervals till 9 WAS in both the PRS and the CRS. To do this, soil samples were collected at 5-cm depth for determination of moisture content, while soil temperature was determined using thermometers inserted into 5- and 10-cm depths of the soil. For agronomic evaluation, eight plants in the middle of each plot were sampled. Data were collected on okra plant height at weekly intervals during 4–9 WAS. Plant height was measured from the soil base to the tip of the plant. Fresh okra fruits were harvested and weighed as from 6 WAS till senescence when fruiting had stopped between 11.5 WAS and 12 WAS in both seasons. Weights of the fresh fruits were cumulatively recorded per plot such that at the end of each cropping season, total fresh fruit yields (TFFY) were obtained and extrapolated to hectarage equivalents.

2.6. Soil physical analysis

Undisturbed soil samples were taken from the soil surface layer around the middle of each plot using 5 cm × 5 cm cylindrical core samplers. They were collected from under the surface mulch at the end of the PRS, and at the beginning of the CRS and used to determine the effect of the mulch treatment on soil bulk density. The undisturbed and the loose soil samples prepared for bulk density and moisture content determination, respectively were oven-dried at 100°C for 24 h. The bulk density was calculated by dividing the mass of the oven-dry soil by the inner volume of the soil core sampler. The effect of the mulch treatment on soil bulk density (Table 2) was utilized in the computation of volumetric moisture content (θ). Soil moisture content was first computed on a gravimetric basis (mass of water divided by oven-dry soil), and the values were multiplied by soil bulk density to obtain θ.

2.7. Computation of soil thermal storage/exchange indices as affected by the mulch treatment

The soil volumetric heat capacity, C_v (J m^{-3} K^{-1}) computes the heat storage capacity of soil per unit volume. The derivation involved two parts; the solid matrix component accounts for heat capacity due to the solid soil matrix, and the water content component accounts for the heat capacity of water which is represented by the factor 4.19 × 10^6. Adding both components gives the soil volumetric heat capacity, C_v (J m^{-3} K^{-1}), as expressed by Equation 1 (Evett et al., 2012).

$$C_v = 2.01 \times 10^6 \varrho_b / 2.65 + 4.19 \times 10^6 \theta \quad [1]$$

where ϱb is soil bulk density (Mg m^{-3}) being the mass of solid phase or oven-dry soil per unit volume of the soil, whereby the values used were based on treatment effect on this index of soil compaction (Table 2); θ is soil volumetric moisture content (volume of water per unit volume of soil); and the factor 2.65 is the average particle density (Mg m^{-3}) of soil minerals.

Soil thermal conductivity (*K*) was calculated by first obtaining the rate of conduction of heat by Stefan Boltzmann's equation according to Equation 2 (Gwani et al., 2013).

$$Rt/A = \delta T^4 \quad [2]$$

where Rt is the rate of heat conduction referred to as radiated power (W), *A* is radiated area (m^2), δ is Stefan Boltzmann's constant, 5.67 × 10^{-8} W m^{-2} K^{-4}, and *T* is soil temperature at 0-5 cm depth interval (Kelvin, K). Therefore, the term Rt/A becomes the heat conduction per unit time (radiated power) passing through a cross-sectional area (radiated area) within the 0-5 cm depth interval. It is expressed as Equation 3.

$$Rt/A = 5.67 \times 10^{-8}\ W\ m^{-2}\ K^{-4} \times T^4\ K^4 = 5.67 T^4 \times 10^{-8}\ W\ m^{-2} \quad [3]$$

To account for radiative losses to the open atmosphere, T^4 was calculated as soil T^4 – ambient T^4. Since *K* refers to the quantity of heat per unit time (radiated power) passing through a unit cross-sectional radiated area per unit change in temperature, it is related to Rt/A as shown in Equation 4.

$$K = \frac{Rt}{A} / \frac{\Delta T}{\Delta D} = \frac{Rt}{A} \times \frac{\Delta D}{\Delta T} \quad [4]$$

where K is thermal conductivity of soil (W m^{-1} K^{-1}), Rt/A is the quantity of heat per unit time or radiated power passing through a unit cross-sectional radiated area (W m^{-2}), and ΔD/ΔT is the inverse of soil temperature gradient, with ΔD representing difference in length between 0–5 and 0–10 cm depth intervals (m), and ΔT representing difference in soil temperature at these two soil depth intervals between where the monitoring of soil K is desired (Kelvin, K).

Soil heat flux (Q, W m^{-2}) was calculated from K and soil temperature gradient (ΔT/ΔD) by Equation 5.

$$Q = K\frac{\Delta T}{\Delta D} \quad [5]$$

Soil thermal diffusivity (D, m^2 s^{-1}) was calculated from K and volumetric heat capacity (C_v) by Equation 6.

$$D = \frac{K}{C_v} \quad [6]$$

2.8. Data analysis

One-way analysis of variance using a linear model of GenStat software was employed. The means were separated using the least significant difference at 5% probability level ($LSD_{0.05}$). Pearson multiple correlation analysis was used to measure the relationships between soil moisture, soil hydrothermal properties, and okra growth and yield attributes for the two cropping seasons combined.

3. RESULTS

3.1. Influence of BEM on soil moisture regimes

In this study, one-time application of BEM at rates not exceeding 6 t ha^{-1} on coarse loamy Ultisols was implemented in two successive cropping seasons of southeastern Nigeria, whereby the rainy-to-dry season was partially rainfed and the second 4.5 months later was completely rainfed for okra. The influence of BEM on soil moisture regimes during the consecutive partially rainfed (PRS) and completely rainfed seasons (CRS) is shown in Figure 2(b). During the PRS, a clear pattern emerged wherein the BEM rates influenced soil volumetric moisture content (θ) at all sampling times, except at 4 weeks after sowing (WAS). The sampling at 4 WAS coincided with the drought due to the reduced rainfall at 3 WAS (Figure 2a), leading to reduced soil θ. In the second half of the PRS when irrigation was employed to compensate for the climatic shortfall, the trend of treatment effect on soil θ was sustained. The second cropping season, fully supported by rainfall and without mulch re-application, showed significant residual effects of previously applied BEM on soil θ during 6, 7, and 9 WAS. Generally, soil θincreased as the BEM rate increased from the no-mulch control to BEM-6, with BEM-6 plots recording the highest values during the first PRS and the second CRS (25.50% and 18.37%, respectively). These highest values occurred at 6 WAS in the PRS, again coinciding with a period of reduced rainfall.

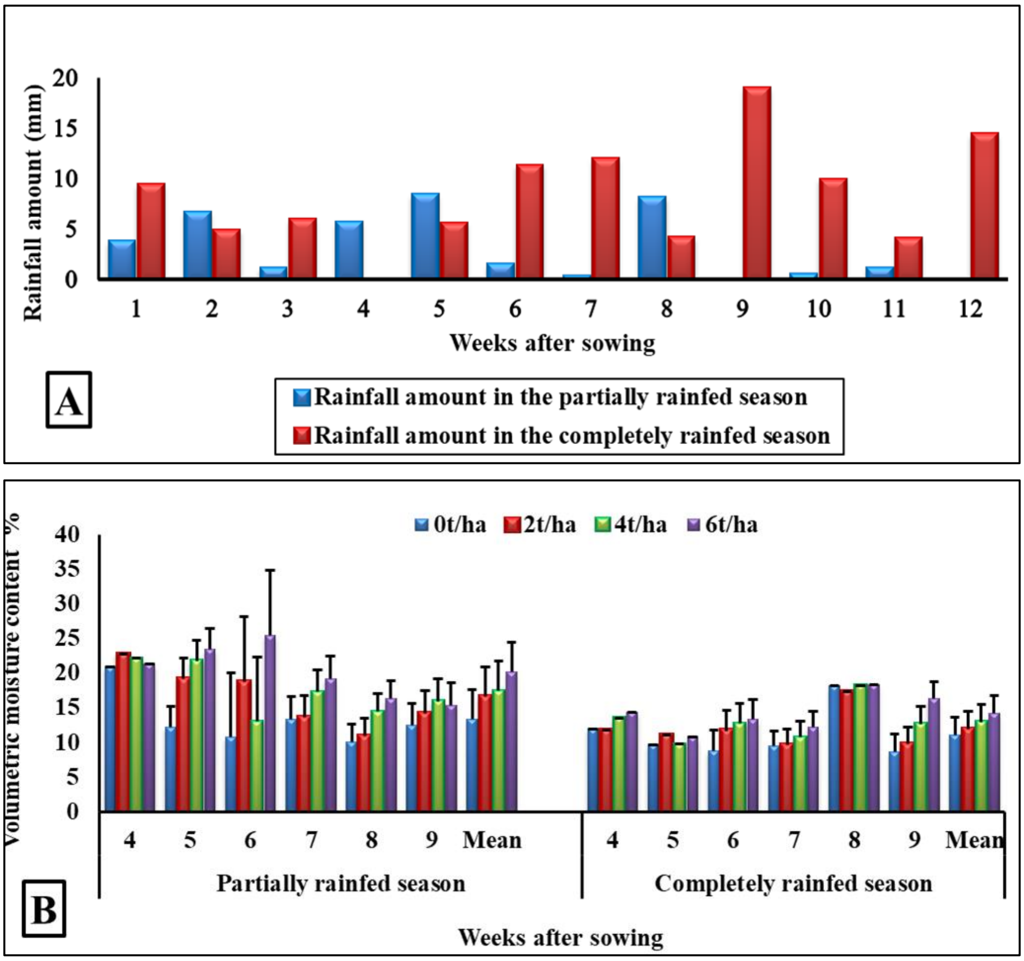

Figure 2. (a) Mean weekly rainfall amount (mm) of the study area for the 12-week duration of the study, and (b) Influence of different bioeconomic mulching (BEM) rates on soil moisture dynamics for the 9-week sampling period in the first partially rainfed and subsequent completely rainfed seasons

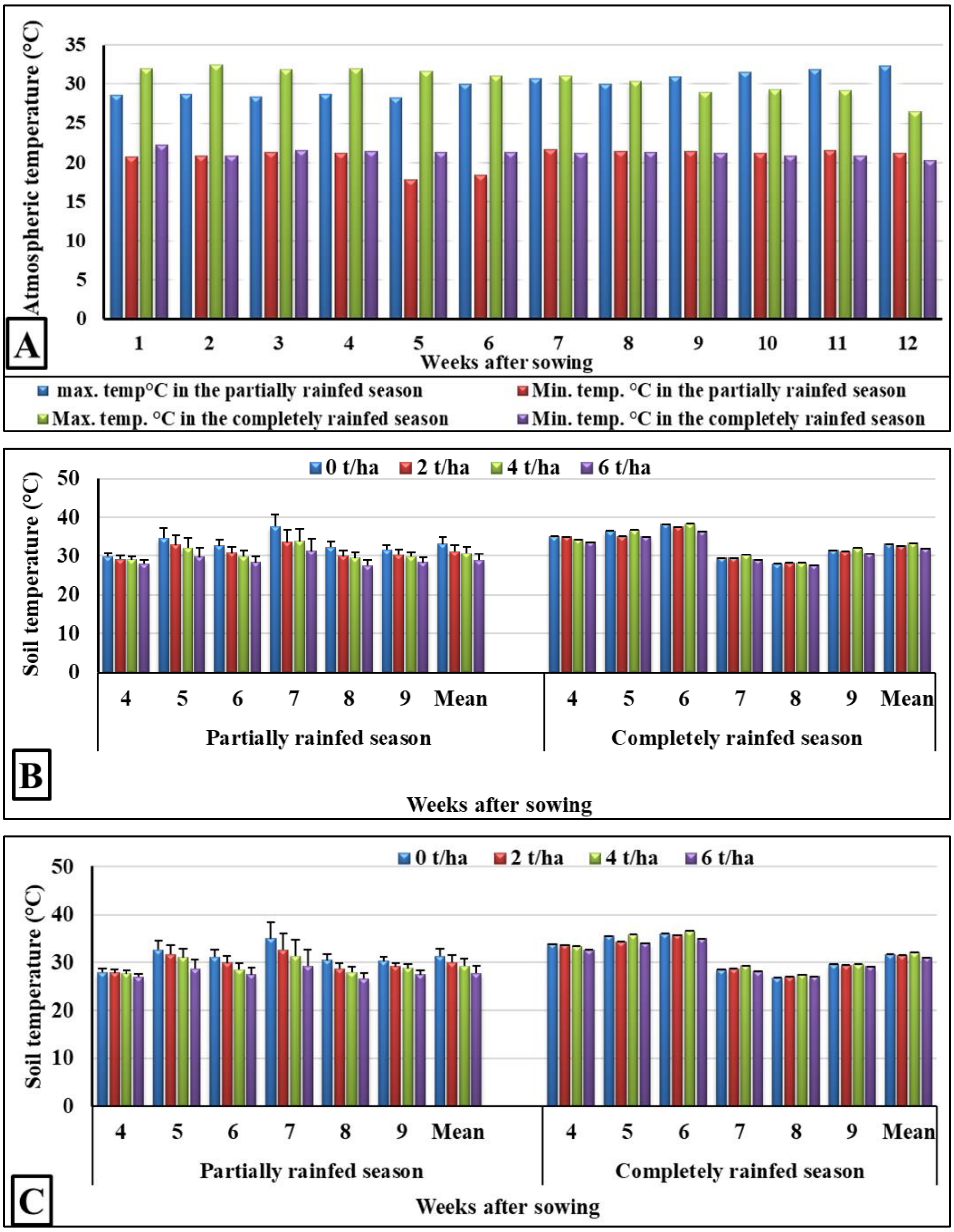

Figure 3.(a) Mean weekly minimum and maximum atmospheric temperatures of the study area for the 12-week study duration, and influence of different bioeconomic mulching (BEM) rates on soil temperature at (b) 5 cm depth and (c) 10 cm depth for the 9 weeks after sowing

Table 2. Soil bulk density (Mg m^{-3}) during the first and second cropping seasons

BEM rates	First partially rainfed season (PRS)	Subsequent completely rainfed season (CRS)
0 t ha^{-1}	1.58	1.27
2 t ha^{-1}	1.56	1.23
4 t ha^{-1}	1.61	1.31
6 t ha^{-1}	1.55	1.27
F-LSD$_{(0.05)}$	NS	0.08

3.2. Influence of BEM on soil temperature

The influence of BEM on soil temperature at 5- and 10-cm depths are shown in Figures 3b and 3c, respectively. The atmospheric temperature was trending up from the first to the last week (Figure 3a). In the PRS, soil temperatures were higher at 5-cm depth than the deeper 10-cm depth. Considering the isohyperthermal regime of the soils, corresponding increases in the bare soil temperature were expected. Nevertheless, the BEM rates reduced soil temperature at both soil depths (range, 26.67–37.67°C) at all sampling times, with BEM–6 giving the highest reductions. At 5- and 10-cm depths, the highest values of 37.67°C and 35°C, respectively, were recorded in the control plots at 7 WAS, whereas the lowest values of 27.47°C and 26.67°C, respectively, were recorded in BEM-6 plots at 8 WAS. In the subsequent CRS, there was no significant difference in the temperature following mulch application in the previous season, hence less pronounced soil temperature fluctuations. However, there was a tendency for higher soil temperature in the plots with no mulch compared to the BEM plots. In particular, during this season, the mean weekly atmospheric temperature decreased from 30.51°C to 21.19°C (Figure 3a).

3.3. Influence of BEM on soil thermal conductivity, thermal diffusivity, and heat flux

Figure 4 shows the pattern of variations in soil thermal exchange indices, including soil thermal conductivity (*K*), thermal diffusivity (*D*), and heat flux (*Q*) under the various BEM rates. Soil *K* values ranged from 0.8114 to 1.8456 W m^{-1} K^{-1} during the PRS and from 0.7789 to 4.8764 W m^{-1} K^{-1} during the subsequent CRS (Figure 4a). Oladunjoye et al. (2013) rated these ranges of *K* values as moderate to high. The differences in soil *K* were significant at some sampling points in the PRS when generally BEM-2 and BEM-6 plots showed the highest and the lowest values, respectively. However, during the CRS, the differences were mostly not significant except for the lower values in BEM-6 plots than the rest at 5 WAS. Generally, BEM-4 plots tended to conduct more heat than the rest of the plots among which there were a lack of distinctness.

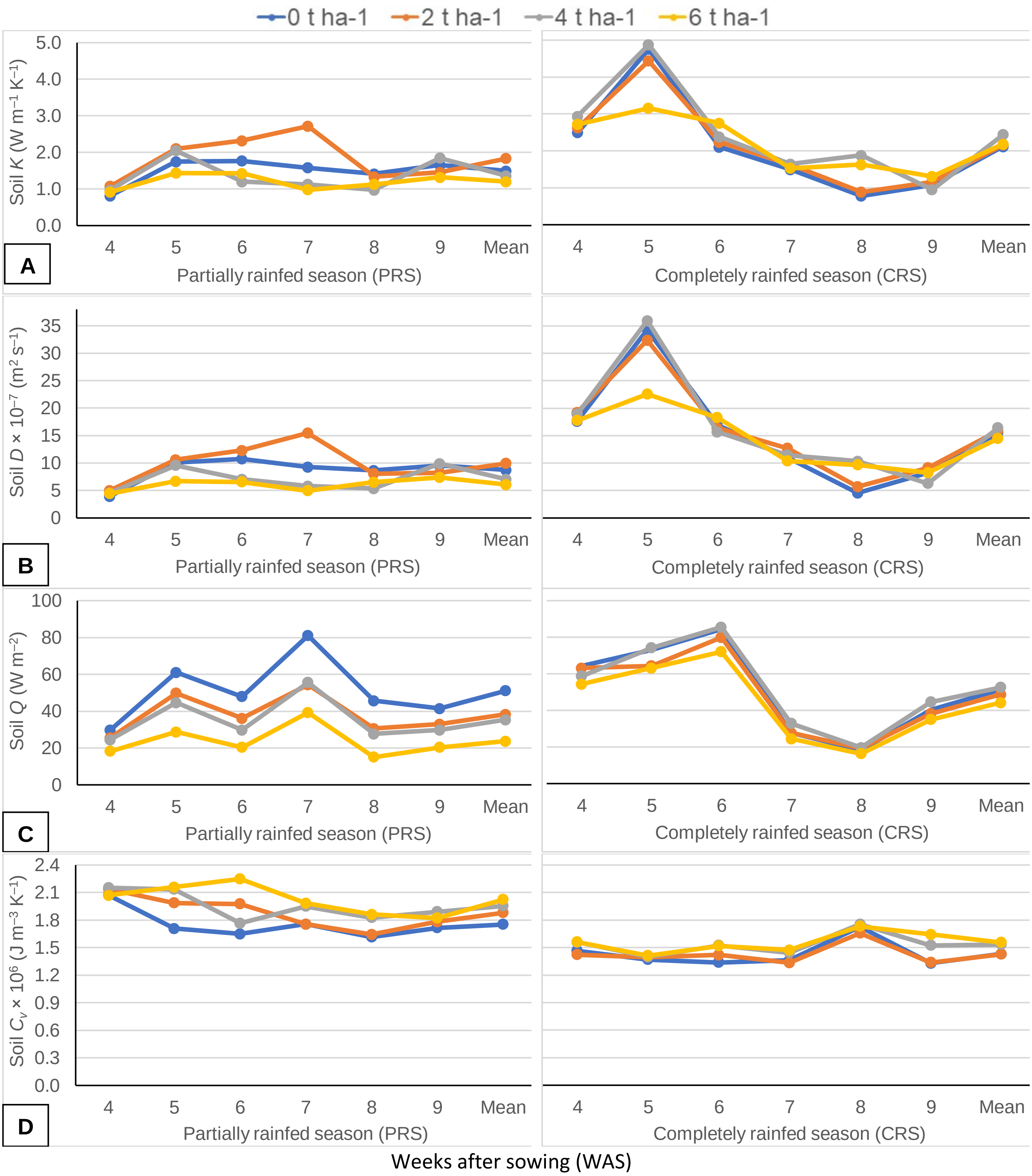

Figure 4. Influence of different rates of bioeconomic mulching *(BEM)* on soil thermal storage and exchange indices including (a) soil thermal conductivity, *K* (b) soil thermal diffusivity, *D* (c) soil heat flux, and (d) soil volumetric heat capacity for the period 4-9 weeks after sowing in the first partially rainfed and subsequent completely rainfed seasons

The results for soil thermal diffusivity, *D,* somewhat toed those for soil *K* (Figure 4b). In the PRS, the soil *D* ranged from 3.95 × 10^{-7} m^2 s^{-1} in the control plots at 4 WAS to 15.47 × 10^{-7} m^2 s^{-1} in BEM-2 plots at 7 WAS; in the CRS the soil *D* values ranged from 4.56 × 10^{-7} m^2 s^{-1} in the control plots at 8 WAS to 35.97 × 10^{-7} m^2 s^{-1} in BEM-4 plots at 5 WAS.

The effect of BEM rates on soil heat flux, *Q,* generally differed thus control > BEM-2/BEM-4 plots > BEM-6 plots in the PRS, whereas in the CRS, the highest and lowest *Q* values were recorded in the BEM-4 and BEM-6 plots, respectively (Figure 4c). The soil *Q* ranged from 15.00 to 85.56 W m^{-2} in both seasons. Generally, soil *Q* decreased as soil θ increased with BEM rate, being clearer in the PRS than the CRS.

3.4. Influence of BEM on soil volumetric heat capacity

Treatment affected soil thermal storage index of volumetric heat capacity (C_v), the effect being more distinct in the PRS than the CRS (Figure 4d). Generally, BEM-6 plots stored the most heat in both seasons, while BEM-2 and BEM-2/control plots stored the least heat in the PRS and CRS, respectively. The soil C_v ranged from 1.62 × 10^6 to 2.25 × 10^6 J m^{-3} K^{-1} in the PRS and from 1.33 × 10^6 to 1.75 × 10^6 J m^{-3} K^{-1} in the CRS. So, the soil stored more heat in the PRS than the CRS. Generally, soil C_v increased as soil θ increased with BEM rate, again being clearer in the PRS than the CRS.

3.5. Influence of BEM on okra plant height

The BEM rates had significant effects on okra plant height at 4, 5, 6, and 7 WAS in the PRS, but were not significant in the CRS (Figure 5a). In the PRS, BEM-6 gave the tallest plants (32.58 cm) at 8 WAS whereas BEM-2 gave the shortest plants (3.88 cm) at 4 WAS. Unlike in the PRS, the second-season CRS had okra entirely rainfed but without mulch re-application.

3.6. Influence of BEM on okra fresh fruit yield

The BEM rates significantly affected okra total fresh fruit yield (TFFY) in both the PRS and the subsequent CRS of the study (Figure 5b). The highest TFFYs were recorded from BEM-6 plots in both cropping seasons; 1.64 t ha^{-1} in the PRS and 2.30 t ha^{-1} in the subsequent CRS. In contrast, the lowest TFFYs were recorded from BEM-2 plots in the PRS (0.37 t ha^{-1}) and BEM-4 plots in the CRS (0.24 t ha^{-1}).

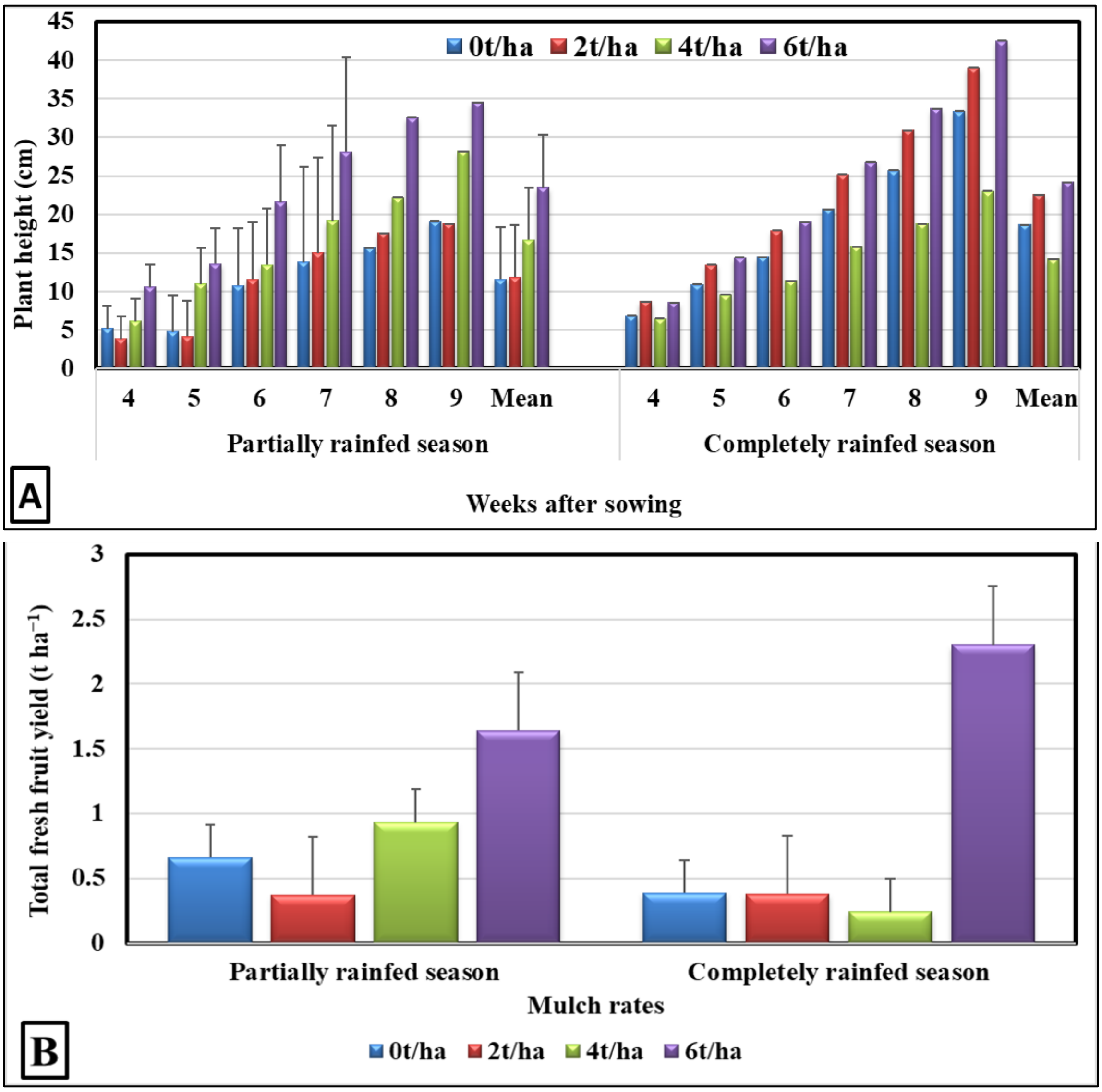

Figure 5. Influence of different bioeconomic mulching (BEM) rates on (a) okra plant height, and (b) okra fresh fruit yield in the first partially rainfed and subsequent completely rainfed seasons

Table 3. Relationships between mean soil hydrothermal properties across the season, okra plant height across the season, and total fresh fruit yield of okra as expressed based on the combined data for the first cropping (partially rainfed) and second cropping (completely rainfed) seasons of the study (n = 8)

	θ	T_{5cm}	T_{10cm}	K	D	Q	C_v	Plant height	TFFY
θ	–								
T_{5cm}	−0.265	–							
T_{10cm}	0.117	0.691*	–						
K	0.331	0.738*	0.475	–					
D	0.378	0.766*	0.603	0.973***	–				
Q	−0.255	1.000***	0.697*	0.741*	0.771*	–			
C_v	−0.251	−0.836**	−0.731*	−0.877**	−0.956***	−0.841**	–		
Plant height	0.924***	−0.152	0.405	0.277	0.379	−0.141	−0.332	–	
TFFY	0.832**	−0.089	0.519	0.234	0.357	−0.077	−0.353	0.981***	–

Notes: θ- volumetric moisture content of the soil at 0–5 cm depth range, T_{5cm} and T_{10cm} - soil temperature at the 5- and 10-cm depths, respectively, K - thermal conductivity, C_v - volumetric heat capacity, D - thermal diffusivity, Q - heat flux, TFFY - total fresh fruit yield; *, **, *** represent significant correlations at 5%, 1% and 0.1% probability levels, respectively.

3.7. Relationships between soil hydrothermal properties and okra growth and yield attributes

The matrix of the Pearson correlations between the soil hydrothermal properties and okra agronomic variables for the PRS and the CRS combined is presented in Table 3. The results show that soil volumetric moisture content (θ) had no significant relationships with thermal conductivity (K), thermal diffusivity (D), heat flux (Q), and volumetric heat capacity (C_v), but had significant positive relationships with plant height and TFFY. Soil K was negatively correlated to soil C_v. Notably, K and C_v were, respectively, positively and negatively correlated with D and Q. However, the correlations of these indices of soil thermal storage and exchange with okra growth and fruit yield were consistently not significant, tending to be positive for K and D, and negative for Q and C_v. The two agronomic variables of okra plant height and TFFY were significantly ($p < 0.001$) correlated.

4. DISCUSSION

Our findings highlighted the trifocal effects of BEM as illustrated in Figure 1. Soil volumetric moisture contents (θ) in all BEM-treated plots were higher compared to the no-mulch control plots not only during the first half but also during the second half of the partially rainfed season (PRS) when manual irrigation was employed to compensate for the climatic shortfall. This trend was sustained even in the subsequent completely rainfed season (CRS) with little or no drought-related constraint, indicating a lasting influence of BEM on soil moisture regime. The highest values of soil θ occurred in the PRS at 6 WAS, again coinciding with a period of reduced rainfall. Overall, these results point out that BEM at rates ≤ 6 t ha^{-1} could be effective in moisture conservation for drought-prone soils of the derived savannah during the rainy-dry season interface, while suggesting that such effectiveness depends on the weather conditions. The increases in soil moisture contents in BEM plots in periods of limited climatic supply could be attributed to reductions of unproductive evaporation from the surface and modifications of soil temperature (Qin et al., 2015). Increases in soil moisture status due to surface mulch are a common phenomenon (Li et al., 2020), and this phenomenon may be experienced not so early but later in the growing season (Bhutia et al., 2017). This increase can also enhance the soil's heat storage capacity (Alnefaie & Abu-Hamdeh, 2020). Our data show that such increases are possible with BEM rates in droughty tropical agroecosystems, not due to decreases in soil bulk density but likely to increases in soil water-stable aggregates and macro-aggregation (Parker et al., 2023).

While atmospheric temperature rose during the early CRS, corresponding increases in the soil temperature were expected. However, BEM rates reduced soil temperature, with BEM-6 giving the highest reductions. This observation aligns with the concept of surface mulching acting as a thermal buffer, reducing excessive heat build-up during peak periods (Osakwe et al., 2023). Soil temperature data and patterns as influenced by BEM rates at the 5- and 10-cm soil depths are consistent with the reports of Yasmina et al. (2020). In the subsequent CRS, soil temperature fluctuations were less pronounced, most likely due to a dampening effect of rain on thermal variability. However, there was a tendency for higher soil temperature in the no-mulch control plots compared to the BEM-treated plots. This situation whereby the control plots only tended to show higher soil temperature than the BEM-treated plots could be due to the lower thermal radiation transmission in the CRS. The generally cooler environment during the CRS compared to the PRS may have played a role in the residual effects of BEM on soil temperature at the soil depths of 5 cm and 10 cm as well as soil K values mostly being similar in the CRS. The soil K data showed a dynamic balance between mulch-induced insulation and enhanced heat transfer, implying that organic mulch helps to shape heat conduction through the soil particularly when freshly applied in a somewhat droughty season. Soil K and C_v showed signs of decreasing and increasing, respectively, with increasing BEM rate and soil moisture especially in the PRS. This situation of decreases in conduction and corresponding increases in storage of soil heat with increasing BEM rate is logical because of the buffering of heat change due to the latent heat in the mulch-conserved soil water. Kader (2020) also reported lower soil K in straw-mulch plots relative to no-mulch plots.

Contrary to our results, Al-Shammary and Al-Sadoon (2014) reported the lowest values of soil K in the no-mulch plots. Soil K data were similar to those for soil thermal diffusivity, D, suggesting that varying moisture conditions can influence the heat transfer properties of the soil. This may have implications for the regulation of soil temperature, plant root development, and overall crop performance and productivity.

In the PRS, the highest and lowest values of soil *Q* were recorded in the control and BEM-6 plots, whereas in the CRS, the highest and lowest values were recorded in the BEM-4 and BEM-6 plots, respectively. This trend across seasons suggests that BEM-6 may contribute to a more stable and moderated thermal environment compared to the control. The observed decrease in soil heat fluxes as soil moisture content increased with BEM rate during the PRS is in line with the findings of Al-Shammary and Al-Sadoon (2014), who reported significant variations in heat flux due to mulching. In their study, no-mulch plots exhibited the lowest heat flux, showing that mulching reduces soil evaporation and heat flux. Our data showed that BEM rates exerted a significant influence on the soil *Q* dynamics in the PRS but not in the following CRS when differences among treatments were less distinct. Similar to these effects, Ezenne et al. (2019) reported that surface-applied grass mulch marginally improved the properties of these coarse-textured Ultisols up until seven months later before the effects diminished on the soil properties.

The significant effects of BEM rates on okra plant height in the PRS can be attributed to the freshness of the applied mulch and to the fact that okra is a warm-season crop. Okra grows best at soil temperatures between 23.89 and 32.22°C (Smith et al., 2020). The surface-applied mulch lowered the soil temperatures to a range that was within this ideal condition. Therefore, the BEM rates of this study moderated the soil temperature to positively influence okra growth. However, the data for the total fresh fruit yield (TFFY) did not follow the typical expectation that higher mulch rates would directly translate to increased yields. Nyajeka et al. (2017) who mulched at the rates of 0, 5, 10, 15 and 20 t ha^{-1} reported that, under drip irrigation, no-mulch plots produced the lowest okra yields in semi-arid Zimbabwe. The lowest yields here were not from the control plots, but from BEM-2 and BEM-4 plots in the PRS and CRS, respectively. This calls for attention to the critical influence of BEM rates on warm-season crops like okra, particularly in response to varying rainfall patterns. Okra is inherently adapted to thrive in warmer temperatures (Adhikari et al., 2023; Das et al., 2020).

The results of correlation analysis indicated that the influence of soil θ during the two seasons on the indices of soil thermal storage and exchange (*K*, *D*, *Q*, and C_v) were consistently insignificant, but this soil θ positively influenced plant height and TFFY (Table 3). Hence, BEM rates that improved soil θ did not improve *K* and *D* but increased okra growth and yield. These results suggest that soil hydrothermal properties can have mutually exclusive influence on crop yield in a given tropical location. Ghuman and Lal (1985) noted a complex relationship between soil texture, moisture content, and thermal diffusivity. Onwuka et al. (2021) opine that the relationship between soil moisture content and heat transfer is important to agriculture since it could directly influence crop production. It appears, however, that these relationships which are crucial for predicting heat and moisture movement as well as crop yields may not be evident in a given soil type.

Soil θ generally increased with BEM rates, mostly during the PRS, but this soil θ had insignificant positive and negative relationships with soil *K* and C_V, respectively. Ghuman and Lal (1985) and Nwaokoro and Nymphas (2020) reported that soil *K* and C_v increased with soil moisture content. Also, increases in soil moisture have been reported to lead to increases in soil *K* for other tropical soils (Ekwue et al., 2015) and soil C_v for a clayey Iranian soil (Al-Shammary and Al-Sadoon (2014). Nwaokoro and Nymphas (2020) explained that concurrent increases in soil moisture and thermal conductivity decreased the heating of the top layer of the soil in reaction to the surface's radiative heating. In organic-rich soil in Northeast China, He et al. (2021) reported that thermal conductivity exhibited specific temperature peaks after initially decreasing slowly from 10 to 0°C, subsequently decreasing gradually with further reductions in temperature, and ultimately increasing and stabilizing at lower soil temperatures.

Generally, soil *D* decreased as θ increased with BEM rate particularly in the PRS. These results agree with the findings of Nwaokoro and Nymphas (2020) in southwestern Nigeria. However, there was a positive – though non-significant – correlation between soil θ and *D* (Table 3), suggesting that higher BEM rates exemplified by BEM-6 could contribute to improved flow of heat through the soil. On the other hand, soil heat flux (*Q*) generally decreased as soil θ increased with BEM rate, treatment effect of which aligns with the negative – though non-significant – correlation between soil θ and *Q* (Table 3). Besides factors such as differences in soil type and mulch material, the suppressive effect of merging of the data for two seasons in the correlations would largely explain those rather strange relationships between soil moisture content and the thermal storage/exchange indices. Okra growth and yield were not affected by these indices. This is despite the fact that soil thermal regime influences organic matter mineralization, seed germination, and availability/uptake of nutrients (Sharma & Kumar, 2023). The present observation underlines the low place of soil thermal regime in agronomic production in the humid tropics; however, the role of organic soil amendments needs to be investigated.

In this study, the effects of BEM-4 often resembling what would be expected from the control plots is noteworthy, especially its recording the lowest TFFY during the CRS. This observation could be due to the fact that the relationship between soil *Q* and θ may be influenced by the dynamics of water availability, plant water uptake, and the overall soil moisture status. In terms of crop response, warm-season crops may show a sensitivity to the modifications in the soil due to BEM rates, as evident here. This emphasizes the need to consider not only the prospects but also the potential constraints of BEM, as would be expected of mulch use in soil and water conservation (Obalum et al., 2011).

The specific soil moisture-temperature requirements of crops should be considered before adopting the BEM strategy in agronomic production in the humid tropics. This will ensure that the implementation of BEM effectively complements crop growth and productivity rather than hindering them, thereby aligning with the expected agronomic benefits of the mulching technology in agriculture, especially under erratic rainfall patterns. Organic mulching could increase soil moisture without corresponding increases in crop yields especially with clayey soils in drier climates (Selolo et al., 2023), the more commonly reported agronomic response to mulch-induced increases in soil moisture status in the tropics is increased productivity. In the derived savannah of southeastern Nigeria, Aniekwe (2015) stated that mulch enhanced soil moisture contents, transpiration rates, nutrient absorption, and photosynthesis, resulting in improvements in the output of fresh and dried vegetable crops. The findings of Obalum et al. (2017) that surface mulching optimized the yield of fluted pumpkins in drought-prone tropical soils of the present study in the dry season corroborates this link between mulch-induced increases in soil moisture and crop yields. Indications are that when organic mulch fails to increase the moisture contents of these soils, no increases in crop yields would occur (Osakwe et al., 2023). Yasmina et al. (2020) reported that mulch improved the various growth-contributing characteristics and yield of *chili* in Jamalpur, Bangladesh.

In proposing the BEM strategy in mulching technology in tropical agriculture, its trifocal attributes of being ecologically, agronomically, and economically viable need to be complete. By enhancing soil moisture status and okra fruit yield in this study, the ecological and agronomic concerns have been met; the economic concern remains to be validated. However, there have been cases of surface organic mulching at heavier application rates leading to increases in soil moisture content, crop yields, and economic benefits. For instance, from the semi-arid Ranga Reddy district of the Indian state of Telangana, Bhutia et al. (2017) reported that thick-layered organic mulch enhanced moisture content of a sandy-loam soil, fruit yield of okra, and benefit-cost ratio under 100% recommended dose of N-fertilizer. Amin et al. (2021) recorded the lowest fruit yield of tomato crops on no-mulch plots and concluded that organic mulch contributed to the outcome in terms of yield, quality, and economic benefits of tomatoes in Dinajpur, Bangladesh.

For the above cited studies, organic mulches were used at rates higher than the BEM strategy proposed here. Drawing inference from these instances, we are optimistic that, when adopted in climate-varying tropical crop production systems, the BEM rates that produced higher okra TFFY compared to the no-mulch control would meet the third requirement of economic viability. Further studies will confirm this notion.

5. CONCLUSION

Bio-economic mulching (BEM) rates ≤ 6 t ha^{-1} moderated soil hydrothermal properties in a season of rainfall deficit. The BEM improved soil volumetric moisture content which in turn marginally influenced soil thermal storage and exchange, but had pronounced positive influence on okra growth and yield. Generally, as BEM rates increased, soil volumetric moisture content and heat capacity increased, whereas soil temperature, thermal conductivity and diffusivity, and heat flux decreased. These trends were evident in the first partially rainfed season but not in the second completely rainfed season when mulch was not re-applied. Merging of the data for these two seasons in establishing the relationships between BEM-induced soil moisture status and soil thermal storage/exchange indices thus showed some relationships which, though were insignificant, seemingly contradicted conventional observations.

In implementing BEM with scarce dry grasses in droughty tropical agroecosystems, the mulch could be applied 6 t ha^{-1}. At this optimal rate, BEM could enhance soil moisture status to boost vegetable crop production during periods of limited climatic supply, and could have a more pronounced residual agronomic effect in the next more humid season. Further study is needed to determine if organic soil amendments would make the contributions of soil thermal regime to agronomic production to be evident under BEM practices. Also, there is a need to assess weed incidence and explore its various control options under BEM. This would be an opportunity to advance our understanding of the implications of such weed incidence for the overall economic viability of the BEM concept.

Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear and influence the work reported in this paper.

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