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# Arduino-Based Monitoring of Soil Temperature under Contrasting Substrate and Rainfall Conditions

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## Abstract

Soil temperature dynamics play a crucial role in various soil processes and plant development. In this study, two experiments were conducted to evaluate the effect of structural and climatic conditions on soil temperature, using a custom-built Arduino-based data logging system. Experiment 1 (Julian days 203 - 257) compared field soil and potted soil under rainy conditions, while Experiment 2 (Julian days 258 - 278 for Rain and 279 - 338 for No Rain) evaluated potted soil versus potted sand under both rainy and dry periods. Interior and surface temperatures were recorded every 40 minutes using buried and exposed sensors, and daily minimum, maximum, and average temperatures were analyzed. Results from Experiment 1 revealed that interior soil temperatures in pots were significantly higher (up to 32.26˚C) and minimum temperatures lower (down to 13.4˚C) compared to field soil. This indicated greater thermal variability in pots, even under rainy conditions. In Experiment 2, no significant differences were observed between sand and soil within pots under rainy conditions; however, temperature values differed markedly between climatic conditions. Under dry conditions, interior maximum temperatures exceeded 34˚C, while minimum temperatures dropped below 8˚C. Additionally, in both experiments, surface temperatures were generally higher than interior temperatures. The data suggest that structural configuration (pot vs. field) and rainfall presence are the primary factors influencing soil thermal behavior, rather than substrate type. The sensor system proved reliable for detecting both thermal contrasts and similarities, providing a valuable tool for evaluating soil temperature under varying environmental conditions. Although each treatment was represented by a single container due to equipment constraints, the findings lay the groundwork for future studies incorporating greater replication and spatial variability.

**Keywords**

Soil Temperature Monitoring, Substrate Comparison, Low-Cost Monitoring System, Soil Surface Temperature, Subsurface Soil Temperature

## 1. Introduction

Soil temperature is a key environmental variable that directly influences seed germination, root development, microbial activity, and nutrient uptake [1] [2]. Its variability is affected by multiple factors, including soil type, moisture, depth, and exposure to solar radiation. Several studies have shown that temperature fluctuations in the upper soil layers can be substantial, while deeper layers tend to buffer daily variations [3] [4]. Short-term temperature changes are typically prominent up to depths of 0.5 to 1.0 meters.

Containerized systems introduce additional complexity in soil thermal dynamics. Numerous investigations have compared the temperature behavior of different container types and substrates. For example, Nambuthiri *et al.* found that black plastic containers could increase substrate temperatures by up to 6˚C compared to biocontainers [5]. Similarly, Million and Yeager [6], and Witcher *et al.* [7], reported that fabric containers reduced maximum substrate temperatures compared to conventional plastic pots. Ingram *et al.* also noted that prolonged exposure to supraoptimal root-zone temperatures—ranging from 46 to 57˚C—can cause direct injury to plant roots, which are more sensitive than stems or leaves to thermal stress [8].

Surface temperature tends to be higher than subsurface levels, particularly in open-field conditions or where canopies provide limited shade [9]. Moreover, rainfall can moderate soil temperature fluctuations by increasing moisture content and thermal conductivity, often resulting in lower maximum temperatures and higher minimum temperatures compared to dry conditions [10].

While past research has characterized soil temperature under various environmental and container-related conditions, fewer studies have implemented continuous monitoring using accessible, low-cost, open-source technologies. Therefore, the aim of this study was to analyze internal and surface soil temperature behavior under two experimental conditions: 1) field soil vs. potted soil and 2) potted soil vs. potted sand. Temperature data were recorded every 40 minutes using an Arduino-based monitoring system over two distinct seasonal periods (rainy and dry). This approach allowed for evaluating the effects of substrate and precipitation conditions on soil thermal dynamics in both surface and subsurface environments.

## 2. Materials and Methods

The experiment was planned at the facilities of the Colegio de Postgraduados, Montecillo Campus. This study was structured in three stages: 1) development of the experimental devices, 2) verification of device functionality (Experiment 1), and 3) comparison of variables across two substrates (Experiment 2), followed by statistical analysis and calculation of average temperatures for each experiment.

## 2.1. Development of the Experimental Devices

The experiment was conducted at a site located at 19˚27'37.0" N and 98˚54'12.1" W. An Arduino Mega 2560™ board was selected due to its proven accuracy, comparable to commercial data acquisition systems [11]. This board has also been used in previous studies to measure soil variables such as moisture and temperature [12] [13], including applications with DS18B20™ sensors [14]. Accordingly, a custom device was built integrating the Arduino Mega 2560™, a DS18B20™ sensor for air temperature, a BGT SEC Z2™ sensor for substrate internal temperature, and an MLX90614 GY 906™ infrared sensor for surface temperature measurement. The infrared sensor operates through the Adafruit MLX90614™ library within the Arduino IDE and has an accuracy of ±0.5˚C [15].

To validate the performance of the DS18B20 sensor, monthly average temperature readings recorded by the sensor from July 2024 to January 2025 were compared with corresponding monthly averages from the Chapingo weather station operated by the Mexican National Meteorological Service (SMN). The average temperature recorded by the DS18B20 during this seven-month period was 17.39˚C, whereas the SMN reported an average of 16.09˚C, resulting in a difference of 1.30˚C. This deviation is considered acceptable for the agronomic purposes of this study, especially considering that the DS18B20 has a manufacturer-stated accuracy of ±0.5˚C within the −10˚C to +85˚C range. The observed variation may be attributed to factors such as spatial distance from the weather station, differences in recording intervals, and sensor-specific variability. Given this result, no additional calibration was applied to the remaining sensors. Regarding the other sensors used, the BGT SEC Z2 has a reported accuracy of ±0.5˚C, and the MLX90614 infrared sensor also offers high accuracy of ±0.5˚C within the 0˚C to +50˚C range for both air and surface temperature measurements.

Additionally, to record the time and store the data on a micro-SD card, DS1302™ RTC (real-time clock) and MLMSD™ modules were used, respectively. Temperature data were recorded every 40 minutes and saved as a text file (.txt) on the micro-SD card.

Rainfall was also measured using the WH-SP-RG™ MISOL digital rain gauge, which operates through pulses and uses a digital INPUT_PULLUP pin in the Arduino IDE. Rainfall data were stored in a text file (.txt) each time a pulse was detected by the sensor, with each pulse corresponding to 0.2794 mm of precipitation. Two identical devices were constructed for the experiment (**Figure 1** Right).

The estimated cost of the Arduino-based monitoring system was approximately USD $90 - 100 per unit, including the Arduino Mega 2560 board, DS18B20 sensor, MLX90614 infrared sensor, DS1302 real-time clock module, microSD card and reader, power adapter, and basic wiring and connectors. A TFT display was also included for visualization, and 3D-printed housing was fabricated using PLA, which adds a minor cost when spread across multiple units. It is important to note that a BGT SEC Z2 sensor was used in this study to measure internal soil temperature; however, this component alone costs approximately USD $220. For applications focused solely on temperature monitoring, this sensor can be substituted with a second DS18B20, significantly reducing the total system cost while maintaining adequate accuracy. This makes the system highly affordable and suitable for replication in agricultural or environmental studies.

### 2.2. Verification of Device Functionality (Experiment 1)

The functionality of the devices was tested through a preliminary experiment (**Figure 1**). For this purpose, the sensors (BGT SEC Z2™ and MLX90614 GY-906™) of one device were installed in bare soil located 50 cm away from a two-story building. The soil was positioned so that it received direct sunlight for only half of the day, while the building provided shade for the remainder. Meanwhile, the sensors (BGT SEC Z2™ and MLX90614 GY-906™) of the second device were installed in a plantless pot with a volume of 0.1845 $ft^3$ (5.225 $dm^3$), placed on the roof of a two-story building to ensure full sun exposure throughout the day. The pot's volume was estimated using a solid of revolution based on height and radius measurements. Both internal soil temperature sensors were installed at a depth ranging from 5 to 15 cm, while the surface soil temperature sensors were positioned 5 cm above the soil surface.

**Figure 1.** Experimental setup for surface and internal soil temperature measurements in field soil (top left) and potted soil (bottom left), from Experiment 1.

The sensors in both devices were placed under these contrasting conditions to ensure that the recorded temperatures would differ. The bare soil setup experienced cooler conditions due to partial shading, while the rooftop pot was fully exposed to solar radiation. Temperature measurements, soil interior temperature (BGT SEC Z2™) and soil surface temperature (MLX90614 GY-906™), were recorded every 40 minutes from July 22, 2024, to September 14, 2024. This first experiment concluded on that date, and comparisons between treatments were subsequently conducted.

## 2.3. Comparison of Variables in Two Substrates (Experiment 2)

A second experiment was conducted between September 16, 2024, and December 4, 2024. The objective of this experiment was to analyze temperature behavior under two conditions: the influence of rainfall and the influence of two different substrates (sand and soil as shown in **Figure 2**). Therefore, the experiment was divided into two periods: the rainy (Rain) period (September 16 to October 6, 2024) and the dry (No Rain) period (October 7 to December 4, 2024). One pot was filled with loamy-soil and the other with sand as the substrate (**Figure 2**).

**Figure 2.** Setup for measuring surface and internal temperatures in pots filled with sand (left) and soil (right), as part of Experiment 2.

Two variables were measured in each pot: internal temperature and surface temperature. To measure internal temperature, a BGT SEC (Z2)™ sensor was placed at a depth of 5 to 15 cm in both pots. Additionally, both pots were placed on the roof of a two-story building to ensure full exposure to sunlight throughout the day.

Air temperature was also measured during this period using a DS18B20™ temperature sensor.

Due to equipment availability at the institution, only one pot was monitored per device setup. This represents a limitation in terms of spatial replication. However, sensors were kept fixed in place throughout the measurement period to avoid potential errors associated with sensor relocation or disturbance of the substrate. While broader replication would strengthen generalization, the main objective of this study was to validate the performance and reliability of the monitoring device under controlled, contrasting conditions.

### 2.4. Comparison of Temperatures under Different Analyzed Conditions

To compare temperatures under the different analyzed conditions, the data were organized into treatments based on similar environmental conditions.

The Experiment 1 was conducted during the rainy season. One sensor measured temperature in a pot filled with soil exposed to full sunlight throughout the day, while another sensor measured temperature in field soil exposed to sunlight for only half the day. As a result, the treatments obtained for the pot with soil were: internal soil temperature (InST-P) and surface temperature (ST-P). For the field soil, the treatments were: internal soil temperature (InST-S) and surface temperature (ST-S). Air temperature was also considered as a separate treatment (AT).

The Experiment 2 covered two periods: a rainy period (Rain) and a dry period (No Rain). The objective was to compare internal and surface temperatures of two different substrates (soil and sand). During the rainy period (September 16 to October 6, 2024), the treatments obtained from the pots were: internal soil temperature (InST-P), internal sand temperature (InST-A), soil surface temperature (ST-S), and sand surface temperature (ST-A). Additionally, air temperature during this period was also considered a treatment.

It is important to note that the same treatments were obtained for the dry period (October 7 to December 4, 2024). In both periods (rainy and dry), air temperature (AT) was included as a treatment.

Statistical Analysis. Statistical analyses were performed using R software version 4.2.2 [16]. Box-and-whisker plots were generated to visualize temperature distributions across treatments. Normality of residuals was tested using the Shapiro-Wilk test (shapiro.test), and homogeneity of variances was assessed with Levene's test (leveneTest, car package) [17]. When assumptions were not met, a Box-Cox transformation (boxcox, MASS package) was applied [18].

If assumptions were satisfied, ANOVA followed by Tukey's HSD test was used. For data that did not meet assumptions even after transformation, non-parametric tests were applied: Kruskal-Wallis (kruskal.test) and, when significant, Dunn's test with Bonferroni correction (dunn.test) for pairwise comparisons [19].

To ensure independence among observations, the data were aggregated by day, calculating daily maximum, minimum, and mean temperatures for each treatment.

Average temperatures per experiment. In the first experiment, the average temperature every 40 minutes (ADT) was calculated by summing all recorded temperature values and dividing by the total number of readings (2200 readings, obtained by measuring temperature every 40 minutes over 55 days). Subsequently, the average daily maximum temperature (MaxADT) was calculated. To obtain this value, the maximum temperature for each day was first identified (55 values from 55 days), then all daily maxima were summed and divided by the number of days (55).

Similarly, the average daily minimum temperature (MinADT) was calculated by first identifying the minimum temperature for each day and then averaging those values.

This procedure for estimating temperature averages was applied in both experiments.

## 3. Results

In the Experiment 1, temperature data were obtained under both analyzed conditions (pot with soil and field soil), including internal soil temperature, soil surface temperature, and air temperature, as shown in **Figure 3**.

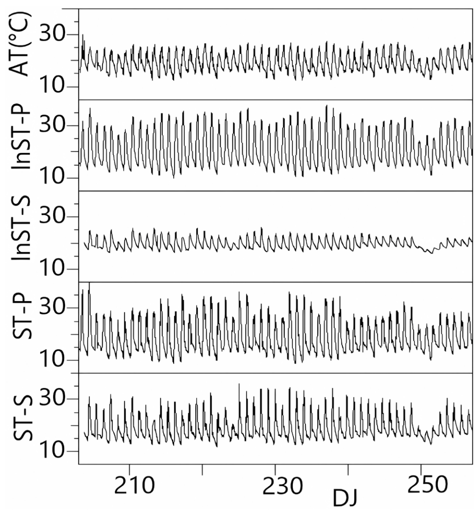


**Figure 3.** Temperature measurements recorded every 40 minutes during Experiment 1 for: air temperature (AT), internal temperature of the pot with soil (InST-P), internal temperature of field soil (InST-S), surface temperature of the pot with soil (ST-P), and surface temperature of field soil (ST-S), across Julian days (DJ) from July 22 to September 14, 2024 (rainy season).

To facilitate the visualization and comparison of temperatures in Experiment 1, a box-and-whisker plot was generated using the daily mean temperature values. The results are presented in **Figure 4**. During this period (July 22 to September 14, 2024), the total recorded precipitation was 165.96 mm. Days without precipitation occurred on July 27; August 4, 5, 7, 10, 11, 19, 20, 25, and 26; and September 4, 6, 7, 9, 12, and 14.

As shown in **Figure 4**, visual inspection suggests that the variance among the data is not homogeneous. Therefore, Levene's test was applied to all groups, yielding a p-value of 2.2e−16, indicating significant differences in variances. Subsequently, the Kruskal-Wallis test was performed, and the null hypothesis of no differences among groups was rejected (p-value < 2.2e−16). As a result, Dunn's test with Bonferroni correction was conducted to identify pairwise differences between treatments. The results of this test are presented in the upper section of Figure 4. Additionally, Levene's test was used to compare the variances between InST-P and InST-S, resulting in a p-value of 0.002522. The same test was applied to ST-P and ST-S, yielding a p-value of 0.9349.

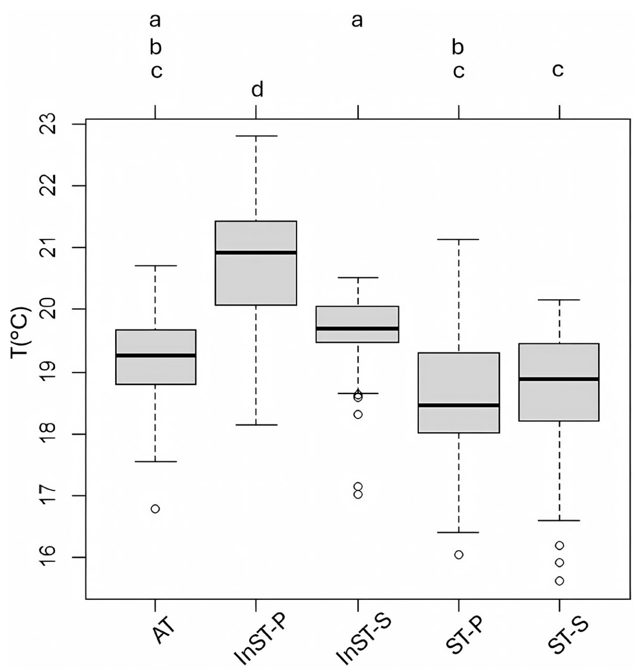


Figure 4. Box-and-whisker plot generated from the first experiment data, showing daily average temperatures for: air (AT), internal temperature of the pot with soil (InST-P), internal temperature of field soil (InST-S), surface temperature of the pot with soil (ST-P), and surface temperature of field soil (ST-S).

Based on the data from Figure 3, daily maximum temperatures were extracted and plotted by treatment using box-and-whisker plots, as shown in Figure 5.

The Shapiro-Wilk test was applied to assess the normality of residuals for each treatment (Figure 5), yielding p-values of 0.07878, 0.0003779, 0.04808, and 0.01847 for InST-P, InST-S, ST-P, and ST-S, respectively. These results indicate that, overall, the residuals do not follow a normal distribution. Similarly, Levene's test was used to evaluate the homogeneity of variances, resulting in a p-value of 9.221e−08, confirming that variance homogeneity was not met for at least one treatment.

Since the assumptions of normality and homogeneity of variances were not satisfied, the non-parametric Kruskal-Wallis test was performed, yielding a p-value of 2.2e−16. This result indicates that at least one treatment differs significantly from the others. Consequently, Dunn's test with Bonferroni correction was conducted to identify pairwise differences. The following treatment pairs did not show statistically significant differences: AT vs. InST-S ($p = 0.0530$), InST-P vs. ST-P ($p = 0.1077$), and ST-P vs. ST-S ($p = 0.7643$). All other pairwise comparisons showed significant differences.

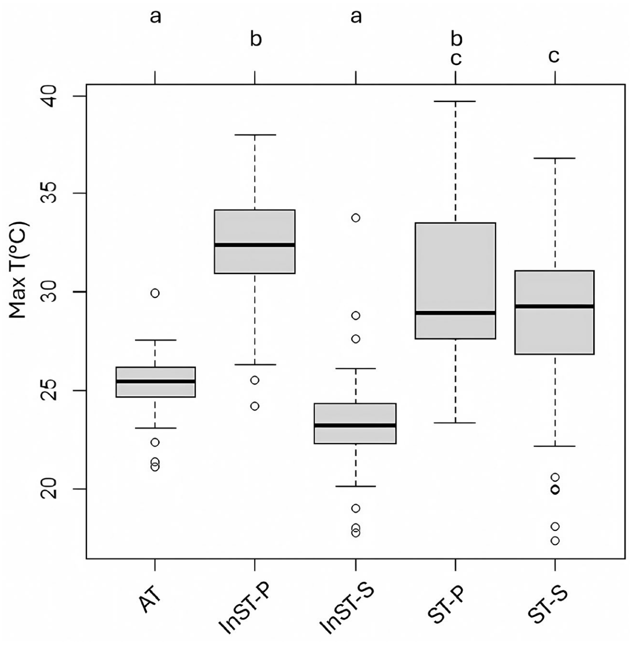


**Figure 5.** Box-and-whisker plot generated from the Experiment 1 data, showing daily maximum temperatures for: air (AT), internal temperature of the pot with soil (InST-P), internal temperature of field soil (InST-S), surface temperature of the pot with soil (ST-P), and surface temperature of field soil (ST-S).

Additionally, daily minimum temperatures were obtained and plotted by treatment using a box-and-whisker plot, as shown in **Figure 6**.

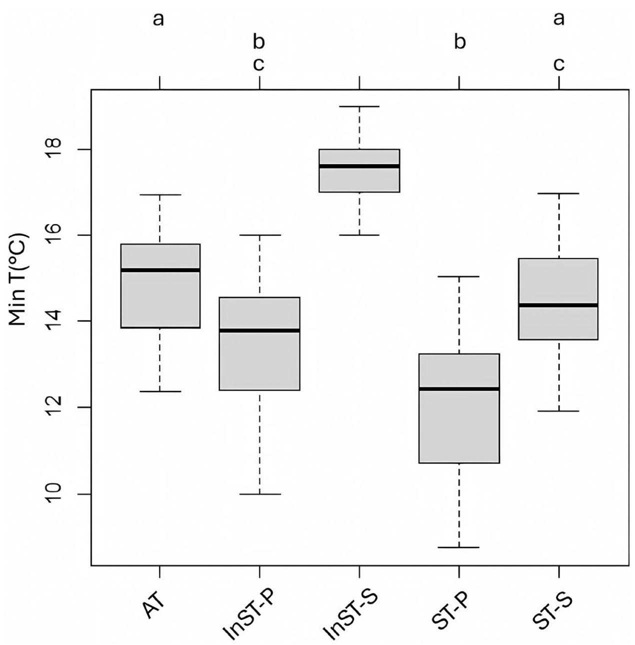


**Figure 6.** Box-and-whisker plot generated from the Experiment 1 data, showing daily minimum temperatures for: air (AT), internal temperature of the pot with soil (InST-P), internal temperature of field soil (InST-S), surface temperature of the pot with soil (ST-P), and surface temperature of field soil (ST-S).

As with the maximum temperatures, the assumptions of normality and homogeneity of variances were not met for the minimum temperatures.

Therefore, the non-parametric Kruskal-Wallis test was applied, yielding a p-value of 2.2e-16, indicating that at least one treatment differs significantly from the others. Subsequently, Dunn's test with Bonferroni correction was performed to identify pairwise differences between treatments. The treatment pairs that did not show significant differences were: "AT" vs. "ST-S" ($p = 1.00$), "InST-P" vs. "ST-P" ($p = 0.0264$), and "InST-P" vs. "ST-S" ($p = 0.0552$).

The Experiment 2 was structured in two periods. Data from the first period (September 16 to October 6, 2024), corresponding to the rainy season, were plotted by treatment according to internal and surface substrate temperatures, as shown in Figure 7. During this period (September 16 to October 6, 2024), the total recorded precipitation was 101.4 mm. No rainfall was recorded on September 17 and 20, and on October 1, 3, and 5.

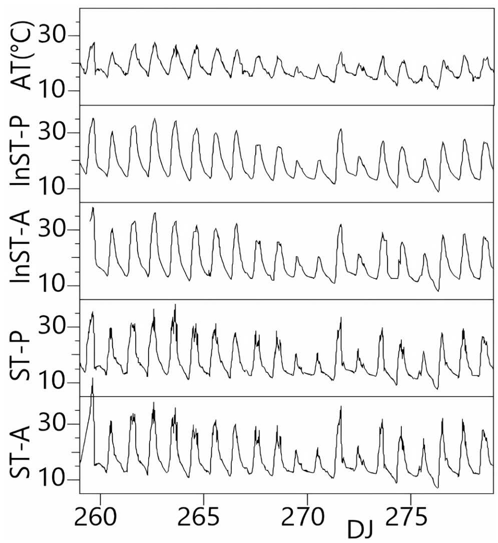


Figure 7. Air temperature (AT) measured every 40 minutes, internal temperature of the pot with soil (InST-P), internal temperature of the pot with sand (InST-A), surface temperature of the soil in the pot (ST-P), and surface temperature of the sand in the pot (ST-A), recorded over Julian days (JD) from September 16 to October 6, 2024.

It is worth mentioning that, similarly, the data from the second period (October 7 to December 4, 2024) of the Experiment 2 were plotted by treatment, considering both the internal and surface temperatures of the substrate corresponding to the rainy season, as shown in Figure 8. During this period (October 7 to December 4, 2024), the total recorded precipitation was only 3.35 mm, confirming the dry conditions. Rainfall was recorded on just three days: October 21, November 2, and November 20.

It is worth noting that the data collected during both periods of Experiment 2 were represented using box-and-whisker plots, based on daily mean temperatures, and separated by rainy and dry seasons, as shown in Figure 9.

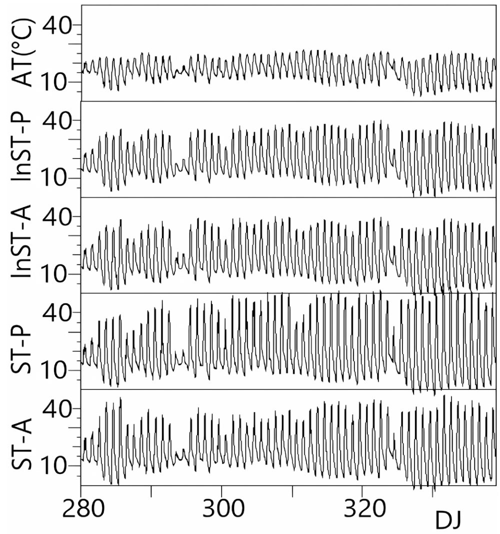


**Figure 8.** Air temperature (AT), temperature inside the pot with soil (InST-P), temperature inside the pot with sand (InST-A), temperature on the surface of the soil in the pot (ST-P), and temperature on the surface of the sand in the pot (ST-A), all recorded every 40 minutes during the Julian days (DJ) from October 7 to December 4, 2024.

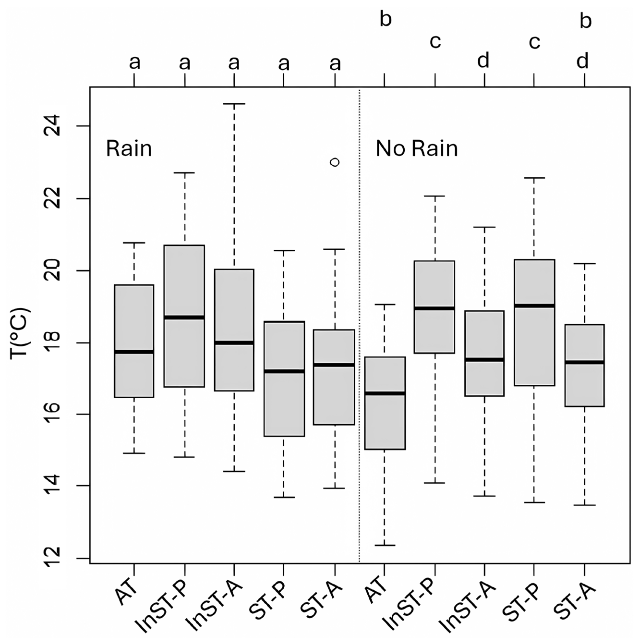


**Figure 9.** Box-and-whisker plot of daily mean temperatures for all variables: air temperature (AT), temperature inside the pot with soil (InST-P), temperature inside the pot with sand (InST-A), temperature on the surface of the soil in the pot (ST-P), and temperature on the surface of the sand in the pot (ST-A), recorded during the rainy period (Rain) and the dry period (No Rain). Letters above the boxes indicate groups with no significant differences ($p > 0.05$).

Based on the data from **Figure 9**, Levene's test was performed to assess the homogeneity of variances. The test was applied separately to the treatments under rainy conditions (p-value = 0.6251) and under dry conditions (p-value = 0.4673).

These results indicate that the assumption of homogeneity of variances was met for both rainy and dry periods.

Additionally, the Shapiro-Wilk test was applied to each treatment under rainy conditions, yielding p-values ranging from 0.333 to 0.728. For the treatments under dry conditions, p-values ranged from 0.0716 to 0.523. These results indicate that the assumption of normality was met for both rainy and dry conditions.

Subsequently, an ANOVA was performed separately for each condition (rain and no rain). Under rainy conditions, the p-value was 0.142, indicating no significant differences among treatments. In contrast, under dry conditions, the ANOVA yielded a p-value of 1.9e−13, suggesting that at least one treatment differed from the others. Therefore, Tukey's test was applied to the treatments under dry conditions, and the significant differences are indicated by the letters above the boxes in **Figure 9**.

On the other hand, the daily maximum temperature data from both periods of Experiment 2 were plotted as box-and-whisker plots, separated by rainy and dry seasons, as shown in **Figure 10**.

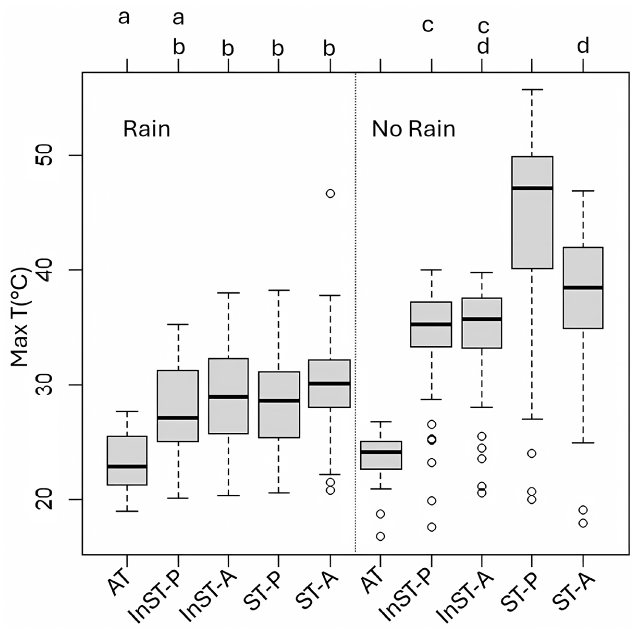


**Figure 10.** Box-and-whisker plot of daily maximum temperatures recorded for air (AT), inside the pot with soil (InST-P), inside the pot with sand (InST-A), on the surface of the soil in the pot (ST-P), and on the surface of the sand in the pot (ST-A), during the rainy period (Rain) and the dry period (No Rain). Letters above the boxes indicate groups with no significant differences ($p > 0.05$).

Shapiro-Wilk and Levene tests were applied to the data from **Figure 10** to assess the assumptions of residual normality and homogeneity of variances, respectively, under both rainy (Rain) and dry (No Rain) conditions, separately. However, the assumptions were not met. A Box-Cox transformation was then applied, and the tests were repeated, but the assumptions still remained unmet.

Levene's test applied to all treatments in Figure 10 yielded a p-value of 1.645e-06, indicating that variances were not homogeneous among treatments. The Kruskal-Wallis test revealed that at least one treatment was significantly different from the others.

Subsequently, group comparisons were conducted separately for the Rain and No Rain conditions. In both cases, the Kruskal-Wallis test indicated significant differences, and thus Dunn's test with Bonferroni correction was applied to identify pairs of treatments with no significant difference. These results are shown as letters above the boxes in Figure 10.

The following treatment pairs showed no significant difference: InST-P: Rain vs. InST-A: Rain (p = 1.00), ST-P: Rain vs. ST-A: Rain (p = 1.00), and InST-P: No Rain vs. InST-A: No Rain (p = 1.00). Moreover, during the rainy season, treatments InST-P, InST-A, ST-P, and ST-A formed a homogeneous statistical group (no significant difference).

Levene's test was also applied to the following treatment pairs (p-values in parentheses, based on Figure 10): InST-P: Rain vs. InST-A: Rain (0.8173), ST-P: Rain vs. ST-A: Rain (0.7374), InST-P: No Rain vs. InST-A: No Rain (0.8721), ST-P: No Rain vs. ST-A: No Rain (0.1798), and AT: Rain vs. AT: No Rain (0.01526).

Finally, the daily minimum temperature data from both periods of Experiment 2 were plotted using box-and-whisker plots, separated by rainy and dry seasons, as shown in Figure 11.

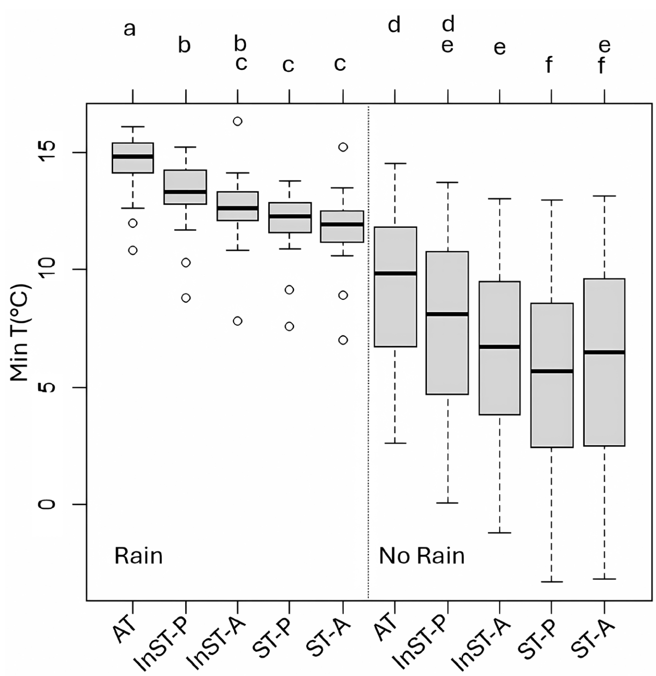


Figure 11. Box-and-whisker plot of daily minimum temperatures recorded for air (AT), temperature inside the pot with soil (InST-P), temperature inside the pot with sand (InST-A), temperature on the surface of the soil in the pot (ST-P), and temperature on the surface of the sand in the pot (ST-A), during the rainy period (Rain) and the dry period (No Rain). Letters above the boxes indicate groups with no significant differences (p > 0.05).

To perform the statistical analysis, Levene's test was first applied to all treatments in Figure 11. The resulting p-value was less than 2.2e−16, indicating a lack of homogeneity of variances among treatments.

Visual inspection of the data suggested similar variances among treatments under rainy conditions, so the statistical analysis was conducted separately for the Rain and No Rain conditions.

For treatments under Rain conditions, the Shapiro-Wilk test was applied to assess residual normality, but the assumption was not met. A Box-Cox transformation was then applied, and the Shapiro-Wilk test was repeated, yielding a p-value of 0.1739, indicating that the residuals followed a normal distribution. Given that the normality assumption was met, Bartlett's test was applied and returned a p-value of 0.9395, confirming homogeneity of variances. With both assumptions satisfied, an ANOVA was performed, revealing that at least one treatment was significantly different. Tukey's test was then used to identify pairwise differences, which are shown by the letters above the boxes in Figure 11.

For the No Rain treatments, the Shapiro-Wilk test indicated that the residuals were not normally distributed. A Box-Cox transformation was applied ($\lambda$ = 1.232323), but residual normality was still not achieved. Consequently, non-parametric tests were used. The Kruskal-Wallis test (p-value = 8.051e−07) was applied, followed by Dunn's test with Bonferroni correction to compare treatment pairs. The results of these comparisons are also indicated by the letters shown above the boxes in Figure 11.

Finally, Levene's test was applied to specific treatment pairs under No Rain conditions. The pairs "InST-P" vs. "InST-A" (p = 0.8271) and "ST-P" vs. "ST-A" (p = 0.1798) showed homogeneity of variances.

## Average Temperatures per Experiment

The average temperatures recorded in each experiment, separated by rainy and dry periods, are shown in Table 1.

Table 1. Average (ADT), minimum (MinADT), and maximum (MaxADT) daily temperatures, and air temperature (AT), recorded during Experiments 1 and 2, separated by Julian day and rainfall condition (Rain and No Rain). Data include soil interior temperature (InST) and soil surface temperature (ST) measured in field soil (-S), potted soil (-P), and potted sand (-A).

| Experiment 1 | Julian days 203 - 257 | | | | |
|---|---|---|---|---|---|
| | Field Soil | | Potted Soil | | |
| Rain | InST-S | ST-S | InST-P | ST-P | AT |
| MinADT[a] | 18.48 | 14.39 | 13.4 | 12.04 | 14.79 |
| ADT[b] | 19.59 | 18.69 | 20.75 | 18.56 | 19.13 |
| MaxADT[c] | 23.19 | 28.66 | 32.26 | 30.19 | 25.28 |

**Continued**

| Experiment 2 | Julian days 258 - 278 | | | | |
|---|---|---|---|---|---|
| | Potted Sand | | Potted Soil | | |
| Rain | InST-A | ST-A | InST-P | ST-P | AT |
| MinADT[a] | 12.48 | 11.63 | 13.08 | 11.85 | 14.38 |
| ADT[b] | 18.36 | 17.38 | 18.89 | 17.34 | 18 |
| MaxADT[c] | 29.11 | 30.73 | 27.93 | 28.84 | 23.41 |
| Experiment 2 | Julian days 279 - 338 | | | | |
| | Potted Sand | | Potted Soil | | |
| No Rain | InST-A | ST-A | InST-P | ST-P | AT |
| MinADT[a] | 6.67 | 6 | 7.88 | 5.67 | 9.48 |
| ADT[b] | 17.74 | 17.26 | 18.87 | 18.76 | 16.39 |
| MaxADT[c] | 34.59 | 37.62 | 34.19 | 44.35 | 23.77 |

[a]Average minimum temperature, [b]Average temperature, [c]Average maximum temperature.

## 4. Discussion

Regarding the Experiment 1 (Field Soil vs. Potted Soil), analysis of daily average temperature clearly showed significant differences between the treatments measuring interior soil temperature, InST-P and InST-S (**Figure 4**). In contrast, the surface temperature treatments, ST-P and ST-S, did not differ significantly.

Additionally, the treatment pair InST-P and InST-S showed a significant difference in variance (Levene's test, p-value = 0.0025), while ST-P and ST-S did not (p-value = 0.9349). This indicates that temperature variability was greater in the internal pot treatment (InST-P) compared to field soil (InST-S), whereas surface temperature variability was similar between treatments.

Moreover, analysis of daily maximum temperatures in the first experiment revealed that interior temperatures in pots were higher than those measured in field soil, with an average difference of 9.07˚C (**Figure 5**). Notably, Nambuthiri *et al.* found average substrate temperatures approximately 6˚C higher in black plastic containers compared to biocontainers [5]. Similarly, Million and Yeager reported that maximum daily substrate temperature (measured 5 cm deep) was on average 6˚C lower in fabric containers than in traditional plastic containers [6]. These findings are consistent with the present study, as the comparison was made between a dark brown plastic pot and partially shaded field soil, resulting in a slightly greater difference than those reported by Nambuthiri *et al.* and Million and Yeager [5] [6].

However, no significant differences were found between surface daily maximum temperatures (soil vs. pot).

Regarding daily minimum temperatures, interior soil temperatures were lower in the pot compared to field soil (**Figure 6**). Also, significant differences were observed for surface temperatures (ST-P vs. ST-S) in **Figure 6**. It is worth mentioning that the average amplitude of surface temperature in field soil was 14.27˚C, while in pots it was 18.15˚C. These results are consistent with Gülser and Ekberli, who reported that in their study of diurnal soil temperature fluctuation, the highest amplitude value (12.31˚C) was observed at the soil surface [20].

These results were expected, as the aim of this first phase of the study was to verify that the sensors could detect clearly contrasting thermal conditions.

In Experiment 2, analysis of daily average temperatures (**Figure 9**) showed that during the rainy period, no significant differences were observed among treatments, regardless of substrate type (soil or sand) or measurement depth (interior or surface).

During the dry period, significant differences were observed between soil and sand treatments for both interior and surface temperatures.

Analysis of daily maximum temperatures in the second experiment (**Figure 10**) revealed that under rainy conditions, there were no significant differences between the interior temperatures of both pots, nor between surface temperature treatments. However, during the dry period, interior temperatures in the pots again showed no significant differences, reaching values around 34˚C - 35˚C (**Table 1**). These findings are in line with Witcher *et al.*, who found that root zone temperatures were highest in black containers and remained above 38˚C and 46˚C for 15% and 17% longer than in white and air-pruning containers, respectively [7]. Given that the pot used in this study was dark brown and partially shaded, lower temperatures, than those found by Witcher *et al.* [7], were expected.

It is also important to note that, when comparing interior maximum temperatures under Rain conditions (29.11˚C in sand and 27.93˚C in soil), these values were lower than those recorded during No Rain (34.59˚C in sand and 34.19˚C in soil). This was anticipated, as Zhang and Liu reported that soils with preferential water flow reached lower steady-state temperatures than soils with limited infiltration [10].

However, surface maximum temperature treatments under No Rain conditions did show significant differences. In addition, Levene's test confirmed that the variance between the treatment pairs was homogeneous, indicating similar variability among the data.

Analysis of daily minimum temperatures (**Figure 11**) under rainy conditions showed no significant differences between treatments measuring interior temperatures in the pots. However, as shown in **Table 1**, minimum temperatures inside both substrates during the rainy season (12.48˚C in sand, 13.08˚C in soil) were higher than those recorded during the dry period (6.67˚C in sand, 7.88˚C in soil). These results are in agreement with Zhang and Liu, who concluded that the infiltration of rainfall increases the temperature of the soil column [10].

Finally, under No Rain conditions, no significant differences were found between interior minimum temperature treatments, nor between surface minimum temperature treatments (**Figure 11**). Likewise, surface treatments in pots did not show significant differences.

This study presents certain limitations that should be considered when interpreting the results. The experiment was conducted under specific environmental conditions, using a single pot per treatment, and results may therefore be site-specific. Additionally, only one pot color and volume were evaluated, which may influence thermal dynamics due to differences in solar absorption and heat retention. As such, extrapolating these findings to other container types, sizes, colors, or climatic regions should be done with caution. Despite these limitations, the study provides valuable insights into soil temperature behavior and validates a cost-effective monitoring system suitable for controlled experimental conditions. Further studies including multiple replicates per treatment are recommended to capture spatial variability and strengthen the generalizability of the results.

## 5. Conclusions

This study evaluated the thermal behavior of soil under different physical configurations (field soil, potted soil, and potted sand) and climatic conditions (rain and no rain), considering both interior and surface temperatures.

In Experiment 1, conducted exclusively during the rainy period, significant differences were observed in both maximum and minimum temperatures between field soil and potted soil. The highest maximum temperatures were recorded in the potted soil (32.26˚C for interior and 30.19˚C for surface), while the lowest minimum temperatures also occurred in the pot (13.4˚C interior and 12.04˚C surface), contrary to initial expectations. This suggests that pots not only enhance daytime heat accumulation but also exhibit greater heat loss at night, leading to a wider thermal amplitude compared to field soil.

In Experiment 2, which compared potted sand and potted soil under both rainy and dry conditions, no significant differences were found between the two substrates during the rainy period. However, under dry conditions, differences between soil and sand were observed in certain variables, such as daily mean (interior and surface) and surface maximum temperatures, while minimum temperatures remained statistically similar. For instance, under dry conditions, the average maximum interior temperature was 34.59˚C for sand and 34.19˚C for soil, while minimum values were 6.67˚C and 7.88˚C, respectively. Although differences between substrates under dry conditions were limited, clear and consistent differences were observed between climatic conditions: temperatures were consistently higher (maximum) and more variable (minimum) during the dry period and more stable during the rainy season.

Additionally, in both experiments, surface maximum temperatures were generally higher than interior temperatures, reflecting the greater sensitivity of the soil surface to external environmental conditions.

Overall, these findings indicate that substrate type (sand vs. soil) does not significantly affect thermal behavior when contained in pots under rainy conditions.

However, structural condition (pot vs. field) and environmental exposure (presence or absence of rainfall) play a critical role in shaping soil thermal dynamics. These results also validate the effectiveness of the sensor system in detecting both thermal differences and similarities across contrasting experimental scenarios.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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