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Soil Temperature and Evaporation Dynamics under Water Stress in Varying Soil Textures and Amendments

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ABSTRACT

This study aimed to assess the effects of various textures and types of soil amendments on soil temperature dynamics and evaporation rates. The experiment was performed using Factorial Randomized Complete Block Design with two independent factors. The first factor was soil textures comprising sand, sandy loam, loam, silt loam, and clay, while the second was the type of soil amendments, including control, guano, and rice husk. Each soil type, amended and unamended, was placed in polybags, saturated with water to field capacity, and subjected to water stress conditions (without additional irrigation) for approximately 34 days. The magnitude of soil temperature fluctuations increased under water stress relative to pre-stress conditions. The highest soil temperature during the day was produced by sandy textures, while at night, the temperature was slightly greater in silt loam and clay. Generally, higher sand fraction correlates with greater temperature during the day and lower at night. The application of soil amendments to all soil textures can produce lower soil temperature during the day and retain heat at night, making soil temperature warmer than the control. Based on the experiment, the highest cumulative evaporation was observed in silt loam soil and samples without the addition of soil amendments. Moreover, extended water stress led to a smaller loss of water by evaporation. To help manage water stress, future studies need to assess the effects of soil amendments on moisture thresholds and the applications in irrigation management.

HIGHTLIGHTS

- Combined soil textures and organic amendments under water stress conditions.
- Guano and rice husk reduced daytime heat and maintained warmth at night.
- Sandy soils heated fastest; clay and silt loam retained heat for longer periods.
- Amendments lowered evaporation and improved soil thermal stability.
- Results support climate adaptation and sustainable soil management efforts.

1. INTRODUCTION

Drought and water stress are still a significant issue globally. According to the Intergovernmental Panel on Climate Change (IPCC) (2023), the high water scarcity in arid lands is caused by global warming. In regions with limited water availability, weather changes can lead to unpredictable or prolonged droughts and affect groundwater availability (Costa de Oliveira et al., 2014). Prolonged water stress adversely affects soil properties (Siebert et al., 2019; Deng et al., 2021; Quintana et al., 2023; Reinsch et al., 2024), plant growth, development, and yield (Silva et al., 2013; Seleiman et al., 2021; Sansan et al., 2024).

The occurrence of water stress is attributed to the lack of sufficient moisture in soil, which affects heat storage and conduction. Differences in this moisture content will affect the thermal properties (Abu-Hamdeh, 2003), particularly temperature dynamics (Zhang et al., 2022). Soil temperature is influenced by changes in moisture content and related properties (Melo-Aguilar et al., 2022), including textures (Akter et al., 2016). Soil textures influence the sensitivity of temperature to moisture (Zhang et al.,

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2022). Therefore, water stress occurring in different soil textures can impact the storage and release of heat from soil (Ali et al., 2024).

Evapotranspiration, comprising transpiration and evaporation, is mainly driven by temperature and influenced by soil moisture (Seneviratne et al., 2010). Evaporation rates are influenced by the amount of available energy and the soil's capacity to store and transmit moisture to the surface (Lehmann et al., 2018). However, the lack of water on arid soil will prevent evaporation from increasing (United Nations Educational Scientific and Cultural Organization (UNESCO), 2020).

Sandy soil has low water-holding capacity (Suzuki et al., 2007), while soil with higher loam, silt, or clay content show moderate to high water-holding capacity (Çakir and Cangir, 2019; Wang et al., 2020). Soil with higher moisture content maintain more stable temperature (Gałęzewski et al., 2022) due to slow heating and gradual cooling (Badía et al., 2017). However, extended periods of warmer temperature can alter microbial activity and affect plant root development (Heinze et al., 2017).

As water stress worsens, soil moisture levels steadily decrease. This low moisture content can lead to a significant rise in soil temperature that is harmful to plant growth and development (Zhang et al., 2022). Therefore, it is crucial to increase initial soil moisture to ensure enough water is available during drought and to prevent extreme temperature spikes.

Soil moisture availability is influenced by soil texture and organic matter. According to previous studies, adding organic matter can increase water-holding capacity (Abukari, 2019; Rehman et al., 2020). This also indirectly impacts soil temperature, in addition to moisture retention (Tuntiwaranuruk et al., 2006; Zhang et al., 2020).

Organic materials can be used as soil amendments to improve water availability, stabilize temperature, and promote healthy plant growth. In the Poso District, guano and rice husks are two locally available organic materials, but remain underutilized. Moreover, Poso is vulnerable to drought as a result of severely limited water resources, particularly for agricultural purposes. Guano (bat excrement) is widely used as a fertilizer (Ajuzieogu et al., 2024; Możdżer, 2024) and rice husks are often applied as compost, biochar, or mulch (Lim et al., 2012; Tan et al., 2024; Budhirani et al., 2025); however, their effects on soil temperature and evaporation under water stress are still poorly understood. Understanding this can provide valuable insights for promoting sustainable soil management in drought-prone areas. Therefore, this study aims to assess the effects on temperature and evaporation when added to different soil textures under water stress.

2. METHODOLOGY

2.1 Study location

This study was conducted in Kawua Village, Poso District, Central Sulawesi (1°25'00"S 120°44'56"E) (Figure 1). Kawua is located at an elevation of 16 meters above sea level, with minimum air temperature ranging from 19.2°C to 23.0°C, maximum temperature 32.8°C to 35.2°C, and average relative humidity between 70.7% and 86.4% (Statistics of Poso Regency, 2024).

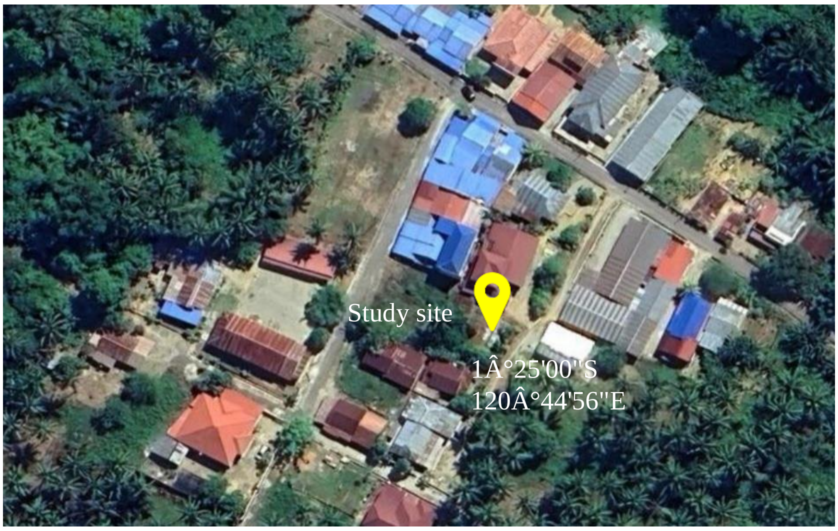

Figure 1. Study site location in Kawua Village, Poso District, Central Sulawesi

2.2 Soil and soil amendments

This study used five soil textures, namely sand, sandy loam, loam, silt loam, and clay, which were classified according to the USDA Soil Taxonomy. Soil amendments used in this study were guano and rice husks, as shown in Figure 2. The guano used consisted of naturally fermented bat feces collected from various cave environments in the Poso District. Rice husks used were raw and obtained directly from a local rice mill. The composition of textures and soil amendments is presented in Table 1.

Figure 2. Guano and rice husk

Table 1. Soil and soil amendments characteristics

Classes of soil textures	Characteristics					
	%Sand	%Silt	%Clay	Bulk density (g/cm^3)	Particle density (g/cm^3)	Porosity (%)
Sand	90	4	6	1.51	2.46	38.4
Sandy loam	59	27	14	1.23	2.20	44.2
Loam	36	41	24	1.32	2.24	41.2
Silt loam	34	51	15	1.10	2.29	52.1
Clay	3	39	58	1.15	1.94	40.8
Soil amendments	**Characteristics**					
	pH H_2O	C/N	Nitrogen	Phosphorus	Potassium	Bulk density (g/cm^3)
			%			
Guano	4.58	12	1.65	1.58	1.74	0.37
Rice husk	7.12	11	1.55	0.29	2.5	0.11

Sand, silt, and clay fractions were quantified for textures determination using the pipette method (Jackson and Saeger, 1935). Soil particle density was measured by the immersion method with a volumetric flask (Santos et al., 2022), Ethanol was replaced with pre-boiled distilled water (Agus and Marwanto, 2022). Furthermore, bulk density was determined using the core or cylinder method (Food and Agriculture Organization of the United Nations (FAO), 2023). Porosity was determined by subtracting the result of dividing bulk density by particle density from one (Agus and Marwanto, 2022).

Soil amendments pH analyses were conducted by measuring the electrical potential with a glass calomel electrode connected to a pH/millivolt meter at a controlled temperature of 25°C, using soil-to-water suspension ratio of 1:2.5 (m:v) (Food and Agriculture Organization of the United Nations (FAO), 2021b). Organic carbon content was determined using the Walkley-Black method (Food and Agriculture Organization of the United Nations (FAO), 2019). Total nitrogen was measured through the Kjeldahl method (Food and Agriculture Organization of the United Nations (FAO), 2021a). Available phosphorus was analyzed using the Olsen method (Olsen et al., 1954). Potassium was determined using a 1 M ammonium acetate (NH_4OAc) solution at pH 7 (Nel et al., 2023), followed by quantification of individual elements through atomic absorption spectrophotometry (AAS) (Food and Agriculture Organization of the United Nations (FAO), 2022).

2.3 Experiment preparation

The experiment was conducted using topsoil obtained from a depth of 0-30 cm. The samples were sun-dried for approximately 4-7 days, depending on weather conditions. Subsequently, soil was ground and sieved using a 2 mm diameter sieve. Guano and rice husks were air-dried for one day and sieved to remove any adhering or attached dirt. The experiment used polybags with a diameter of 20 cm and a height of 30 cm. An air temperature and humidity measuring instrument (Model TL-303, aiqiua, China) was placed in the screen house to monitor temperature and humidity conditions every 3 h.

2.4 Experiment design and implementation

The experiment used a factorial randomized complete block design with two single factors. The first factor was soil textures, namely sand (T1), sandy loam (T2), loam (T3), silt loam (T4), and clay (T5). The second factor was the type of soil amendments applied, including a control treatment (A0), guano (A1), and rice husks (A2). These two factors were combined, leading to 15 treatment combinations, as shown in Table 2. Every treatment combination was repeated 3 times.

Table 2. Combination treatment of soil textures and soil amendments

Code	Description
T1A0	Sandy soil without amendment
T1A1	Sandy soil with guano
T1A2	Sandy soil with rice husks
T2A0	Sandy loam without amendment
T2A1	Sandy loam with guano
T2A2	Sandy loam with rice husks
T3A0	Loam without amendment
T3A1	Loam with guano
T3A2	Loam with rice husks
T4A0	Silt loam without amendment
T4A1	Silt loam with guano
T4A2	Silt loam with rice husks
T5A0	Clay without amendment
T5A1	Clay with guano
T5A2	Clay with rice husks

The sieved soil was mixed with soil amendments according to the treatment combination and placed into a polybag of equal volume. Guano was applied at 150 g/polybag, while rice husks were added at 100 g/polybag. The soil was maintained under moist conditions for 34 days (an estimated 6-day incubation period for the soil amendments followed by a 28-day vegetative period for shallots). During this time, the soil was saturated with water and maintained in consistently moist conditions. After this period, the soil was subjected to water stress for 34 days (the soil moisture content fell below 10%).

Soil temperature was measured every 3 h daily using soil thermometer (4-in-1 Soil Survey Instrument (Soil Test Meter), Shenzhen Handsome Technology Co., Ltd/Walcom International Industry Ltd., China). Evaporation was estimated by weighing soil-filled polybags every 3 days. The difference between successive weights represented the amount of water lost to evaporation during each interval. Evaporation can be measured using equation 1:

$$E = W1 - W2 \quad (1)$$

Where; E=evaporation loss during the interval (g), W1=weight of soil-filled polybag at the beginning of the interval (g), W2=weight of soil-filled polybag at the end of the interval (g).

2.5 Statistical analyses

The data obtained were tested for normality using the Shapiro-Wilk test. Data that followed a normal distribution were analyzed using analysis of variance (ANOVA) to determine the effect of treatment factors on each observation parameter. Treatment factors that showed significant or highly significant effects were further evaluated using Duncan's Multiple Range Test (DMRT) at a 95% confidence level (α=0.05) to compare treatment means. Normality testing, ANOVA, and post hoc analyses were performed using SPSS Statistics version 27.

3. RESULTS

3.1 Weather conditions in site study

The intensity of rainfall and the relative sunshine duration are shown in Figure 3. The monthly rainfall during the study period ranged from 254.0 to 364.0 mm, with the number of rainy days ranging from 15 to 19. The average relative sunshine duration ranged from 55% to 65%.

The fluctuations in air temperature are presented in Figure 4. The highest average air temperature, 36.11°C, was recorded at noon, while the lowest of 27.48°C, was recorded at 6:00 am. The average air temperature increased from 6:00 am and reached the highest at noon subsequently, the average air temperature significantly decreased from noon (36.11°C) to 9:00 pm (28.32°C). Temperature decreased between 9:00 pm and 6:00 am, with an average decline of 0.84°C.

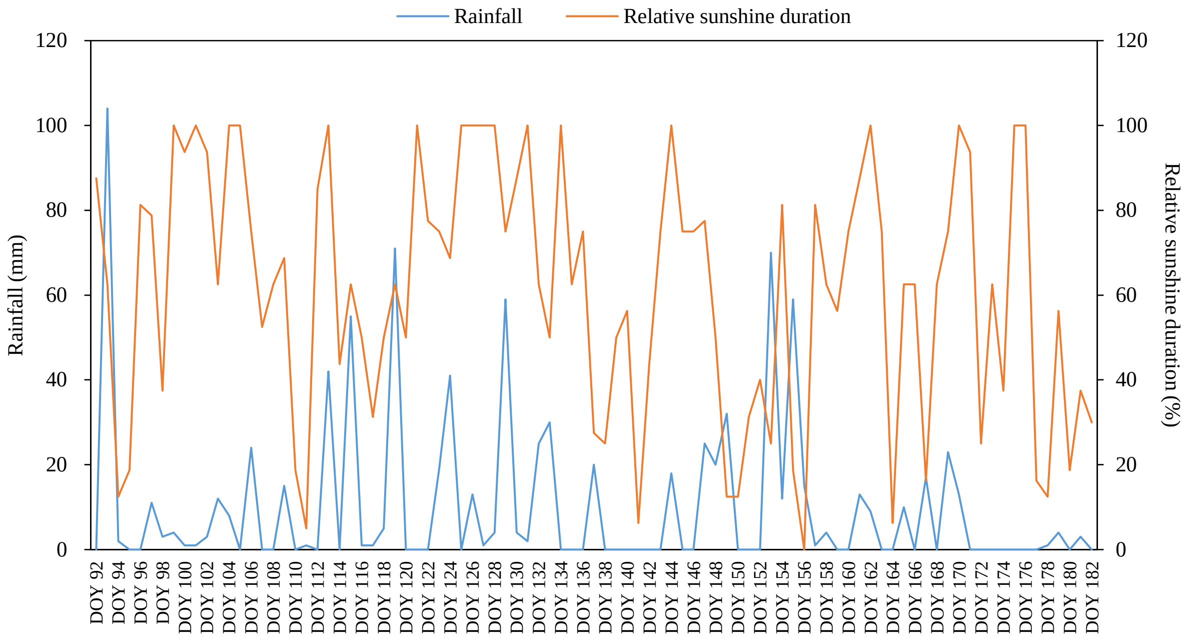

Figure 3. Rainfall intensity and relative sunshine duration during the study

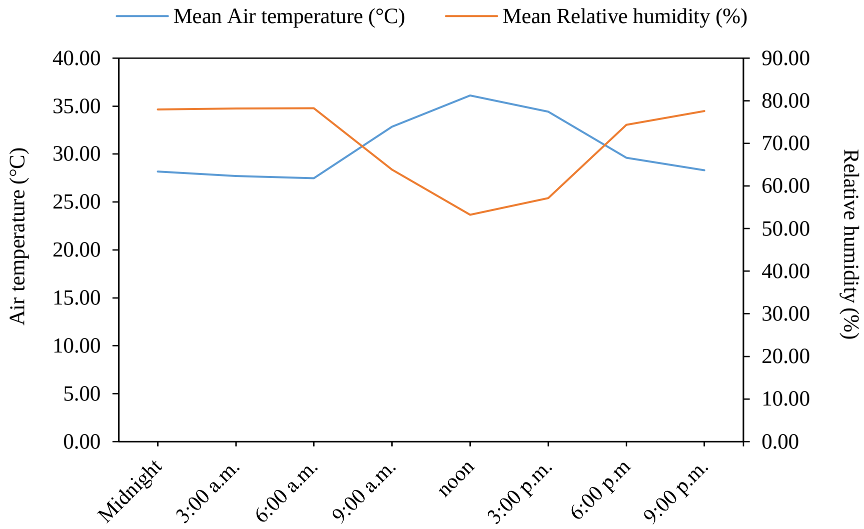

Figure 4. Average air temperature and relative humidity every 3 hours during the study

The dynamics of air humidity are shown in Figure 4. Air humidity was inversely proportional to air temperature. The lowest average air humidity was recorded at noon, at 53.24%, while the highest was at 6:00 am (78.25%). The average air humidity decreased significantly from 6:00 am to noon, and slightly increased by 3:00 pm (57.17%). The most significant increase in air humidity occurred between 3:00 pm and 6:00 pm, when the average was 74.33%. This was followed by a gradual increase until 6:00 am, although the rise was minimal and remained approximately constant.

3.2 Soil temperature dynamics

The dynamics of soil temperature before and after stress on different soil textures and soil amendments are shown in Tables 3 and 4. Based on the results, soil temperature fluctuations for all treatment combinations followed the same pattern before and after water stress. Generally, the lowest soil temperature was recorded at 6:00 am, while the highest was at noon from 6:00 am to noon, a gradual increase in temperature was observed. At 3:00 pm, temperature slightly increased or decreased, but the changes were minimal. Soil temperature decreased significantly from 3:00 pm to 6:00 pm and continued to decline until 6:00 am the following day. As shown in Tables 3 and 4, temperature recorded between 9:00 pm and 6:00 am did not vary substantially, indicating a slight decrease.

3.2.1 Soil temperature before water stress

Table 3 showed that soil textures affected temperature at all observation times. In comparison, adding soil amendments significantly affected soil temperature at midnight, 3:00 am, noon, 6:00 pm, and 9:00 pm. The interaction effect of the two factors was observed only at 3:00 pm.

Soil temperature varied significantly with soil texture (Table 3), with sand showing the highest daytime peak (38.20±0.31°C) and clay and silt loam remaining cooler (35.83±0.58°C and 35.90±0.40°C, respectively; $p<0.01$). Nighttime temperatures were more uniform, ranging from 26.55±0.05°C in sand to 27.17±0.07°C in clay and silt loam, with differences not statistically significant. Among the amendments, guano and rice husk slightly moderated daytime peaks (reductions of ~0.20-0.23°C) and slightly increased nighttime temperatures (~0.05-0.11°C); these effects were statistically significant at peak daytime hours ($p<0.05$) but not at night. The interaction between soil texture and amendment was not significant, indicating that soil type is the main driver of diurnal temperature variation, while amendments contributed only minor, observed adjustments. Detailed measurements and statistical comparisons are provided in the Table 3.

3.2.2 Soil temperature after water stress

Table 4 showed that soil textures affected temperature after water stress at all observation times. In comparison, adding soil amendments significantly affected soil temperature from 9.00 am to 9:00 pm. There was no interaction effect between textures and soil amendments on soil temperature after stress. Soil textures affected the average temperature at all observation times, while the impact of soil amendments on average soil temperature was only shown during observations from 9:00 am to 9:00 pm.

Soil temperature varied primarily with soil texture, and these differences were statistically significant at all time points ($p<0.01$). Sand heated most rapidly, reaching the highest temperatures around midday (~39°C at noon), whereas finer-textured soils such as clay and silt loam remained cooler (~36-37°C), reflecting their greater water-holding capacity. Amendments showed minor effects: peak daytime temperatures were slightly lower with rice husk or guano, with reductions of ~0.3-0.5°C in clay. These differences were statistically significant at 9:00 am, noon, and 3:00 pm ($p<0.05$), whereas nighttime temperatures (~26-27°C) were unaffected ($p>0.05$). The interaction between soil texture and amendment was not significant at any time, indicating that soil type is the main driver of diurnal temperature variation, while observed differences among amendments were relatively small. Soil temperature patterns after stress resembled pre-stress trends, but with higher values.

3.3 Cumulative evaporation

Cumulative evaporation was strongly influenced by soil texture. Sand had the lowest evaporation (31.29±1.34 mm), reflecting its low water-holding capacity, while silt loam was highest (62.23±17.33 mm). Loam (57.49±2.37 mm), sandy loam (56.63±7.75 mm), and clay (55.06±13.44 mm) showed intermediate values, indicating a balance between water retention and loss. Soil amendments significantly reduced evaporation; guano (51.60±31.64 mm) and rice husk (50.77±31.87 mm) lowered cumulative water loss by 3-8 mm compared with the control (55.25±37.59 mm). The soil texture and amendment interaction was also significant ($p<0.05$), with rice husk reducing evaporation by ~15 mm in clay soils (from 57.40±1.23 mm to 48.79±1.23 mm), while amendments had minimal effect in sand (31-32 mm). These results indicate that although soil texture is the primary determinant of evaporation, organic amendments, particularly rice husk, can substantially enhance water retention in fine-textured soils under prolonged stress.

Table 3. Effect of treatment combinations, textures, and soil amendments on average soil temperature before water stress

Treatment	Soil temperature (°C) by time point							
	Midnight	3.00 am	6.00 am	9.00 am	Noon	3.00 pm	6.00 pm	9.00 pm
Soil textures								
Sand	27.20±0.09 a	26.55±0.05 a	25.86±0.00 a	31.58±0.19 d	38.20±0.31 d	37.70±0.29 d	31.41±0.37 a	28.37±0.18 a
Sandy loam	27.75±0.06 b	26.93±0.08 c	26.13±0.12 b	30.68±0.10 c	36.49±0.19 c	36.63±0.30 c	32.06±0.11 b	29.17±0.24 b
Loam	27.82±0.06 c	26.89±0.07 b	26.16±0.07 b	30.42±0.07 b	36.31±0.11 b	36.51±0.19 bc	32.15±0.16 b	29.23±0.20 bc
Silt loam	27.86±0.09 c	27.17±0.07 d	26.27±0.07 c	30.35±0.14 b	35.90±0.40 a	36.42±0.22 b	32.34±0.26 c	29.32±0.26 c
Clay	27.99±0.24 d	27.17±0.07 d	26.40±0.17 d	30.23±0.43 a	35.83±0.58 a	36.11±0.53 a	32.48±0.19 c	29.56±0.25 d
Sig.	**	**	**	**	**	**	**	**
Amendment								
Control	27.69±0.80 a	26.92±0.67 a	26.15±0.48	30.72±1.45	36.69±2.53 b	36.73±1.66	32.00±1.16 a	29.07±0.19 a
Guano	27.76±0.83 b	26.97±0.69 b	26.18±0.58	30.64±1.37	36.49±2.50 a	36.64±1.50	32.15±1.02 b	29.14±0.29 ab
Rice husk	27.72±0.085 ab	26.94±0.71 ab	26.15±0.58	30.60±1.58	36.46±2.74 a	36.65±1.78	32.10±1.17 ab	29.18±0.19 b
Sig.	*	*	ns	ns	**	ns	*	*
Interaction of soil textures and soil amendments								
T1A0	27.17±0.06	26.54±0.00	25.86±0.08	31.65±0.10	38.33±0.04	37.80±0.09 e	31.27±0.14	28.32±0.08
T1A1	27.24±0.03	26.57±0.00	25.86±0.00	31.50±0.18	38.08±0.20	37.57±0.09 e	31.57±0.11	28.33±0.06
T1A2	27.20±0.03	26.55±0.06	25.86±0.16	31.58±0.10	38.18±0.11	37.74±0.32 e	31.38±0.19	28.45±0.07
T2A0	27.74±0.04	26.90±0.02	26.15±0.02	30.73±0.12	36.57±0.21	36.76±0.29 d	32.04±0.15	29.06±0.07
T2A1	27.77±0.09	26.96±0.00	26.15±0.03	30.68±0.08	36.42±0.07	36.60±0.06 cd	32.02±0.07	29.23±0.06
T2A2	27.73±0.06	26.92±0.03	26.07±0.03	30.64±0.11	36.49±0.02	36.52±0.14 cd	32.11±0.03	29.24±0.19
T3A0	27.85±0.04	26.89±0.03	26.18±0.03	30.45±0.11	36.36±0.16	36.43±0.12 c	32.08±0.24	29.32±0.09
T3A1	27.82±0.05	26.92±0.02	26.18±0.03	30.43±0.03	36.29±0.12	36.51±0.06 cd	32.21±0.03	29.23±0.08
T3A2	27.80±0.04	26.86±0.03	26.13±0.02	30.39±0.03	36.27±0.14	36.58±0.16 cd	32.14±0.20	29.15±0.07
T4A0	27.83±0.02	27.14±0.00	26.25±0.00	30.37±0.15	36.07±0.03	36.33±0.07 bc	32.21±0.12	29.21±0.09
T4A1	27.90±0.08	27.20±0.02	26.25±0.03	30.39±0.05	35.88±0.04	36.43±0.09 c	32.38±0.06	29.29±0.07
T4A2	27.85±0.02	27.17±0.02	26.30±0.02	30.29±0.21	35.75±0.28	36.51±0.07 cd	32.42±0.17	29.45±0.13
T5A0	27.88±0.04	27.14±0.00	26.32±0.00	30.42±0.14	36.10±0.13	36.35±0.11 bc	32.40±0.21	29.44±0.08
T5A1	28.05±0.04	27.19±0.02	26.45±0.02	30.19±0.09	35.77±0.11	36.07±0.28 ab	32.56±0.15	29.62±0.20
T5A2	28.05±0.06	27.19±0.02	26.42±0.02	30.07±0.08	35.63±0.07	35.92±0.07 a	32.48±0.04	29.62±0.07
Sig.	ns	ns	ns	ns	ns	*	ns	ns

Note: The numbers followed by the same letter in the same factor and column are not significantly different at α=0.05. ns: not significant at α=0.05. T1: sand, T2: sandy loam, T3: loam, T4: silt loam, T5: clay, A0: unamended (control), A1: guano, A2: rice husk

Table 4. Effect of treatment combinations, soil textures, and soil amendments on average soil temperature after water stress

Treatment	Soil temperature (°C) by time point							
	Midnight	3.00 am	6.00 am	9.00 am	Noon	3.00 pm	6.00 pm	9.00 pm
Soil textures								
Sand	27.35±0.05 a	26.52±0.04 a	25.66±0.02 a	32.21±0.42 d	38.98±0.45 e	38.02±0.17 d	31.59±0.26 a	28.53±0.11 a
Sandy loam	27.75±0.05 b	26.82±0.04 b	25.96±0.09 b	31.23±0.20 c	37.33±0.33 d	37.00±0.33 c	32.18±0.09 b	29.29±0.13 b
Loam	27.79±0.07 b	26.82±0.05 b	25.99±0.11 bc	31.05±0.19 b	37.10±0.31 c	36.86±0.15 bc	32.33±0.12 c	29.31±0.18 b
Silt loam	27.94±0.09 c	27.05±0.04 c	26.02±0.05 cd	30.99±0.31 b	36.83±0.31 b	36.74±0.20 b	32.31±0.25 c	29.31±0.26 b
Clay	27.96±0.08 c	27.06±0.05 c	26.05±0.04 d	30.70±0.22 a	36.47±0.38 a	36.39±0.31 a	32.43±0.19 c	29.69±0.37 c
Sig.	**	**	**	**	**	**	**	**
Amendment								
Control	27.74±0.65	26.85±0.59	25.94±0.43	31.35±1.65 b	37.50±2.67 b	37.10±1.58 b	32.10±0.92 a	29.17±1.08 a
Guano	27.78±0.67	26.86±0.59	25.94±0.41	31.19±1.51 a	37.26±2.54 a	36.92±1.65 a	32.24±0.84 b	29.24±1.15 ab
Rice husk	27.75±0.67	26.86±0.60	25.92±0.42	31.16±1.50 a	37.26±2.61 a	36.98±1.71 a	32.16±0.92 ab	29.27±1.22 b
Sig.	ns	ns	ns	**	**	**	*	*
Interaction of soil textures and soil amendments								
T1A0	27.33±0.03	26.51±0.03	25.66±0.02	32.40±0.24	39.20±0.20	38.08±0.23	31.50±0.15	28.49±0.07
T1A1	27.37±0.03	26.52±0.02	25.67±0.02	32.15±0.29	38.86±0.16	37.95±0.16	31.71±0.14	28.53±0.09
T1A2	27.34±0.07	26.54±0.01	25.65±0.02	32.08±0.21	38.89±0.09	38.04±0.28	31.57±0.20	28.58±0.11
T2A0	27.74±0.04	26.81±0.01	25.97±0.02	31.31±0.09	37.49±0.17	37.13±0.21	32.14±0.04	29.24±0.05
T2A1	27.78±0.06	26.84±0.00	25.99±0.02	31.15±0.15	37.25±0.06	36.87±0.17	32.21±0.05	29.34±0.03
T2A2	27.75±0.04	26.82±0.02	25.92±0.00	31.24±0.15	37.25±0.07	36.99±0.14	32.18±0.03	29.28±0.12
T3A0	27.82±0.04	26.82±0.03	26.01±0.01	31.13±0.18	37.23±0.11	36.93±0.20	32.28±0.16	29.38±0.09
T3A1	27.78±0.05	26.83±0.01	26.01±0.02	30.99±0.10	36.98±0.15	36.82±0.07	32.38±0.01	29.31±0.03
T3A2	27.76±0.05	26.80±0.03	25.94±0.03	31.01±0.07	37.09±0.04	36.83±0.10	32.32±0.13	29.23±0.01
T4A0	27.90±0.03	27.03±0.00	26.00±0.01	31.12±0.13	36.96±0.08	36.83±0.10	32.19±0.09	29.19±0.05
T4A1	27.97±0.02	27.06±0.01	26.01±0.02	31.00±0.04	36.83±0.05	36.68±0.11	32.37±0.01	29.32±0.08
T4A2	27.94±0.02	27.06±0.01	26.04±0.04	30.87±0.18	36.71±0.12	36.70±0.16	32.37±0.17	29.41±0.09
T5A0	27.93±0.02	27.06±0.02	26.06±0.05	30.80±0.14	36.65±0.03	36.53±0.12	32.37±0.09	29.54±0.09
T5A1	28.00±0.02	27.05±0.01	26.04±0.04	30.68±0.14	36.40±0.09	36.29±0.16	32.52±0.04	29.69±0.16
T5A2	27.96±0.01	27.09±0.02	26.03±0.04	30.63±0.12	36.36±0.08	36.35±0.08	32.39±0.05	29.85±0.09
Sig.	ns	ns	ns	ns	ns	ns	ns	ns

Note: The numbers followed by the same letter in the same factor and column are not significantly different at α=0.05. ns: not significant at α=0.05. T1: sand, T2: sandy loam, T3: loam, T4: silt loam, T5: clay, A0: unamended (control), A1: guano, A2: rice husk

3.4 Soil moisture volume during water stress

All soils exhibited a steady decline in moisture over 34 days following water stress, with the rate of loss influenced by soil texture and amendments (Figure 5). In unamended soils, sand lost moisture most rapidly, dropping from ~850 mL to near 0 mL, whereas sandy loam and loam decreased from ~1,750 mL to 250-400 mL. Silt loam and clay retained more water, ending around 400 mL and 750 mL, respectively, with a slower decline after ~20 days, indicating resistance to further evaporation.

Amendments slowed moisture loss across all textures. With guano, sand still lost water rapidly, decreasing from ~1,050 mL to ~150 mL, while sandy loam and loam retained slightly more moisture, declining from ~1,700 mL to 400-500 mL. Silt loam and clay ended near 550 mL and 900 mL, indicating improved buffering against prolonged stress. Rice husk further enhanced water retention: sand approached 0 mL more slowly than the control, sandy loam and loam finished around 400-450 mL, and silt loam and clay retained the highest moisture, ending near 750 mL and 1,150 mL (Figure 5).

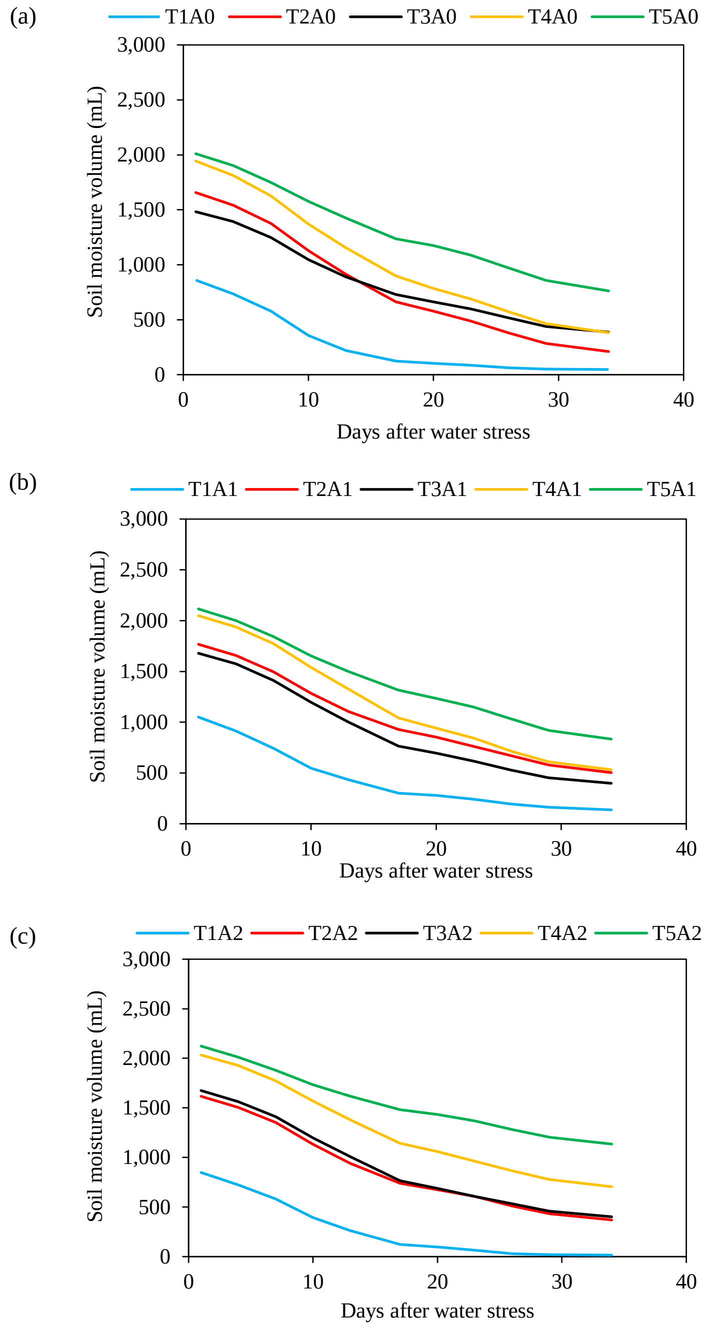

Figure 5. Effects of water stress on water volume across soil textures: unamended (a), guano-amended (b), and rice husk-amended soil (c). Note: T1: sand, T2: sandy loam, T3: loam, T4: silt loam, T5: clay, A0: unamended (control), A1: guano, A2: rice husk.

4. DISCUSSION

Water stress significantly increased soil temperature across all textures, although the overall temperature trends remained similar to pre-stress conditions. Akter et al. (2016) also reported comparable soil surface temperature patterns under both moist and dry conditions. Soil temperature was lowest at 6:00 a.m. and gradually rose until noon. A slight decrease occurred at 3:00 pm, particularly in sandy soil without amendments. In contrast, sandy loam, loam, silt loam, and clay soils showed no significant temperature drop between noon and 3:00 pm, reflecting higher thermal inertia due to finer particle distribution and greater water retention. By 6:00 pm, a substantial temperature reduction was observed, especially in sandy soil, with an average drop of approximately 7°C, likely caused by its low heat capacity and rapid radiative cooling. Temperatures stabilized between 3:00 am and 6:00 am, following a pattern similar to air temperature, indicating that soil temperature rises and falls alongside ambient conditions. Solar radiation also strongly influenced both soil and air temperature (Yolcubal et al., 2004; Onwuka and Mang, 2018; Khamidov et al., 2023).

During water stress, soil temperature is higher than under moist or wet conditions. This difference arises because moist soil cools more effectively through evaporation, which consumes energy as latent heat (Szilagyi et al., 2024). When soil moisture declines under stress, less energy is used for evaporation, causing the soil to heat more rapidly (Lozano-Parra et al., 2018). Soil moisture thus acts as a buffer, moderating temperature fluctuations (Zhang et al., 2022; Greiser et al., 2024). Wet soils warm more slowly due to water's high specific heat, which requires more energy to raise temperature (Howe and Smith, 2021). In contrast, under water stress, solar energy is absorbed directly by the soil, resulting in higher temperature increases (García-García et al., 2023).

Temperature changes were more pronounced in sandy soil. Between 6:00 am (25.66±0.02°C) and noon (38.98±0.45°C), soil temperature rose by approximately 13°C, reflecting sandy soil's low water-holding capacity and high thermal conductivity. By 6:00 pm, temperature decreased by 7°C to 31.59±0.26°C. These fluctuations were slightly smaller than those observed before water stress (Table 3). Water stress also increased the diurnal temperature range (Zhang et al., 2020). For example, sandy loam and loam soils experienced a ~10°C drop from noon to midnight, compared to ~8°C under non-stress conditions. These results highlight that soil moisture is critical for stabilizing soil temperature (Al-Kayssi et al., 1990).

Sandy soil heated more quickly during the day but cooled faster at night, while clay soil remained warmer at night. This indicates that higher sand content amplifies diurnal temperature swings due to lower specific heat and volumetric heat capacity (Abu-Hamdeh, 2003; Akter et al., 2016). Differences in soil texture also influence water retention, which in turn affects temperature dynamics (dos Santos et al., 2021; Stumpe et al., 2023). Soil temperature, surface moisture, and thermal properties are closely interconnected (Melo-Aguilar et al., 2022).

Soil amendments mitigated temperature increases during the day and maintained warmth at night (Table 3). This thermal buffering results from higher moisture retention and improved heat storage. Amendments increase porosity and water content (Liberalesso et al., 2021; Bhanwaria et al., 2022), which cools the soil through evaporation during the day and releases heat gradually at night (Tuffour et al., 2014; Jandaghian and Colombo, 2024). Enhanced porosity also improves aeration, supporting overall soil health (Abuarab et al., 2019).

Rice husk and guano affected soil temperature and evaporation through distinct yet complementary mechanisms. The lighter color and fibrous texture of rice husk likely increased soil albedo, reflecting a greater portion of incoming radiation and thereby reducing net heat absorption. In contrast, guano, with its high organic matter content, enhanced soil aggregation and porosity, which decreased bulk density and thermal conductivity, ultimately slowing heat transfer within the soil profile. Both amendments also improved water retention, increasing the soil's specific heat capacity and promoting evaporative cooling that further stabilized surface temperature. As a result, rice husk primarily influenced the soil's radiative energy balance, while guano modified subsurface thermal properties. Together, these effects contributed to the observed reductions in temperature peaks and evaporation rates.

Water stress affected cumulative evaporation differently across soil textures. Silt loam showed the highest cumulative evaporation, while sandy soil had the lowest (Table 5), reflecting differences in water retention capacity (Lehmann et al., 2018). Clay soil retained more water but had minimal evaporation, likely due to its high moisture retention (Song et al., 2016). Soil amendments reduced evaporation by increasing moisture retention, limiting daytime heating, and improving microporosity and aggregate stability (Das et al., 2023; Feng et al., 2023; Wang et al., 2024). Higher soil moisture also raises specific heat capacity, reducing susceptibility to solar heating and minimizing additional moisture loss through evaporation (Liu et al., 2020; Zhang et al., 2020). Soil with low moisture content tended to produce less evaporation that could be converted into vapor (Baalousha et al., 2022; Priyanka et al., 2024).

Table 5. Cumulative evaporation from different soil textures, amendments, and the combination of textures and soil amendments

Treatment	Cumulative evaporation (mm)
Soil textures	
Sand	31.29±1.34 a
Sandy loam	56.63±7.75 b
Loam	57.49±2.37 b
Silt loam	62.23±17.33 c
Clay	55.06±13.44 b
Sig.	**
Amendment	
Control	55.25±37.59 b
Guano	51.60±31.64 a
Rice husk	50.77±31.87 a
Sig.	*
Interaction of soil textures and soil amendments	
T1A0	31.89±2.98 a
T1A1	30.83±2.77 a
T1A2	31.15±1.24 a
T2A0	60.17±7.21 c
T2A1	54.08±4.02 bc
T2A2	55.65±4.52 bc
T3A0	57.15±2.13 c
T3A1	58.58±2.15 c
T3A2	56.73±3.02 c
T4A0	69.63±3.78 d
T4A1	55.53±1.90 bc
T4A2	61.53±4.19 c
T5A0	57.40±1.23 c
T5A1	58.98±3.63 c
T5A2	48.79±1.23 b
Sig.	*

Note: The numbers followed by the same letter in the same factor and column are not significantly different at α=0.05. ns: not significant at α=0.05. T1: sand, T2: sandy loam, T3: loam, T4: silt loam, T5: clay, A0: unamended (control), A1: guano, A2: rice husk

The availability of soil moisture strongly influenced evaporation rates during stress. At the onset of stress, moisture declined sharply, consistent with the observation that initial water content drives evaporation rate (An et al., 2018). Over time, evaporation slowed as water availability decreased and remaining water became tightly bound within the soil matrix (Han and Zhou, 2013; Whalley et al., 2013; Qing et al., 2023; Nachum, 2025).

These findings show that soil thermal responses under moisture deficits are strongly influenced by both texture and amendments. In field-scale shallot cultivation, sandy soils, which dry rapidly and heat quickly, require closer monitoring and more frequent irrigation to avoid yield losses. Conversely, finer-textured soils like clay and silt loam retain heat and moderate temperature swings, allowing longer intervals between irrigation. Adding organic amendments such as guano or rice husks further stabilizes temperature, improves water retention, and enhances irrigation efficiency during drought. Maintaining favorable thermal and moisture conditions through amendments and texture-specific management can reduce irrigation frequency, optimize water use, improve crop resilience, and strengthen climate adaptation in agricultural systems.

5. CONCLUSION

This study demonstrates that water stress elevates soil temperatures, with sandy soils experiencing the highest daytime heat, while clay and silt loam retain more warmth overnight. The application of soil amendments across all textures effectively buffers temperature fluctuations and maintains higher nighttime temperatures. It also reduces cumulative evaporation, which is influenced by both soil texture and moisture availability. These findings provide novel insights into the interactions among soil texture, temperature dynamics, and water stress.

Further studies are recommended to assess the effects of soil amendments on critical soil moisture thresholds and to refine irrigation management strategies for mitigating the impacts of water stress. Such investigations will provide essential insights for optimizing soil and water management under changing climatic conditions.

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AUTHOR CONTRIBUTIONS

Author KDJ collected and curated data, performed data analysis, wrote the original draft, edited, and finalized the manuscript. OC, K, and M conceived the idea and designed the study, providing supervision or mentorship. All authors read and agree to the submission of the manuscript to the journal.

DECLARATION OF CONFLICT OF INTEREST

The authors declare that there is no conflict of interest in the publication.

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