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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^{TM}) and soil surface temperature (MLX90614 GY-906^{TM}), 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)^{TM} 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^{TM} 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**.

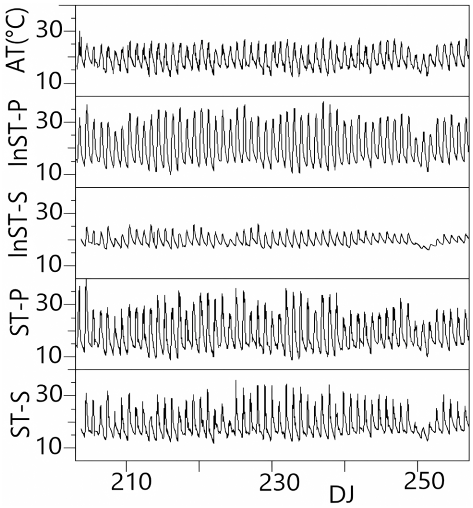

Figure 3. Temperature measurements recorded every 40 minutes during Experiment 1 for: air temperature (AT), internal temperature of the pot with soil (InST-P), internal temperature of field soil (InST-S), surface temperature of the pot with soil (ST-P), and surface temperature of field soil (ST-S), across 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.

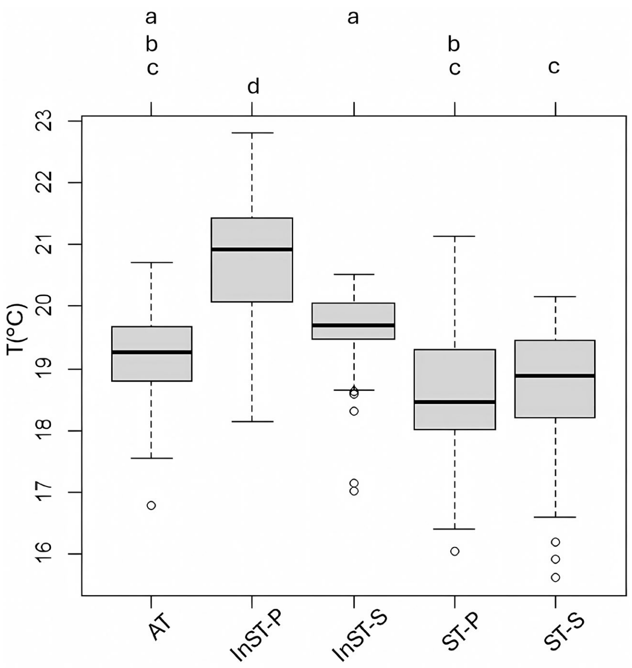

Figure 4. Box-and-whisker plot generated from the first experiment data, showing daily average temperatures for: air (AT), internal temperature of the pot with soil (InST-P), internal temperature of field soil (InST-S), surface temperature of the pot with soil (ST-P), and surface temperature of field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

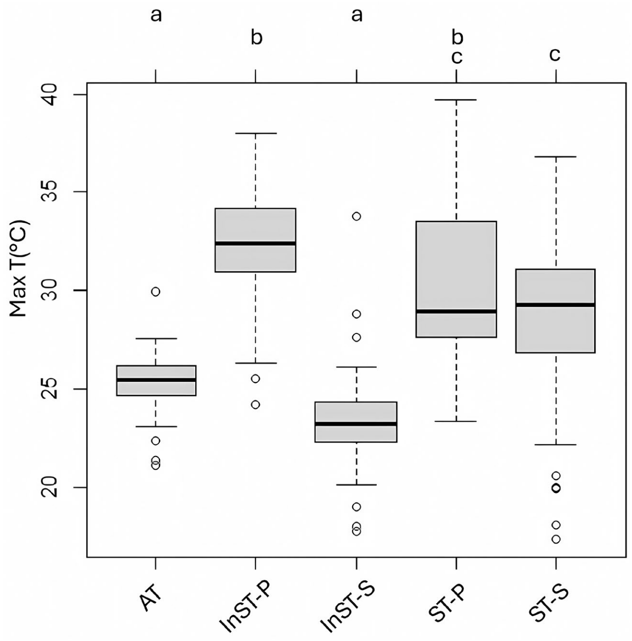

Figure 5. Box-and-whisker plot generated from the Experiment 1 data, showing daily maximum temperatures for: air (AT), internal temperature of the pot with soil (InST-P), internal temperature of field soil (InST-S), surface temperature of the pot with soil (ST-P), and surface temperature of field soil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

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

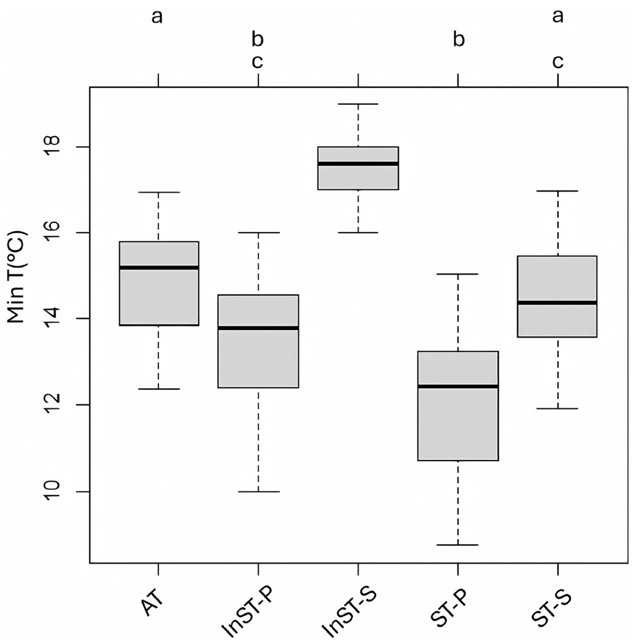

Figure 6. Box-and-whisker plot generated from the Experiment 1 data, showing daily minimum temperatures for: air (AT), internal temperature of the pot with soil (InST-P), internal temperature of field soil (InST-S), surface temperature of the pot with soil (ST-P), and surface temperature of field soil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

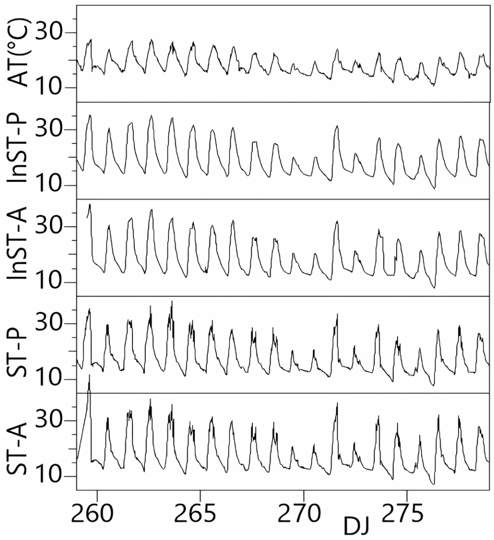

Figure 7. Air temperature (AT) measured every 40 minutes, internal temperature of the pot with soil (InST-P), internal temperature of the pot with sand (InST-A), surface temperature of the soil in the pot (ST-P), and surface temperature of the sand in the pot (ST-A), recorded over Julian days (JD) from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

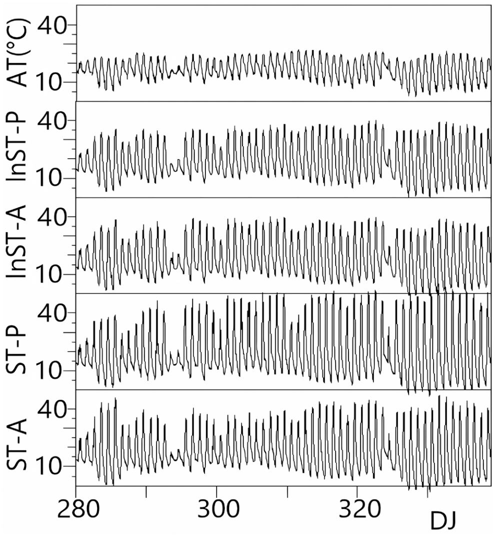

Figure 8. Air temperature (AT), temperature inside the pot with soil (InST-P), temperature inside the pot with sand (InST-A), temperature on the surface of the soil in the pot (ST-P), and temperature on the surface of the sand in the pot (ST-A), all recorded every 40 minutes during the Julian days (DJ)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

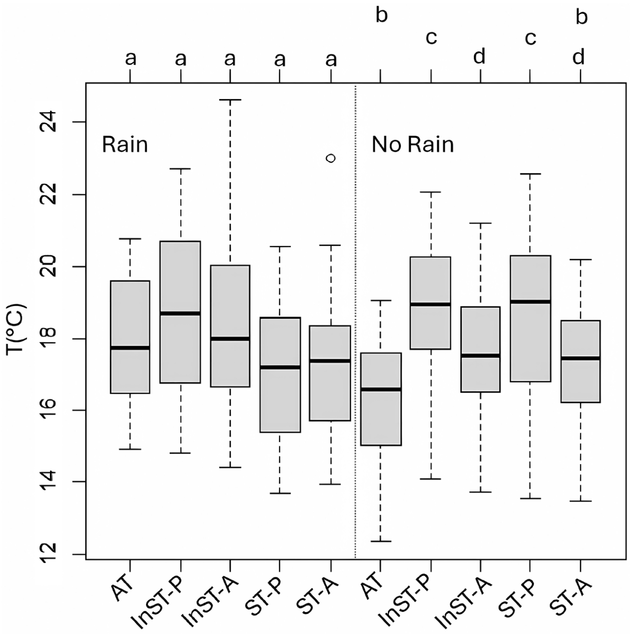

Figure 9. Box-and-whisker plot of daily mean temperatures for all variables: air temperature (AT), temperature inside the pot with soil (InST-P), temperature inside the pot with sand (InST-A), temperature on the surface of the soil in the pot (ST-P), and temperature on the surface of the sand in the 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**.

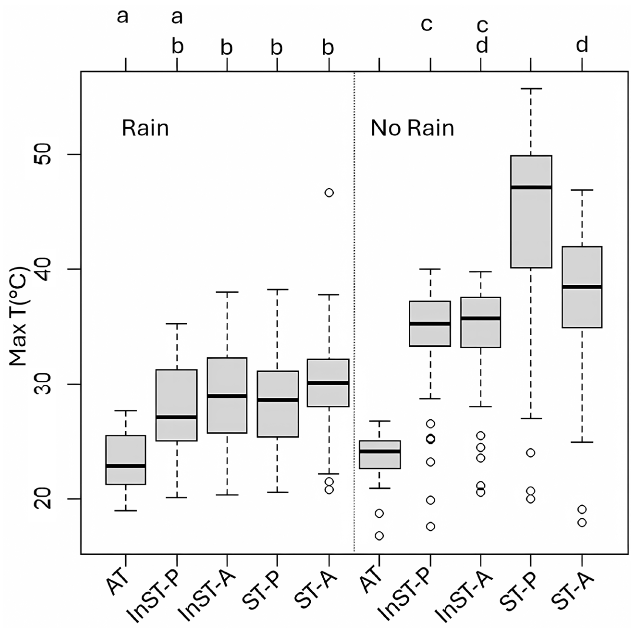

Figure 10. Box-and-whisker plot of daily maximum temperatures recorded for air (AT), inside the pot with soil (InST-P), inside the pot with sand (InST-A), on the surface of the soil in the pot (ST-P), and on the surface of the sand in the pot (ST-A), during the rainy period (Rain) and the dry period (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.

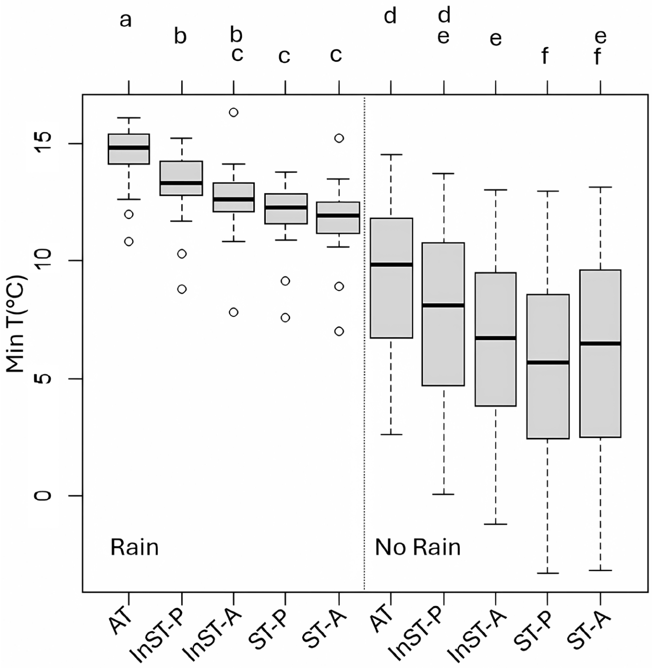

Figure 11. Box-and-whisker plot of daily minimum temperatures recorded for air (AT), temperature inside the pot with soil (InST-P), temperature inside the pot with sand (InST-A), temperature on the surface of the soil in the pot (ST-P), and temperature on the surface of the sand in the pot (ST-A), during 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 (λ = 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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Soil Policy and Governance in Lebanon: Challenges, Opportunities, and the Path Forward

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Abstract

Soil health is a fundamental factor for agricultural productivity and environmental sustainability in Lebanon. However, Lebanon faces multiple challenges related to soil degradation, including erosion, desertification, contamination, and loss of fertility. The country's governance structures remain fragmented, and policy implementation is inconsistent due to political instability, insufficient data, and weak inter-sectorial coordination. This study addresses the research question: "How can Lebanon address institutional fragmentation and data gaps to improve soil governance?" Using a qualitative methodology combining policy analysis and stakeholder mapping within the Soils4Med Project framework, this paper identifies key challenges and opportunities. It provides recommendations for improving soil protection and sustainable land management through a data-driven approach.

Keywords

Soil Governance, Lebanon, Land Degradation, Policy, Sustainability, Soils4Med, Soil Health

1. Introduction

Soil degradation is a pressing environmental and agricultural issue in Lebanon, posing significant challenges to food security, economic stability, and sustainable land management. The country's diverse topography, ranging from coastal plains to mountainous terrains and fertile valleys, makes its soils highly vulnerable to degradation processes such as erosion, desertification, and contamination. These issues originate from both natural forces, such as climate variability, and human activities, including rapid urban expansion, deforestation, unsustainable farming practices, and industrial pollution [1] [2]. In particular, sources of soil contamination include industrial waste disposal, landfill seepage, improper chemical use, and pesticide residues, all of which have significant governance implications. The management of industrial and landfill waste remains inadequately regulated, resulting in persistent contamination hotspots that degrade soil quality and threaten public health. These contamination sources require cross-sectorial governance responses involving environmental regulations, waste management policies, and enforcement mechanisms, which currently remain fragmented in Lebanon.

Lebanon's agricultural sector, which remains a vital component of the national economy, depends on healthy soils to maintain productivity and sustainability. However, land mismanagement, excessive reliance on chemical inputs, and poor irrigation practices have led to severe soil degradation, resulting in reduced crop yields and increased soil infertility. The impacts of climate change further exacerbate these challenges, leading to intensified droughts, erratic rainfall patterns, and increased desertification, particularly in regions such as the Bekaa Valley and northern Lebanon [3] [4]. Without a structured, evidence-based approach to soil conservation, Lebanon risks further environmental degradation, which could have long-term socio-economic consequences.

Despite the urgent need for intervention, soil governance in Lebanon remains highly fragmented. Multiple governmental bodies, including the Ministry of Agriculture (MOA), the Ministry of Environment (MOE), and the Ministry of Energy and Water (MEW), manage soil-related policies and regulations, yet there is a lack of coordination among these entities [5]. This disjointed governance framework results in policy inconsistencies, ineffective enforcement mechanisms, and minimal stakeholder collaboration. Furthermore, there is an evident gap in soil monitoring initiatives, with insufficient data collection and analysis hindering policymakers from developing well-informed strategies [6].

To address these challenges, the Soils4Med Project provides a comprehensive framework for improving soil monitoring and governance in Lebanon. The project integrates methodologies such as remote sensing technologies, GIS-based mapping, and field-based soil health assessments. These methodologies offer valuable insights that Lebanon can incorporate into its governance framework to enhance policy effectiveness and soil conservation efforts. Furthermore, by establishing standardized monitoring approaches, developing a centralized national soil database, and utilizing predictive modeling and AI-driven analysis, Lebanon can ensure data-driven decision-making and improve regulatory enforcement [7]. This integrated framework will help address both current and future risks related to soil degradation and climate change, creating a more resilient and evidence-based governance structure for soil management.

Strengthening soil monitoring and integrating these methodologies into national policies will not only improve environmental sustainability but also contribute to long-term agricultural resilience and economic stability [8]. This study employs a qualitative research methodology to examine soil governance and degradation in Lebanon.

2. Materials and Methods

2.1. Previous Work

A systematic review of peer-reviewed journal articles, books, and scholarly reports was conducted to explore key issues related to soil degradation, agricultural practices, and governance frameworks within Lebanon. The review aimed to synthesize existing knowledge, identify gaps, and contextualize the drivers and consequences of soil degradation in the country. Emphasis was placed on historical and current factors contributing to soil erosion, land mismanagement, and agricultural unsustainability in Lebanon [9] [10]. The review also examined the prevailing governance structures and their influence on soil degradation, providing a foundation for understanding the socio-political and environmental challenges surrounding soil management.

2.2. Policy Analysis

A critical analysis of national policies was conducted to evaluate Lebanon's approaches to soil conservation, land use, water management, and environmental protection. Primary documents reviewed included National Agricultural Strategies, policies, Lebanon's National Action Plan for Desertification (NAP), the Lebanese Environmental Policy, and environmental provisions within the Lebanese Constitution [8] [11]. This analysis aimed to assess policy coherence, effectiveness, and gaps in existing environmental policies related to soil governance, highlighting opportunities for strengthening Lebanon's soil governance framework. The roles of various institutional actors in shaping and enforcing soil-related policies were also examined.

2.3. Stakeholder Mapping

Stakeholder mapping identified the key actors in Lebanon's environmental landscape, exploring the dynamics between governmental, non-governmental, and private sector actors in shaping soil governance policies [12]. This approach offered a thorough understanding of the multi-dimensional challenges surrounding soil degradation, integrating local and international perspectives (**Table 1**).

Table 1. Stakeholder mapping.

Stakeholder	Role	Influence Level	Potential Conflicts
Ministry of Agriculture (MoA)	Policy formulation and enforcement on agricultural land	High	Conflicts with Ministry of Environment over land use priorities
Ministry of Environment (MoE)	Environmental regulation and pollution control	High	Overlaps with MoA and MEW in jurisdiction
Ministry of Energy and Water (MEW)	Water resource management impacting soil	Medium	Competes with MoA on irrigation policies

Continued

Local Municipalities	Land use planning and local enforcement	Medium	Limited capacity; conflicting priorities with national agencies
Environmental NGOs	Advocacy and community engagement	Medium	Oppose some private development projects
Private Developers	Land development and construction	High	Conflict with environmental groups and municipalities
Research Institutions	Soil data collection and analysis	Low	Limited influence on policy decisions
Farmers Associations	Agricultural practices and adoption	Medium	Diverse interests; sometimes resist regulation

2.4. Data Analysis

Data from the literature review, policy analysis, and previous studies were subjected to thematic analysis. This process identified recurring themes such as institutional fragmentation, insufficient data availability, policy enforcement challenges, and the need for greater public awareness and education on soil degradation. The thematic analysis also focused on identifying synergies and opportunities for policy improvement and effective governance mechanisms [13] [14].

2.5. Synthesis and Recommendations

Based on the findings from the literature review, policy analysis, and data gathering, a synthesis of the data was conducted to develop actionable policy recommendations. These recommendations aimed at enhancing Lebanon's soil management practices and governance framework. The final recommendations focus on enhancing institutional coordination, improving data availability, strengthening policy enforcement, and fostering public awareness and educational campaigns on soil conservation.

3. Results

The results of this study offer critical insights into the state of soil governance and degradation in Lebanon.

3.1. Fragmentation of Soil Governance

Lebanon's soil governance framework is marked by significant lack of coordination among key governmental institutions, severely delaying the effective implementation of soil-related policies. Despite involvement of ministries such as MoA, MoE, and MEW, there is no unified or comprehensive strategic approach to tackling soil degradation, including erosion, desertification, and contamination. Each ministry often works separately without clear coordination or shared vision (**Figure 1**). This fragmentation leads to inconsistent policy enforcement and overlapping mandates [15] [16].

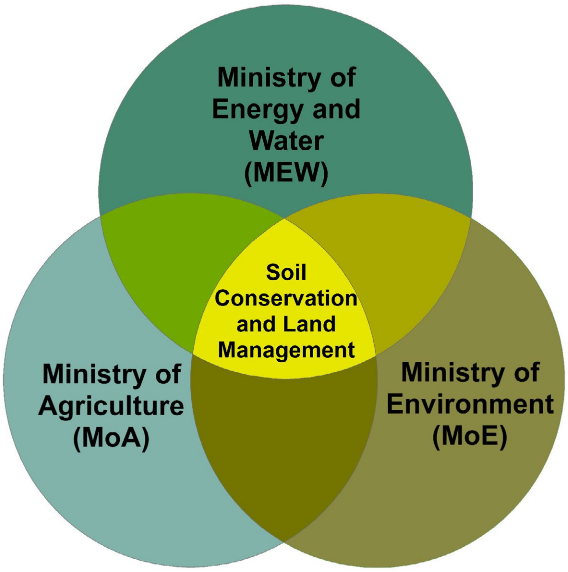

Figure 1. Responsibility fragmentation of soil governance among institutions.

Examples of successful coordination models from the Soils4Med project and Mediterranean countries illustrate pathways for Lebanon. For instance, Italy's regional soil monitoring committees foster multi-stakeholder collaboration, integrating data collection with policy enforcement. Similarly, Tunisia's national soil conservation program centralizes monitoring and incentivizes sustainable practices through coordinated institutional efforts. These examples provide practical frameworks Lebanon can adapt to improve soil governance effectiveness.

This institutional fragmentation leads to inconsistent policy enforcement and an individual approach to land management. For instance, while the MoA focuses on agricultural practices and land cultivation, the MoE addresses environmental concerns, and the MEW manages water resources. However, these ministries frequently operate independently, often duplicating efforts and leaving critical gaps in policy coherence and enforcement. There is considerable overlap in the mandates of these ministries, yet the lack of inter-ministerial collaboration and integration weakens the effectiveness of interventions [17] [18].

Lebanon's policy framework fails to adequately address the socio-political factors that exacerbate soil degradation, such as unregulated urban expansion, unsustainable agricultural practices, and deforestation [19]. This lack of integration and response coordination exacerbates the vulnerability of Lebanese soils to degradation, particularly in urbanized areas. As a result, Lebanon faces increasing challenges in mitigating soil erosion, preventing desertification, and managing contamination levels. These issues are further compounded by the absence of a national soil policy that integrates land use planning, environmental conservation, and water management [20] [21].

The absence of a cohesive, cross-sectoral strategy for soil governance not only hinders effective soil conservation efforts but also limits Lebanon's ability to meet international environmental commitments, such as those set forth by the United Nations Convention to Combat Desertification (UNCCD) and the Sustainable Development Goals (SDGs). Addressing these challenges requires a rethinking of Lebanon's institutional framework, moving beyond fragmented mandates towards a more integrated, collaborative approach that brings together stakeholders from multiple sectors [22].

To move forward, it is essential for Lebanon to establish a unified soil governance framework that aligns the responsibilities of various ministries and fosters cross-sectoral collaboration. Such a framework would ensure that policies aimed at mitigating soil degradation are implemented in a cohesive, systematic manner, maximizing their potential to preserve the country's natural resources sustainably.

3.2. Gaps of Current Policies

The policy analysis revealed that Lebanon's existing national policies do not adequately address the root causes of soil degradation. While frameworks like the National Action Plan for Desertification (NAP) and various provisions within the Lebanese Environmental Policy provide some direction for soil conservation, they often lack clear implementation mechanisms. The objectives of these documentations are not effectively integrated into broader agricultural, environmental, and water management strategies [8] [11]. A significant gap identified in the policy landscape is the insufficient prioritization of soil protection within the context of Lebanon's overall environmental and agricultural policies. Furthermore, existing policies often fail to address the socio-economic drivers of soil degradation, such as unsustainable farming practices and rapid urbanization, and lack the necessary regulatory measures to monitor and enforce compliance [3].

In Lebanon, agricultural policies tend to focus more on production and economic goals rather than environmental sustainability. While there may be some initiatives related to sustainable agriculture, the emphasis on soil conservation is often minimal (**Figure 2**). Soil conservation is not always a core priority within agricultural policies, which tend to prioritize increasing yield, mechanization, and meeting market demands. As a result, soil governance is often overlooked.

- Lebanese National Agricultural Strategy (2010): This strategy emphasizes improving agricultural productivity to enhance food security and rural development but does not address soil conservation in a comprehensive way. It focuses more on enhancing yields through modern farming techniques and increasing market access.
- National Strategy for the Sustainable Agricultural Development (2018): This document does highlight sustainable agricultural practices, some of which could promote soil health (such as crop rotation and organic farming), but soil conservation is not a primary focus.

Lebanon's environmental policies have made great steps in recent years, particularly regarding pollution control and protected areas. However, soil conservation is still a relatively underdeveloped focus within broader environmental frameworks. While environmental policy addresses land degradation, waste management, and biodiversity, specific soil conservation initiatives may not be fully integrated into environmental policy, which leads to a medium integration rating (**Figure 2**).

- Lebanese Environmental Action Plan (2011-2015): This plan targets land degradation through broader environmental protection efforts. However, the focus is on pollution and biodiversity, with soil conservation mentioned only in relation to land degradation caused by deforestation and overgrazing.
- Law 444 (2002) – Environmental Protection Law: The law outlines frameworks for environmental protection in Lebanon, including the need to combat desertification and land degradation, but it lacks specific mandates or programs focused solely on soil conservation.

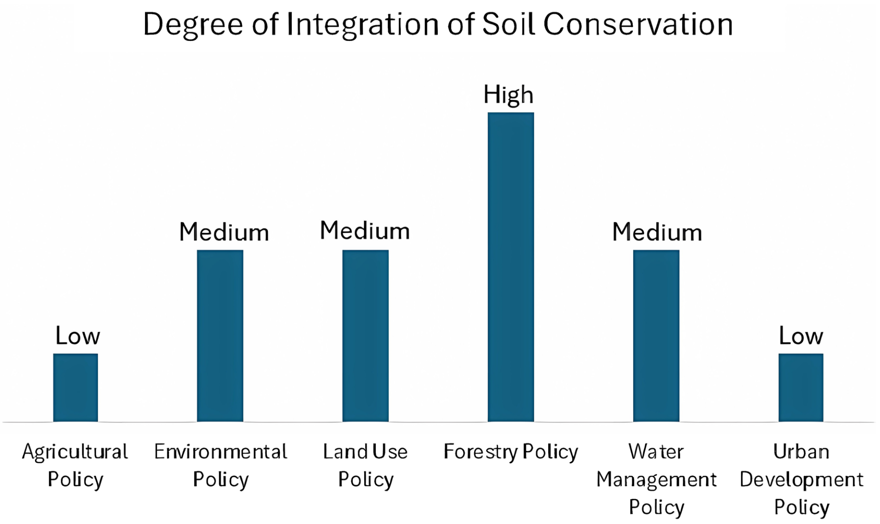

Figure 2. Gaps in policy integration for soil governance.

Lebanon's land use policy focuses on urbanization and the use of agricultural land. While there may be efforts to mitigate land degradation, these policies often prioritize urban development and infrastructure expansion over sustainable land use practices. Soil conservation is sometimes incorporated into land use policies, especially when it intersects with urbanization and agricultural expansion. However, there is often insufficient attention paid to long-term soil health and its integration into national land-use strategies.

- Lebanon National Land Use Master Plan (2004): This plan sets out a framework for land development across Lebanon, including zoning regulations for urban and rural areas. Soil conservation is recognized as part of sustainable land management, but it's overshadowed by the priorities of urban development and infrastructure expansion.
- Land and Environment Support Project (2010): This project aims to improve land and water management, with some notices for soil erosion control in agricultural regions, but the focus is broader on land use and less on soil as an

independent resource.

Forestry policies often emphasize conservation and sustainable management of forest ecosystems, which include soil protection. The roots of trees prevent soil erosion, making soil conservation a natural aspect of forestry policy. Lebanon has strong programs related to forest preservation and reforestation, and soil conservation is often an integral part of forest management strategies. Hence, this policy framework shows a higher degree of integration for soil conservation (**Figure 2**).

- National Reforestation Plan (2010): Soil conservation is a key objective of this plan. By focusing on reforestation, the policy addresses soil erosion, particularly in mountainous regions. Forests play a crucial role in protecting the soil from erosion through root systems that stabilize the land.
- Lebanese Forest Strategy (2015): This strategy focuses on forest restoration and management, incorporating soil conservation as a primary component. Sustainable forest management practices directly help prevent soil erosion, making this a highly integrated policy framework for soil health.

Water management in Lebanon involves controlling water resources, managing irrigation systems, and addressing water scarcity, which can influence soil health. However, soil conservation is not always prioritized as a key component of water policy. While soil and water are interlinked (e.g., erosion affects water quality), water policies may focus more on water distribution and infrastructure rather than soil preservation. Thus, soil conservation is only moderately integrated in this policy framework.

- National Water Sector Strategy (2012): This strategy addresses water conservation and management in Lebanon but only indirectly tackles soil issues. Soil conservation is discussed in the context of preventing water loss due to erosion, especially in agricultural regions, but it's not the central focus of the policy.
- National Irrigation Strategy (2015): This strategy aims to improve irrigation infrastructure and water efficiency in agriculture, but soil conservation is only considered in relation to reducing soil erosion and improving water retention in agricultural lands.

Urban development policies often prioritize economic growth, infrastructure development, and population expansion, with little consideration for environmental impacts such as soil conservation. Urbanization typically leads to soil degradation through construction, land sealing, and the conversion of agricultural land. Soil protection is not usually a central issue in urban planning policies, which leads to a low integration rating.

- National Physical Master Plan for the Lebanese Territory (2009): This plan focuses on urban expansion and economic development. Soil conservation is not considered, and the urbanization process typically leads to soil degradation through construction and land sealing (paving over natural soils).
- Urban Planning and Development Law (2017): This law focuses on land development for urban needs, with no specific measures for soil conservation, as the primary concern is the growth of infrastructure and housing.

Table 2. Historic and recent policies in Lebanon related to soil governance.

POLICY FRAMEWORK	EXAMPLE POLICIES (FROM 1920S ONWARD)	INTEGRATION OF SOIL CONSERVATION
AGRICULTURAL POLICY	• Lebanese Agricultural Law (1926)	Low: Focused primarily on agricultural productivity and land use, without direct emphasis on soil conservation.
	• Lebanese National Agricultural Strategy (2010)	Low to Medium: Some mention sustainable practices, but soil conservation is a secondary concern compared to productivity.
ENVIRONMENTAL POLICY	• Lebanese Environmental Protection Law (Law 444, 2002)	Medium: Environmental protection measures include addressing soil degradation in the broader context of land and water protection, but not in-depth on soil conservation.
	• Lebanese Environmental Action Plan (2011-2015)	Medium: Includes land degradation concerns, with some references to soil erosion but little focus on soil health specifically.
LAND USE POLICY	• Lebanon National Land Use Master Plan (2004)	Medium: Focuses on zoning and urban planning, with some recognition of the risks of soil erosion but limited policies targeting soil health.
	• Land and Environment Support Project (2010)	Medium: Focused on land management and reducing soil erosion, but not purely about soil conservation as a primary goal.
FORESTRY POLICY	• Forests Law (1949)	High: Established frameworks for forest conservation, with soil conservation integrated into forest management, as trees help prevent soil erosion.
	• National Reforestation Plan (2010)	High: Directly integrates soil conservation through forest restoration and reforestation efforts.
	• Lebanese Forest Strategy (2015)	High: Strong emphasis on soil protection through forest cover and sustainable forestry practices.
WATER MANAGEMENT POLICY	• National Water Sector Strategy (2012)	Medium: Soil conservation is addressed as part of water management, particularly in reducing erosion that affects water quality, but not a main focus.
	• National Irrigation Strategy (2015)	Medium: Focus on improving irrigation efficiency with some connection to preventing soil erosion in agricultural lands.
URBAN DEVELOPMENT POLICY	• National Physical Master Plan for the Lebanese Territory (2009)	Low: Primarily focused on urbanization and infrastructure development without regard for soil conservation.
	• Urban Planning and Development Law (2017)	Low: Urban growth and infrastructure development priorities often contribute to soil degradation without integrating soil conservation.

The policy landscape in Lebanon regarding soil governance has evolved over several decades, shaped by both historical events and contemporary challenges (Table 2). Historically, Lebanon's soil policies were often general rather than practical, with early efforts focusing primarily on agricultural development and land preservation. However, these initiatives were largely fragmented and lacked effective integration across different sectors. In recent years, there has been a shift towards more comprehensive soil governance, with the introduction of new policies aimed at addressing soil degradation, promoting sustainable agriculture, and mitigating the impacts of climate change. Recent policies, the National Agricultural Strategies includes sustainable management of soil resources, which aims to enhance soil conservation practices and integrate soil governance into broader environmental and land use planning frameworks. Despite these efforts, implementation has been slow, largely due to political instability, inadequate enforcement mechanisms, and limited public awareness. The complexity of Lebanon's political landscape and the lack of coordination between governmental agencies have further hindered the successful integration of soil policies, resulting in persistent gaps in policy execution. This fact highlights the need for a more cohesive and strategic approach to soil governance in Lebanon.

The most recent policy which is the 2020-2025 agricultural strategy that was developed to address the key challenges facing Lebanon's agricultural sector and provide a framework for recovery and development over the next decade. The strategy places a stronger emphasis on economic resilience, food security, and the integration of sustainability into agricultural practices. Within this strategy:

- Soil conservation is mentioned as part of sustainable agricultural practices that aim to protect soil fertility and prevent erosion, particularly in hillside farming regions. The strategy also encourages the use of agroecological practices that improve soil health, including reduced tillage, use of organic fertilizers, and increasing organic farming practices that maintain soil structure and fertility.
- promotes drought-resistant crops and techniques to mitigate soil erosion due to extreme weather events. The strategy also promotes the use of water-efficient technologies, such as drip irrigation, that not only conserve water but also help prevent soil degradation.
- Soil conservation is integrated into this strategy by promoting education on sustainable land management and providing farmers with incentives to adopt these practices.
- efforts include reforestation, afforestation, and land reclamation programs that help restore soil fertility and prevent further erosion.
- The policy pushes for the modernization of agriculture through the adoption of new technologies and practices, including those that help improve soil health (e.g., precision agriculture, crop monitoring systems).
- It includes providing farmers with access to information and resources on soil conservation and sustainable farming.
- comprises the establishment of financial mechanisms (e.g., subsidies, grants) to support farmers who are transitioning to sustainable practices. This includes financial support for soil conservation efforts, such as erosion control measures and soil fertility programs.

3.3. Challenges Posed by Data Limitations

Data limitations emerged as a significant challenge in both assessing the extent of soil degradation and formulating effective soil management strategies. Comprehensive, accurate, and up-to-date soil data are scarce, and existing data is fragmented across various agencies. The lack of a centralized, accessible database on soil health hinders the development of targeted policies and actions. Stakeholders are faced with the unavailability of reliable data on soil erosion rates, contamination levels, and desertification trends, which severely delays efforts to understand the full scope of the problem (**Figure 3**). As noted by several researchers [4] [23], without robust data, it is difficult to assess the effectiveness of existing policies and design evidence-based solutions to address Lebanon's soil degradation.

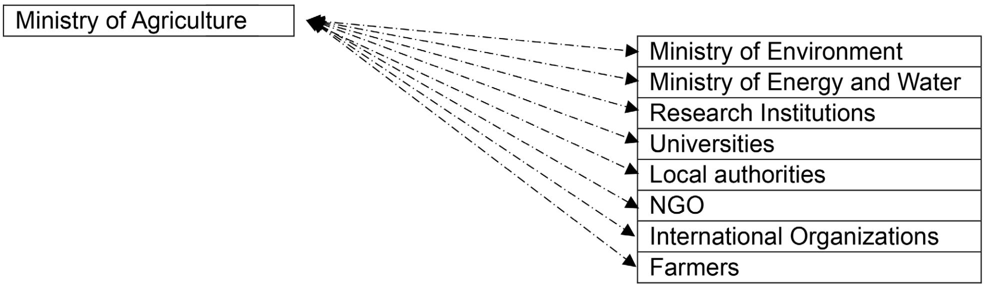

Figure 3. Fragmentation of soil data (Dashed lines: fragmented/missing connections).

3.4. Opportunities for Improved Coordination and Public Engagement

Despite these challenges, there are various opportunities to strengthen Lebanon's soil governance framework. Improving institutional coordination between key ministries and stakeholders was consistently cited as a crucial step. A more integrated approach, possibly through the establishment of a national coordinating body for soil protection, would allow for a more cohesive strategy for soil management. The establishment of such a body could enhance policy alignment across sectors and facilitate more efficient resource allocation for soil conservation efforts.

Increasing public awareness of soil health, particularly among farmers, policymakers, and local communities, is critical for promoting sustainable land management practices. Educational campaigns and capacity-building programs, especially targeting rural communities and agricultural practitioners, could help reduce the use of harmful agricultural practices and promote more sustainable alternatives. The success of similar initiatives in other countries suggests that Lebanon could benefit from such efforts [24] [25].

Enhancing the availability of comprehensive soil data through collaborative efforts among governmental, academic, and non-governmental sectors was identified as a key opportunity for improving soil governance (**Figure 4**). International partnerships and research projects could help build local capacity for soil data collection and analysis. Additionally, using remote sensing technologies and satellite imagery could provide more timely and accurate assessments of soil health across Lebanon's diverse regions [26].

Figure 4. Opportunities for strengthening soil governance.

4. Discussion

This study reveals fragmented and inefficient state of soil governance in Lebanon, with a lack of coordinated institutional efforts, inadequate policies, and significant data gaps. However, the study also points to several promising opportunities for reform. By enhancing institutional coordination, prioritizing soil protection in national policies, improving data availability, and fostering public awareness and engagement, Lebanon can develop a more effective and sustainable soil governance framework. These improvements would help address the ongoing challenges of soil degradation and support long-term environmental sustainability in the country.

The findings contribute to a deeper understanding of Lebanon's soil governance challenges and provide a foundation for the development of targeted, evidence-based recommendations aimed at improving the country's soil health and management practices.

5. Conclusions and Recommendations

Lebanon's soil governance challenges are deeply rooted in institutional fragmentation, inadequate data, and a lack of coordinated efforts across sectors. The findings of this study underscore the importance of adopting a more integrated, evidence-based approach to soil management. The lack of a unified soil policy and the fragmented governance structure have resulted in insufficient action on soil degradation despite the mounting environmental pressures. Lebanon's policymakers must prioritize the development of a comprehensive national soil policy that integrates soil health into broader environmental and agricultural strategies.

The establishment of a national soil monitoring system, as Soils4Med project performing, combined with improved coordination among stakeholders, can significantly enhance Lebanon's capacity to address soil degradation. International collaboration, as well as capacity-building initiatives, can provide Lebanon with the tools and resources necessary to implement sustainable soil management practices and ensure the long-term sustainability of its agricultural lands. Effective soil governance will not only improve environmental sustainability but will also contribute to greater food security and resilience in the face of climate change. Key recommendations could be risen:

- Establish a Unified Soil Governance Framework.
- Develop a National Soil Policy.
- Enhance Data Collection and Monitoring Systems.
- Promote Public Engagement and Education.
- Strengthen Policy Integration.
- Foster International Collaboration.
- Encourage Sustainable Agricultural Practices.
- Develop and Implement Financial Mechanisms for Soil Protection.
- Address Urbanization's Impact on Soil.
- Strengthen Inter-Ministerial Coordination.

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Conflicts of Interest

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

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Application of *Leucaena leucocephala* (Lam.) and Biochar Improved the Performance and Yield of Pearl Millet (*Pennisetum glaucum* (L.) R. Br.) and Sorghum (*Sorghum bicolor* (L.) Moench) in Saline Soils While Reducing Intrinsic Biochemical Attributes

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Abstract

Soil salinity is increasingly becoming a limiting factor for crop productivity in sub-Saharan Africa. This study aimed to assess the impact of organic and inorganic soil amendments on the growth, yield, and biochemical attributes (total protein, proline, and malondialdehyde) of pearl millet and sorghum in salt-affected soils. The experiment was conducted over two consecutive cropping seasons, from June to September 2021 and January to April 2022. Pearl millet variety IP 19586 and sorghum variety ICSV-700 were exposed to five soil amendments, including a control, *Leucaena leucocephala* (a green manure applied at 5 t/ha), biochar (5 t/ha) made from palm shells, rock phosphate (2.5 t/ha), and dolomitic lime (3.3 t/ha). The experimental design used a split-plot design with randomized blocks, with crops as the primary plot factor and amendments as the subplot factor, each replicated three times. Inorganic fertilizers were applied to each plot at rates of 150 kg/ha NPK (15-15-15) and 100 kg/ha urea (46%). Results showed that different amendments significantly affected sorghum height, while pearl millet growth was not affected ($P < 0.05$). Amended plots showed a substantial improvement in pearl millet grain yield by approximately 64% (ranging from 49% to 101%) and sorghum grain yield by 159% (from 93% to 202%). Proline and MDA contents in pearl millet and sorghum were higher under the control treatment compared to other soil amendments. Leucaena and biochar were the most effective amendments in mitigating soil salinity throughout the crop growth periods. These treatments significantly improved pearl millet and sorghum grain yield and associated MDA content. It can be concluded that organic soil amendments (biochar and leucaena) significantly outperformed ($P < 0.05$) mineral soil amendments (rock phosphate and dolomite) in mitigating soil salinity. This finding holds great promise for agricultural researchers and practitioners seeking to enhance crop productivity in salt-affected soils while also reducing intrinsic biochemical attributes. However, further research is warranted to understand the seasonal dynamics of salinity under organic-based soil amendments.

Keywords

Salinity, Soil Amendments, Crop Yields, West Africa

1. Introduction

Soil degradation is a significant global concern, particularly affecting developing countries where a large portion of the population depends directly on the soil for their livelihoods [1]. Various forms of physical, chemical, and biological land degradation, such as compaction, inorganic/organic contamination, and reduced microbial activity and diversity, have arisen due to excessive human pressures over the last century. These processes have severely impacted global natural resources [2]. Climate change has exacerbated salinity challenges in the root zone, especially in shallow water tables and coastal areas [3] [4]. Soil salinization is a major degradation process, particularly in semi-arid and arid zones [5]. Globally, over one billion hectares of soil are affected by salinity [6] [7]. By 2050, soil salinization is projected to impact more than half of the world's agricultural land [8] [9]. According to the FAO [10], approximately 1.5 million hectares of cropland lose production, and 20 - 46 million hectares experience a decrease in potential production annually due to land salinization, resulting in an annual revenue loss of about $31 million.

Salinity affects 19.09 million hectares in Sub-Saharan Africa (SSA) [1], mainly in Eastern Africa, the coast of Western Africa, the Lake Chad Basin, and isolated areas of Southern Africa [10]-[12]. In Togo, salt-affected soils are documented along the lagoon from Lake Togo to the Mono River, at the edge of the Zio River valley, and in the village of Atti-Apedokoe [13] [14]. In agricultural ecosystems, soil salinity refers to the excessive accumulation of soluble salts within the root zone of plants, resulting in elevated pH (>8.5), sodium adsorption ratio (<13%), exchangeable sodium percentage (<15%), and electrical conductivity (EC > 4 dSm-1). This condition reduces crop yield and compromises soil health. In regions where soil salinity remains unaddressed, a significant portion of agricultural land is abandoned [15].

Soil salinity, arising from both natural and human-induced causes, is predominantly caused by inappropriate irrigation practices and seawater intrusion into coastal farming areas. This issue is further exacerbated by rising sea levels due to climate change and excessive groundwater extraction [9] [11] [16]. Salt-affected soils accumulate soluble salts such as NaCl, $NaHCO_3$, and Na_2CO_3 in the root zone [11] [17]-[19], leading to adverse effects on soil fertility, stability, and biodiversity [20] [21]. The elevated concentration of soluble salts, or salinity, primarily impacts plant growth and crop production by increasing the osmotic potential of the soil solution [22] [23]. Consequently, salinity poses significant challenges to agricultural production, with far-reaching implications for rural livelihoods, economic sectors, environmental sustainability, and overall development [1] [6] [21] [24]. Notably, since 75% of the population across SSA relies on subsistence farming, addressing salinity-related issues is crucial for ensuring food security and sustainable agricultural practices [25] [26].

Mitigating and preventing salinity is crucial for advancing agricultural development, particularly in SSA. This region is transitioning from traditional rain-fed agricultural systems to intensive irrigated agriculture to combat food insecurity, poverty, and climate change. To achieve these goals, proper agricultural field management and adaptation for increased productivity are essential. Additionally, efficient food supply chains are needed to support a growing population in SSA.

A comprehensive set of adaptations and mitigation measures, including the use of salt-tolerant crop varieties [27]-[29] and effective soil and water management practices [22] [25] [26] [30], is essential to address the challenges posed by salinity. Among these measures, soil amendments play a crucial role. Salt-affected soils can be rehabilitated through inorganic and organic amendments. The physical, chemical, and biological properties of soil can be improved by applying organic matter, which accelerates salt leaching, improves aggregate stability, and increases water holding capacity [31], thereby enabling better plant growth in salt-affected soils. Additionally, adding organic matter (OM) can decrease the exchangeable sodium percentage (ESP) and electrical conductivity (EC) [32]. It can also enhance both cation exchange capacity and soluble exchangeable K+, which competes with Na+ in saline sodic soil, limiting its entry at exchangeable sites [31]. This adaptation and mitigation technology is cheaper compared to saltwater drainage and small-scale irrigation technologies. Furthermore, some studies [27] [33] used chemicals such as gypsum to reclaim salt-affected soils, which release Ca2+ to replace Na+ at soil exchangeable sites, followed by leaching with a good quality water supply.

The village of Atti-Apédokoe in Togo is renowned for its high market gardening production and its suitability for cultivating cereals such as rice, millet, and sorghum. However, salt accumulation in the water and soil has negatively affected crop yields, leading to land abandonment by vegetable growers [34]. The residents of Atti-Apédokoe depend on agriculture for their livelihood, and increasing salinization threatens their income and existence. Despite the critical situation, no specific studies have been conducted to explore cropping strategies that could alleviate soil salinity. The combination of salt-tolerant crops and soil amendments under drip irrigation may be a promising strategy to address the salinity of agricultural lands in Atti-Apédokoe. This study aims to assess the effect of various organic and inorganic soil amendments on millet and sorghum growth and yields in salt-affected soils.

2. Materials and Methods

2.1. Study Site

The study was conducted during two consecutive seasons (June to September 2021 and January to April 2022) at Atti-Apedokoe. The village is located 50 km northwest of Lome in the prefecture of Ave, in the maritime region of Togo (longitude 0˚54’ E and latitude 6˚26’ N). The area experiences a tropical sub-guinea climate with a bimodal rainfall distribution, featuring two rainy and two dry seasons. The main rainy season spans from March to June, and the second from August to October. Atti-Apedokoe receives an average annual rainfall of approximately 1200 mm, with temperatures ranging from 24˚C to 33˚C. Subsistence agriculture is the primary economic activity in the village, providing employment for approximately 80% of the population.

The experiment was conducted on-farm at a location chosen specifically for testing and demonstrating agricultural technologies as part of the RESADE project (Improving Agricultural Resilience to Salinity through the development and promotion of pro-poor technologies and management strategies in saline-affected agricultural areas). The soil at the site is characterized as silty-sandy near the surface (0 - 30 cm) and silty-clay-sand at greater depths (>30 cm). The initial physicochemical parameters of the soil at the beginning of the experiment are detailed in **Table 1**. The experiment was repeated in the second season on the same plot.

Table 1. Physicochemical parameters of the topsoil (0 - 30 cm) before the experiment.

	Sand (%)	Silt (%)	Clay (%)	OM[a] (%)	N[b] (%)	P[c] (ppm)	K[d] (meq/100)	pH[e]	ECs (dS/m)	CEC (meq/100)
2021	81	8.6	10.4	2.30	0.064	5.00	0.11	6.3	2.17	13.47
2022	78	12	10	1.79	0.056	2.91	0.08	6.4	1.78	15.22

[a] Walkley and Black method as outlined by Nelson et Sommers [35]; [b] Kjeldahl method; [c] Olsen and Sommers [36]; [d] Helmke et Sparks [37]; [e] Dilution method, Jackson [38].

2.2. Plant Materials

The plant materials used comprised millet variety IP 19586 and sorghum variety ICSV-700. Genotype seeds were received from the International Center for Biosaline Agriculture (ICBA). These specific varieties were chosen for their demonstrated tolerance to saline soil and irrigation water. The characteristics of the millet and sorghum genotypes used in this study are presented in Table 2.

Table 2. Characteristics of crop genotypes used.

Crop	Variety	Origin	Race/ Biological status	Cycle duration (days)	Salinity sensitivity	Height (m)	Use	Yield potential (t/ha)
Sorghum	ICSV-700	ICRISAT	Guinea-OPV	120 - 130	Tolerant	3.0 - 3.5	Dual purpose	3
Millet	IP 19586	ICRISAT	Traditional cultivar/ Landrace	75	Tolerant	1.8	Dual purpose	2.7

OPV: Open Pollinated Varieties.

2.3. Treatments Formulation

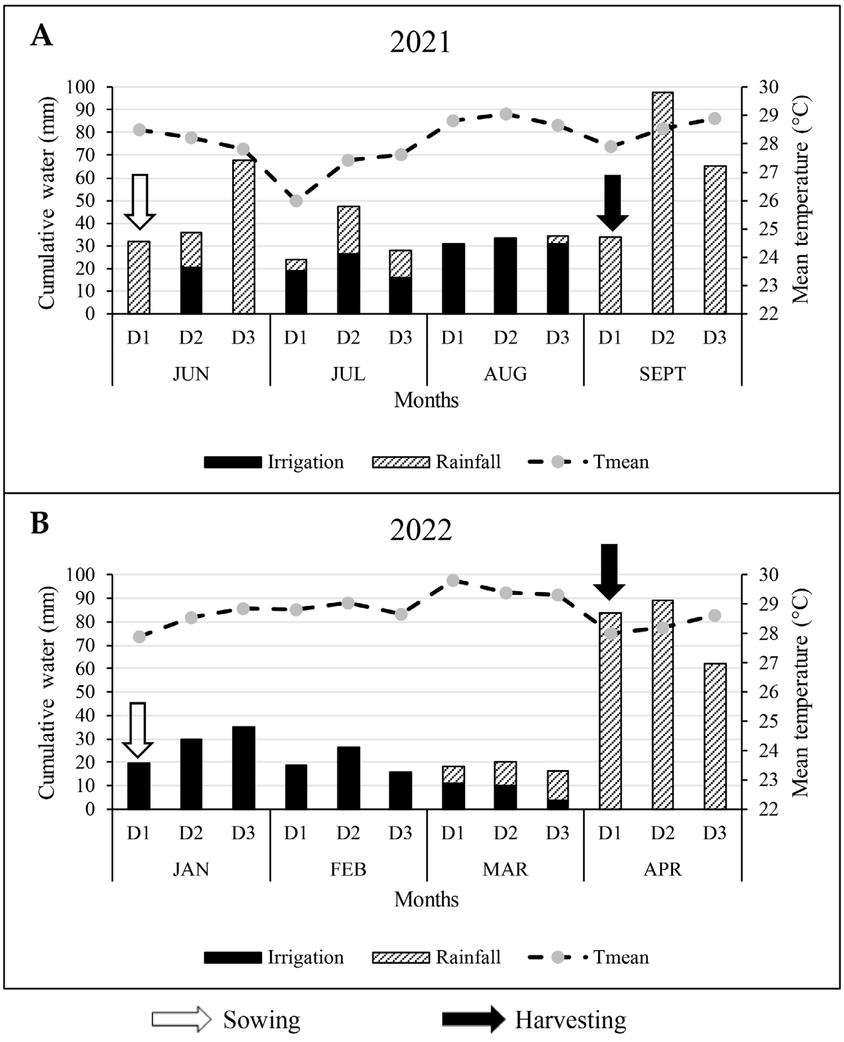
The treatment consisted of five sources of amendment, including the control (Amendment 1), green manure (*Leucaena leucocephala*, Amendment 2), biochar made from palm shells (Amendment 3), rock phosphate (Amendment 4), and lime (Amendment 5). Table 3 shows each amendment's sources and application rate according to recommendations in Togo. The amendments were applied and incorporated into the soil by plowing each year before sowing. *L. leucocephala* (Amendment 2) was air-dried in the shade for two weeks before application. Each plot received mineral fertilizer at 150 kg/ha NPK 15-15-15 and 100 kg/ha urea (46%). The mineral fertilizer rate is recommended by the Togolese Institute of Agricultural Research (ITRA) for cultivating sorghum and millet. The effect of the amendments will be assessed through the difference between the control and the other amended plots.

Table 3. Source of amendments and application rates.

Treatments	Source	Rate	
		kg/6m^2	t/ha
Amendment 1	Control (no application)	0	0
Amendment 2	*Leucaena leucocephala*	3	5
Amendment 3	Biochar (with palm shells)	3	5
Amendment 4	Togo Rock phosphate	1.5	2.5
Amendment 5	Dolomite (28% - 32% CaO) 17% - 18% (B, Cu, Zn, MgO, SO^{3-})	2	3.3

2.4. Experimental Design

A randomized complete block design (RCBD) arranged in a split plot with three replications was used. Crops (pearl millet and sorghum) were assigned to the main plots, while the amendments were assigned to the subplots. The crops were sown in elementary plots of 6 m^2 (3 m × 2 m). Sowing spacing was 80 cm × 30 cm, resulting in a plant density of 83,333 plants per hectare. Weed and pest management, disease control, and bird scaring were conducted as recommended by the Togolese Institute of Agricultural Research (ITRA).



D1: decade 1, D2: Decade 2, D3: decade 3

Figure 1. Cumulative water quantity (rainfall and irrigation) and mean temperature during the experiment in 2021 (A) and 2022 (B).

The experiment's total water input (irrigation + rainfall) amounted to 366 mm in 2021 and 283 mm in 2022. The irrigation water applied was 171 mm in 2021 and 114 mm in 2022. Irrigation was administered daily, except on rainy days, based on the water requirements of pearl millet and sorghum. Irrigation water was sourced from groundwater in the experiment area. The chemical characteristics of the irrigation water are detailed in **Table 4**, with an average EC of 5.6 dS/m, indicating moderate salinity [39], neutral pH, and moderate SAR according to Shainberg and Letey [40]. **Figure 1** illustrates the cumulative water (rain + irrigation) and mean air temperatures (Tmean) per decade during the experiment.

Table 4. Chemical characteristics of used irrigation water.

Year	pH	ECw (dS/m)	Na^+ (mg/l)	K^+ (mg/l)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	SAR
2021	7.33	5.46	25.63	19.3	36.0	12.4	5.2
2022	7.21	5.77	22.3	20.3	38.6	16.3	5.9

2.5. Data Collection

To assess the effect of salinity on plant growth, plant height and stem diameter measurements were taken at 30, 60, and 90 days after sowing (DAS). At physiological maturity, fifteen randomized hills from each subplot were harvested to assess grain yield (Y) and plant biomass (YB) after a controlled drying process.

To assess the plant's adaptive response to salinity, three leaves were collected randomly from each plot for laboratory determination of biochemical parameters: total protein, proline, and malondialdehyde contents, whose accumulation in the plant indicates salt stress. Total protein and proline were determined according to Bradford [41] and Bogdanov *et al.* [42], respectively, as modified and adapted for plant material analysis. The extraction and determination of malondialdehyde (MDA) were conducted following the method described by Heath and Packer [43]. These biochemical parameters were calculated using the following equations:

$$\mathrm{P}\left(\mathrm{mg/gFW}\right)=\frac{\mathrm{D}*\mathrm{R}*\mathrm{V}}{\mathrm{W}*\mathrm{Vs}} \tag{1}$$

where P is protein content; D is possible dilution; R is the value read on the spectrophotometer; V is the total volume of the extract; W is the weight of fresh material (here, leaves); Vs is the sample volume.

$$\mathrm{Pro}\left(\mu\mathrm{g/mgProtein}\right)=\frac{\left(\left(\mathrm{Ae/As}\right)*\left(\mathrm{Ws/Wf}\right)\right)}{\mathrm{Qp}} \tag{2}$$

where Pro is proline content; Ae is the absorbance of the leaf extract; As represents the absorbance of the proline standard solution; Ws is the proline weight in the standard solution (µg); Wf stands for the fresh weight of the leaf (g); Qp is the amount of protein (mg/g fresh material).

$$\mathrm{CMDA}\left(\mathrm{mg/gFW}\right)=\frac{\mathrm{Ae}}{\epsilon*\mathrm{L}} \tag{3}$$

where CMDA is the MDA concentration; Ae is the absorbance of the leaf extract; Є is the molar extinction coefficient; L is the width of the cell (1 cm).

The grain yield index (Gij) was calculated (Equation (4)) to evaluate the effect of amendments (leucaena, biochar, rock phosphate, and dolomite) compared to the non-application of amendments (control):

$$Gij = \frac{(Yij - Y1j)}{Y1j} \tag{4}$$

where Yij is the biomass/grain yield of crop j under amendment i (i = leucaena, biochar, rock phosphate, and dolomite); Y1j is the yield from the control treatment.

2.6. Statistical Analysis

Statistical analyses were performed using R, version 4.2.2. Data from the two years were pooled for each crop and parameter according to the randomized complete block design (RCBD). The data were subjected to analysis of variance (ANOVA). Treatment means were separated using the Least Significant Difference (LSD) at the 5% probability level.

3. Results and Discussion

3.1. Experimental Conditions

Figure 1 shows the cumulative water quantity (rainfall and irrigation) and the average air temperature during the experiments in 2021 and 2022. In 2021, a total of 366 mm of water was received, compared to 283 mm in 2022. During the first 30 days of the 2021 experiment, plants received more rainfall, reducing their exposure to pronounced salt stress. In 2022, plants received only irrigation water during the first 60 days, coinciding with the flowering and stem extension phases for millet and sorghum, respectively. As a result, the amount of salt water received during the experiment was higher in 2022. The average temperature during both years was similar, with a mean of 29˚C. Table 5 shows the nutrient content and chemical characteristics of the different amendments used.

Table 5. Chemical properties of the amendments during the evaluation of pearl millet and sorghum at Atti-Apedokoe.

	N (%)	P (ppm)	K (meq/100)	OM (%)	Na (meq/100g)	Mg (méq/100g)	Ca (méq/100g)	pH
Leuceana leucocephala	5.60	1.154	0.157	42.14	-	-	-	7.05
Biochar*	2.45	1.470	0.256	36.49	-	-	-	7.20
Rock phosphate	0.1	22.74	2.43	-	0.27	2.77	1.73	7.01
Dolomite (28% - 32% CaO) 17% - 18% (B, Cu, Zn, MgO, SO^{3-})	0.1	-	-	-		87.5	86.7	9.91

-: non determined, *Biochar is made with palm oil shells, N: nitrogen, P: available phosphorus, OM: organic matter, Mg: Magnesium, Ca: calcium.

3.2. Effects of Amendments on Sorghum and Millet Growth

- **Effect on pearl millet and sorghum height**

The impact of different amendment sources on plant height under saline soil and water conditions is shown in **Figure 2**. Millet height ranged from 29.5 cm (control treatment in 2022) to 320.0 cm with Leucaena in 2021, while sorghum height ranged from 43.3 cm (Leucaena treatment in 2022) to 386 cm (rock phosphate in 2021). Although plant height increased from tillering (30 DAS) to maturity (90 DAS) for pearl millet, the growth rate was lower than in the early growth stages (1 - 30 DAS). The growth rate for sorghum remained constant between the growth stages (**Figure 2(C)** & **Figure 2(D)**). No significant effect of amendment sources was observed on the height of both crops ($P > 0.05$), except at flowering (90 DAS) for sorghum ($P < 0.05$). Plant height was statistically similar for plots with different amendments but differed from plants under control (no amendment) at flowering. There was a significant difference in plant height at all growth stages between years ($P < 0.05$) (**Table 6**). Plants in 2022 were shorter than those in 2021 (**Figure 2**). Plant height was not affected by the interaction between amendment sources and year (**Table 6**).

Table 6. ANOVA results on pearl millet and sorghum plant height, stem diameter, protein, proline, malondialdehyde, dry biomass, and grain yield.

Crop	Source of variation	Plant height			Stem diameter			Salt stress indicators			Dry biomass	Grain yield
		30	60	90	30	60	90	Total Protein	Proline	MDA		
Millet	A	0.3668^{ns}	0.448^{ns}	0.273^{ns}	0.9326^{ns}	0.7129^{ns}	0.909^{ns}	0.827^{ns}	0.0191*	0.000434***	0.591^{ns}	0.0012**
	Y	07e−08***	1.37e−08***	3.33e−09***	1.25e−11***	3.47e−08***	1.87e−07***	0.281^{ns}	0.617^{ns}	0.233^{ns}	0.0381*	0.5315^{ns}
	M*Y	0.2908^{ns}	0.726^{ns}	0.791^{ns}	0.9778^{ns}	0.4141^{ns}	0.883^{ns}	0.742^{ns}	0.836^{ns}	0.593^{ns}	0.1973^{ns}	0.5707^{ns}
Sorghum	A	0.257^{ns}	0.413^{ns}	0.0409*	0.939^{ns}	0.515^{ns}	0.582^{ns}	0.22^{ns}	0.637^{ns}	0.00946**	0.00237**	0.0474*
	Y	1.98e−09***	9.37e−06***	2.3e−08***	9.06e−13***	2.93e−08***	1.52e−08***	0.318^{ns}	0.441^{ns}	0.152^{ns}	0.365^{ns}	0.9533^{ns}
	A*Y	0.311^{ns}	0.911^{ns}	0.2067^{ns}	0.656^{ns}	0.260^{ns}	0.345^{ns}	0.612^{ns}	0.835^{ns}	0.97^{ns}	0.278^{ns}	0.1215^{ns}

A: amendment source, MDA: Malondialdehyde, Y: year, A*Y: Amendment and year interaction, ns: not significant, *Significant at the 0.05 probability level; **Significant at the 0.01 probability level; ***Significant at the 0.001 probability level.

Salinity negatively affects plant growth by increasing soil osmotic pressure and interfering with plant nutrition [22]. In this study, we found that applying different amendments under saline conditions did not statistically affect pearl millet plant height during the vegetative growth stages (**Figure 2**). This indicates pearl millet's ability to maintain its growth rate in stressful environments, reflecting its tolerance or adaptation to salt stress. The results corroborate the work of Qaoud *et al.* [44], who demonstrated that pearl millet genotypes moderately tolerate salinity. The soil amendments used in this study appeared favorable for sorghum growth (plant height). During the 2022 cropping season, sorghum plants from the amended plots were taller than those in the control. The significant difference in effect between the control and amendment application on sorghum height at 90 DAS can be attributed to the combined effect of reduced salinity severity induced by the amendment and a decrease in cell division during abiotic stresses (salt and water) [45]. This result corroborates the findings of Punia *et al.* [46], who observed higher plant heights at later stages of crop growth in sorghum. Moreover, Benmahioul *et al.* [47] pointed out that the presence of NaCl in the culture medium leads to a significant decrease in stem length.

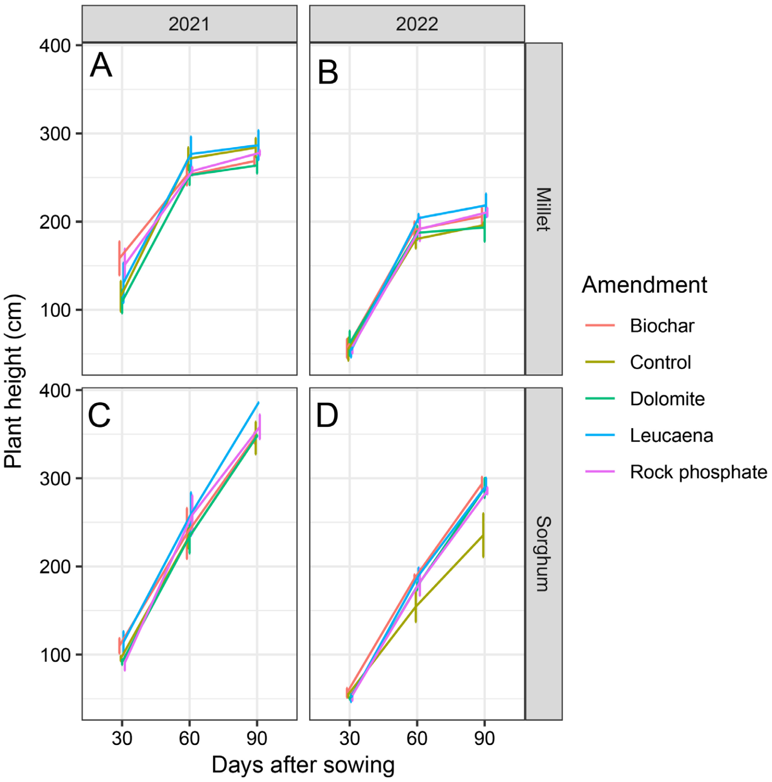


Figure 2. Plant height (cm) measurements were conducted on pearl millet (A and B) and sorghum (C and D) grown in plots amended with biochar, dolomite, leucaena, and rock phosphate at Atti-Apedokoe.

- **Effect on sorghum and millet stem diameter**

Figure 3 shows the stem diameter at all growing stages for millet and sorghum. The stem diameter ranged from 0.64 cm (control in 2022) to 2.8 cm (Biochar in 2021) for millet and from 1.46 cm (control in 2022) to 2.7 cm (Dolomite in 2021) for sorghum. A highly significant effect of the year was observed for stem diameter at all growing stages. In 2022, plants showed the smallest stem diameter at all stages for both millet and sorghum (**Figure 3(B)** & **Figure 3(D)**). Salt stress did not influence the stem diameter at different stages. Neither amendment sources nor the interaction between amendment sources and year affected the stem diameter. This result aligns with Nasri and Benmahioul [48], who found no effect of salt stress on argan stem diameter when grown in a sand and peat mixture. However, it was observed that, irrespective of amendment sources, the stem diameter increased slightly between 30 to 60 DAS and between 60 to 90 DAS in 2021 for both millet and sorghum (**Figure 3(A)** & **Figure 3(C)**). In contrast, stem diameter increased significantly between 30 to 60 DAS (on average 0.54 to 1.49 cm) and slightly between 60 to 90 DAS (on average 1.49 to 1.7 cm) (**Figure 3(D)**), except for millet, where stem diameter decreased after 60 DAS in 2022 (**Figure 3(C)**). This decrease in millet stem diameter in 2022 might be due to plant senescence and/or osmotic effects. Under saline conditions, plants find themselves in a toxic environment and face osmotic pressure [22] [49].

Several studies have reported findings on the effect of salt on plant growth. These findings vary with crops, genotypes [15] [28], experimental conditions (laboratory vs. field) [27] [28] [33] [48], and salt concentrations (low, moderate, and high concentrations) [50]-[53].

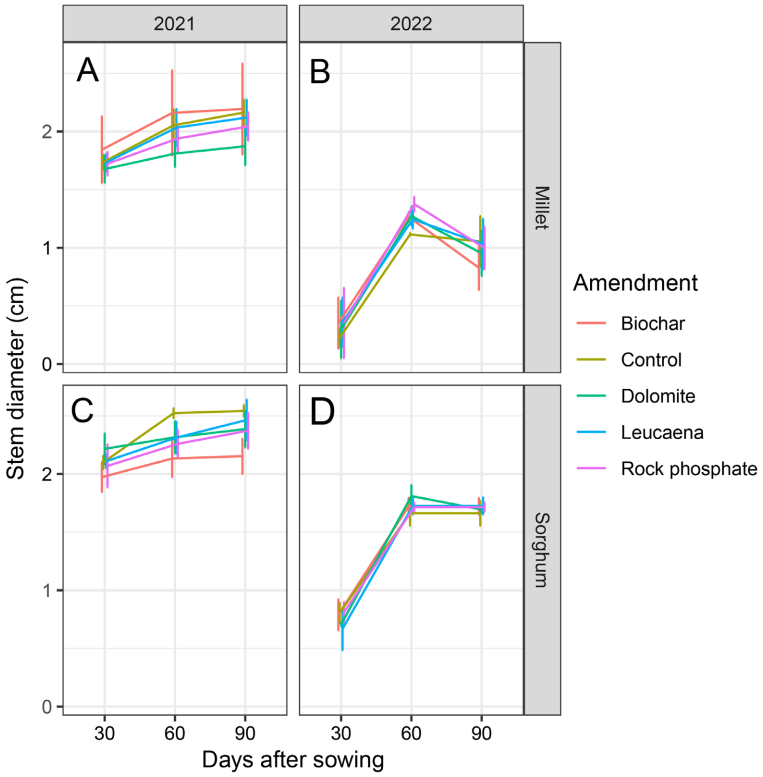
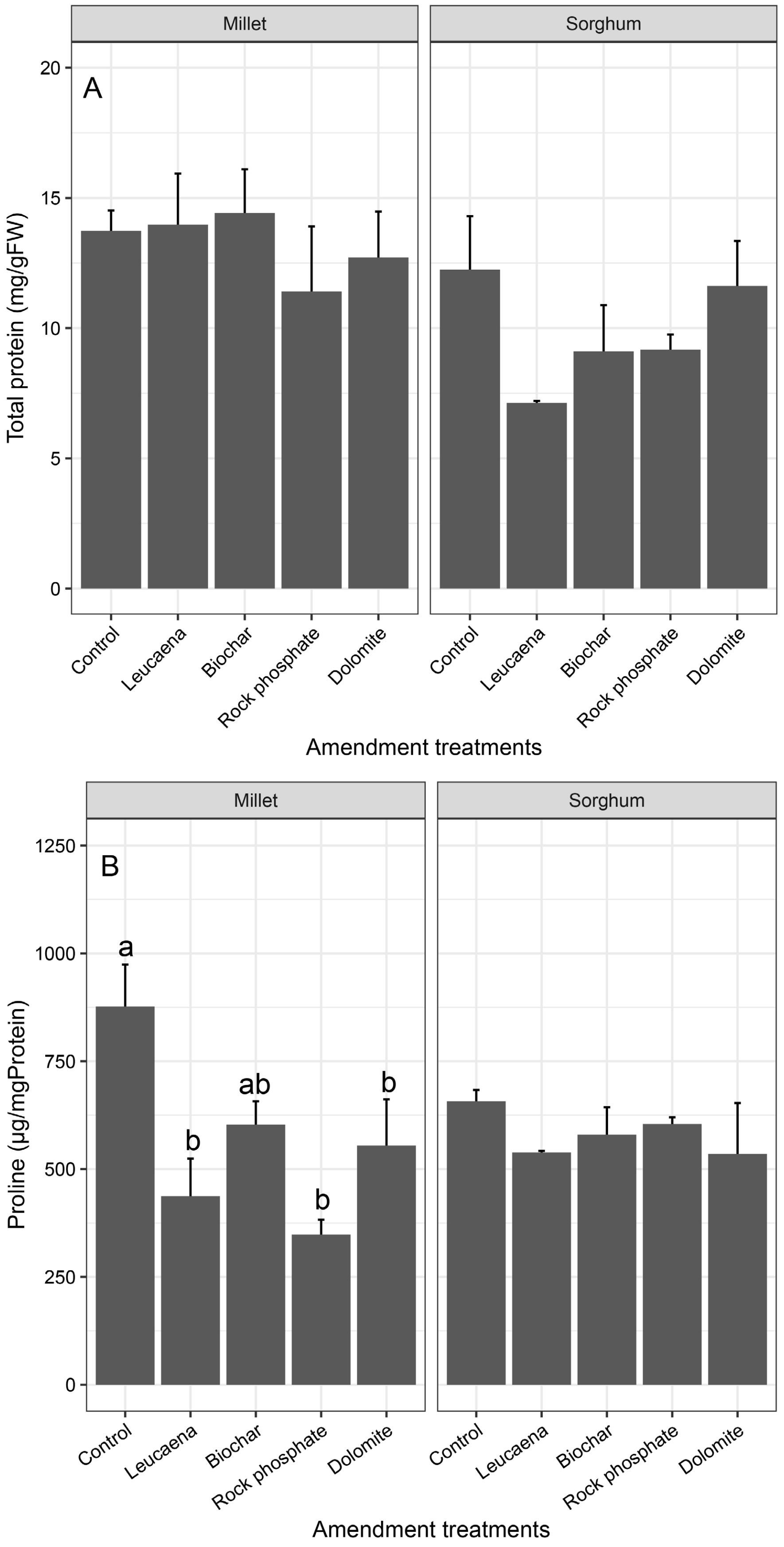
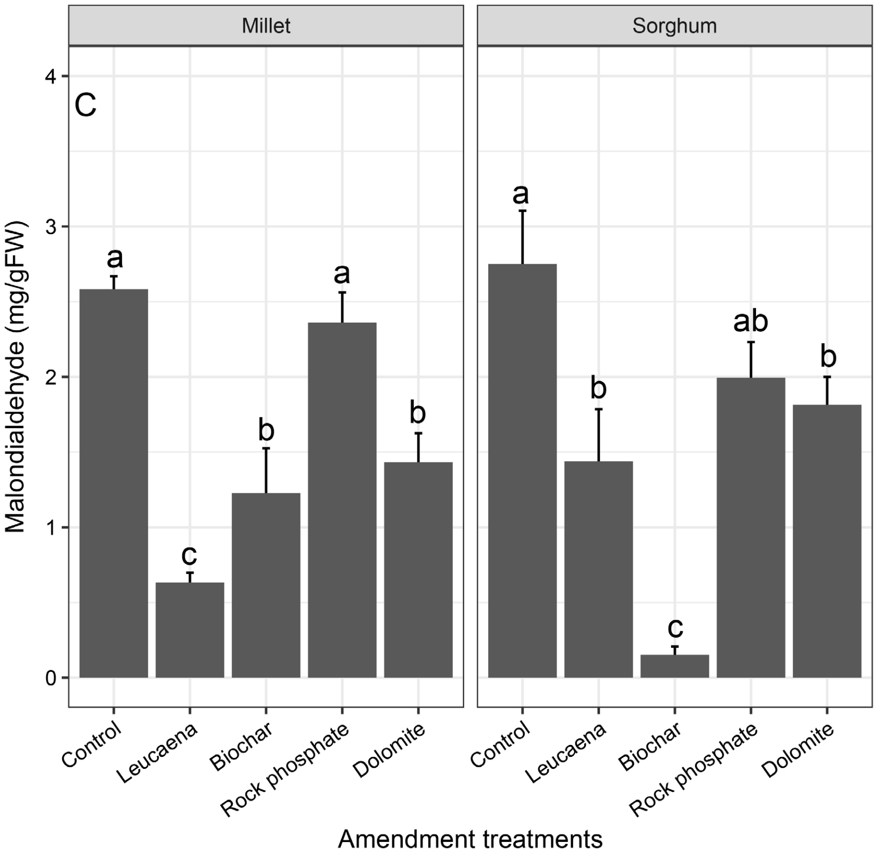


Figure 3. Plant stem diameter measurement was conducted on pearl millet (A and B) and sorghum (C and D) grown on plots amended with biochar, dolomite, leucaena, and rock phosphate at Atti-Apedokoe.

3.3. Plants' Responses to Salt Stress in Amended Soils

Sorghum leaves showed the lowest total protein content where leucaena, biochar, and rock phosphate treatments were applied (**Figure 4(A)**). However, the total protein content in the leaves of millet and sorghum did not differ statistically with the different amendments for both crops ($P > 0.05$) (**Table 6**). This indicates that soil amendments did not produce differences in the accumulation of total protein content compared to the control. Previous studies reported similar findings. Zahra *et al.* [54] reported insignificant differences between stresses (saline and non-saline pots) for protein content in roots of two maize genotypes. However, Tort and Turkyilmaz [55] found that protein content in barley leaves varied with salt concentration, with 120 mM of sodium chloride inducing higher protein content.


Millet
Sorghum
A
Total protein (mg/gFW)
0
5
10
15
20
Control
Leucaena
Biochar
Rock phosphate
Dolomite
Amendment treatments
Millet
Sorghum
B
Proline (µg/mgProtein)
0
250
500
750
1000
1250
a
b
ab
b
b
Control
Leucaena
Biochar
Rock phosphate
Dolomite
Amendment treatments



Histograms without letters are not significantly different.

Figure 4. Biochemical attributes in leaves at 30 DAS: total protein (A), proline (B), and malondialdehyde (MDA) (C).

Statistical analysis showed significant differences in millet leaves' proline content ($P < 0.05$), whereas for sorghum, there was no significant difference (**Table 6**). The proline content for millet was significantly high under control conditions, where no soil amendments were applied. This suggests that amendments influenced proline content. Plants from plots amended with rock phosphate, leucaena, and dolomite showed the lowest proline content, while those under biochar application showed intermediate proline content (**Figure 4(B)**). Plants usually accumulate proline in response to stress [56]. Treatments with lower proline content relative to the control for millet indicate that those amendments contributed less to salt stress. However, proline content has been reported to increase in plants with salt stress by Savouré *et al.* [57] and Toumi *et al.* [58]. Our results for pearl millet suggest the contrary. In sorghum leaves, proline content did not differ among amended treatments, possibly due to a higher threshold of salt stress in sorghum [58] [59]. This salt insensitivity in sorghum plants could also be attributed to the intrinsic characteristics of the genotypes, such as salt tolerance and salt sensitivity.

The MDA concentration effectively assesses oxidative stress damage to the cell membrane [60]. In this study, no difference was observed in MDA accumulation between the control and rock phosphate treatments on pearl millet. Biochar, leucaena, and dolomitic lime significantly reduced MDA in both pearl millet and sorghum leaves (**Figure 4(C)**). There was no significant difference in MDA between the control and rock phosphate treatments in pearl millet and sorghum. Millet and sorghum showed the lowest MDA accumulation under leucaena and biochar amendments, respectively. The low level of MDA accumulation indicates better protection of cell membranes against oxidative damage induced by salt accumulation in plants. Our findings align with several studies [58] [61]-[63] that reported various MDA content depending on the stress level and the genotype of sorghum, halophyte (*Atriplex halimus* L. and *Atriplex canescens* (Pursh) Nutt), pearl millet, and colza. It can be concluded that soil amendment with leucaena and biochar reduces salt accumulation in the root zone, and millet and sorghum differ in their ability to respond to salinity in their leaf cells.

3.4. Effect of Soil Amendment on Crop Yields under Saline Conditions

- **Dry biomass yield**

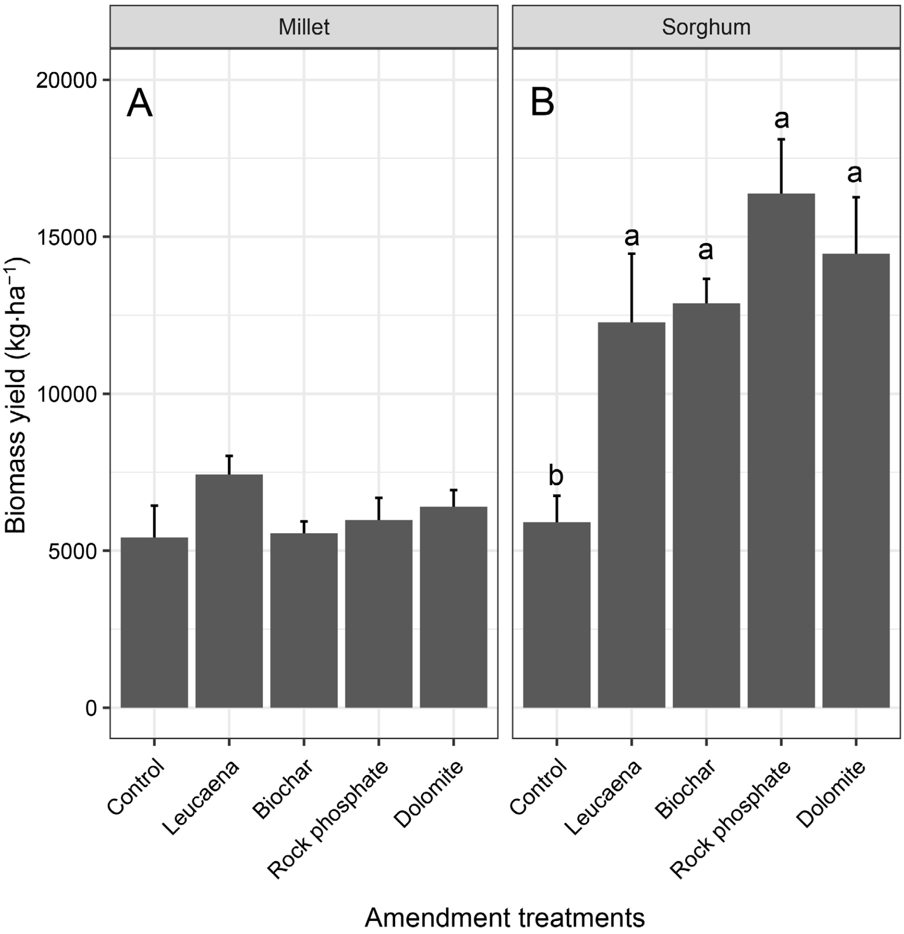


Figure 5. Effect of amendment sources on dry biomass yields measured from pearl millet (A) and sorghum (B) at Atti-Apedokoe. (Histograms without letters are not significantly different).

The results for the dry biomass yield are depicted in **Figure 5**. Average dry biomass yield varied from 5418.6 kg/ha (control) to 7424.5 kg/ha (leucaena) for millet (**Figure 5(A)**) and from 5912.5 to 16371.9 kg/ha for sorghum (**Figure 5(B)**). Amendment sources affected dry millet and sorghum biomass differently. Notably, there was a significant effect only on the dry biomass yield of sorghum ($P < 0.01$) (**Table 6**). The lowest average dry biomass yield was obtained from the control treatment, while the application of amendments induced high biomass production. Application of rock phosphate showed the highest dry biomass; however, this was not significantly different from the biomass recorded from leucaena, dolomite, and biochar applications (**Figure 5**). In general, the application of soil amendments increased dry biomass by 106 to 177%. Furthermore, there was a significant difference between years only for millet dry biomass, with 2021 showing the highest biomass. The amendment-year interaction was not statistically significant for dry biomass yield for both millet and sorghum ($P > 0.05$) (**Table 6**). Rekaby *et al.* [64] reported similar findings, observing that applying organic amendments (biochar, humic acid, and compost) significantly increased the dry biomass yield of barley compared to a control treatment.

- **Grain yield**

The results showed that neither year nor amendment-year interaction significantly affects grain yield for millet and sorghum. However, soil amendments significantly affected grain yields ($P < 0.05$) (**Table 6**). For millet, the lowest grain yield (1100.3 kg/ha) was observed under the control (without amendment application), followed by rock phosphate (1640.8 kg/ha), biochar (1681.4 kg/ha), and dolomite (1691.7 kg/ha), which were statistically not different. The leucaena treatment showed the highest grain yield for millet (2214 kg/ha) (**Figure 6(A)**). The application of amendments improved grain yields for millet by 49% - 101%, with an average increase of 64%. For sorghum, the application of biochar and leucaena showed the highest grain yields (1153.3 and 1158 kg/ha, respectively), followed by rock phosphate (946.9 kg/ha) and dolomite (737.3 kg/ha), whereas the control showed the lowest grain yield (381.3 kg/ha) (**Figure 6(B)**). The application of amendments improved grain yields by 93% to 202% (an average increase of 159%) for sorghum. Applying amendments, regardless of the crop, resulted in better grain yields than not applying them, which is the farmers' usual practice in the area. Millet performed better than sorghum, and grain yield responses to amendments under saline conditions varied slightly depending on the amendment source. Organic amendments (biochar and leucaena) responded better to salinity than chemical amendments (rock phosphate and dolomite), which produced intermediate grain yields for millet and sorghum. Leucaena, in particular, outperformed all other amendment sources (**Figure 6**). The amendments significantly improved salt-affected soil conditions by reducing salinity and sodicity, enhancing soil structure, and increasing nutrient availability. Organic amendments like leucaena and biochar likely improved the soil's physical properties, water retention, and microbial activity more effectively than inorganic amendments like dolomite and rock phosphate. Increasing water infiltration and drainage helps leach out excess salts.

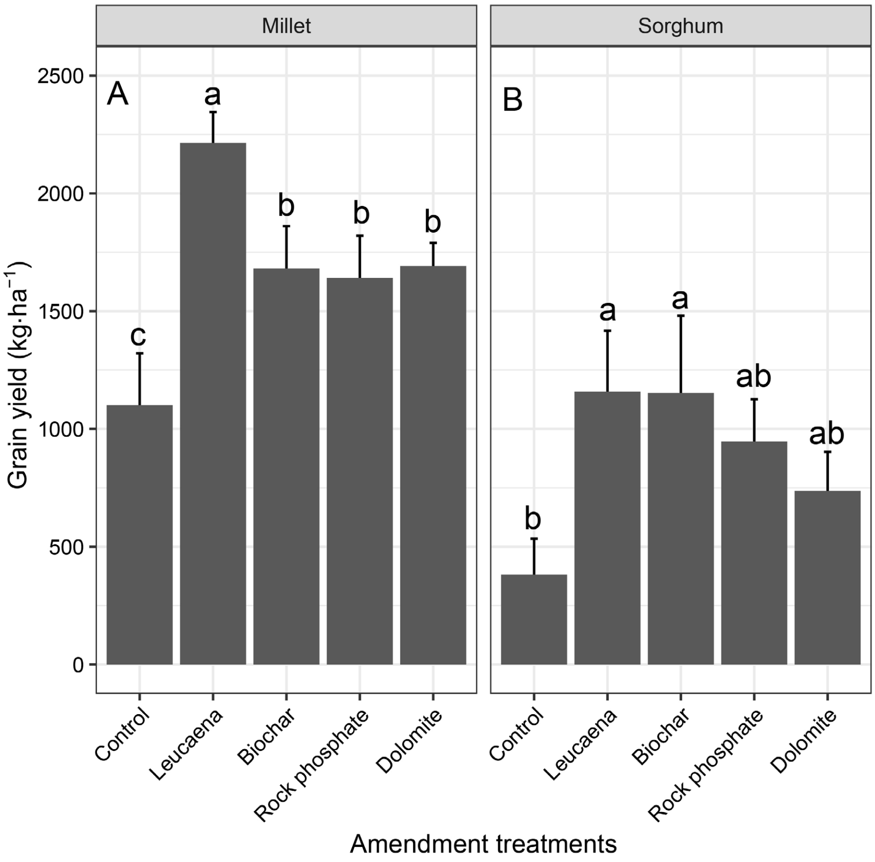


Figure 6. Effect of amendment sources on grain yields measured from pearl millet and sorghum at Atti-Apedokoe. (Histograms with the same letter are not significantly different).

Organic matter (OM) improves the mineral nutrient status and growth of plants in saline soils by supplying nutrients, particularly N, P, and K [32] [65]. Moreover, mulching benefits saline soils by reducing evaporation from the soil surface and encouraging a downward flow of soil water [49]. The response of crops to amendments under saline conditions depends on the type of amendment (organic vs. mineral) and the type of organic matter (leucaena vs. biochar) (**Table 5**). The characteristics of each amendment used in the study were compared. Leucaena and biochar showed high OM and N content, making them crucial for improving soil structure, supporting plant nutrient provision, and limiting soil water evaporation. Amendment with dolomite did not perform as well as leucaena and biochar. However, this amendment contains calcium and magnesium, reducing soil sodium levels and increasing calcium and sulfur provision to plants. The low performance of dolomite compared to the organic amendments might be due to the timing of application (one day before sowing). There was likely insufficient time for reactions to occur in the soil. Our findings align with Litardo *et al.* [66], who found that the application of mineral and organic amendments on rice affects its reproductive growth. Among all their treatments, compost, sugarcane filter cake, and leonardite showed the highest yield values compared to control under saline conditions. However, the authors observed that the application of the amendments did not affect vegetative growth (plant height, tiller number, and straw dry mass weight). Other authors, such as Choudhary *et al.* [67], showed that in the case of saline-sodic irrigation, sugar yield from sugarcane under farmyard manure treatment was comparable to the combination of gypsum and farmyard manure treatment but was significantly higher than that of gypsum alone.

Additionally, the significant increase in millet grain yield with leucaena and sorghum yield with biochar and leucaena was associated with the plant's MDA content. Treatments with lower MDA content produced more yield, likely due to better cell membrane protection from oxidative damage, which might influence photosynthesis and the accumulation of assimilates. Toderich *et al.* [63] found similar results for pearl millet in response to different soil salinity levels, with yield decreasing as salinity increases. Few studies have reported on the benefits of biochar and leucaena for plants under saline conditions. In a critical review, Ali *et al.* [68] noted that biochar application increased plant growth, biomass, and yield under saline conditions. Ibrahim *et al.* [69] found that biochar soil amendment effectively alleviated the effects of salinity on sorghum seedling growth. Among all biochar levels tested, a 5% biochar level had a significant impact on mitigating salt stress. Kul *et al.* [70] also found that biochar amendments at 5% and 10% (v/v) significantly decreased malondialdehyde (MDA) and proline contents while improving tomato plant performance, including plant height, leaf area, shoot fresh and dry weight, number of leaves, and root fresh and dry weight under saline conditions. *L. leucocephala* showed promise for afforestation of sodic soils due to its potential to produce higher biomass and improve the fertility of these soils [71].

The experimental conditions impacted the results. Crop response to the application of amendments was more positive in 2021 than in 2022 (**Figure 2** and **Figure 3**). This can be explained by the experiment being conducted during the short dry season in 2021, which was not completely dry. The crops benefited from rain and probably leaching, which likely reduced the severity of salinity. However, the analysis of variance for the amendments and year interaction was not significant for all parameters measured. Therefore, the plants reacted similarly to the amendments during both years.

4. Conclusion

The findings of this study have potential implications for agricultural practitioners and professionals in soil science and crop production. The differential impact of amendments on the growth of pearl millet and sorghum in saline conditions, with sorghum showing positive effects and pearl millet showing no significant impact, suggests the need for crop-specific approaches to soil salinity management. The study also revealed that both pearl millet and sorghum experienced osmotic and oxidative stresses, as indicated by elevated proline and MDA levels in the control group compared to the amended plants. The application of amendments led to a substantial improvement in grain yield, with an increase of up to 101% (averaging 64%) for pearl millet and up to 202% (averaging 159%) for sorghum. Among the various amendments tested, leucaena and biochar were identified as the most effective in mitigating soil salinity. These treatments significantly enhanced the grain yield of both pearl millet and sorghum and were correlated with MDA content. Notably, the organic amendments, specifically biochar and leucaena, outperformed the mineral amendments, such as rock phosphate and dolomite, in mitigating soil salinity.

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Conflicts of Interest

The authors declare no conflicts of interest. The funders had no role in the study's design, data collection, analysis, interpretation, manuscript writing, or decision to publish the results.

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Application of Artificial Neural Networks to Optimize Nitrogen Supply to Meet Plant Needs for Soil Conservation: Case Study, M'Bahiakro Irrigated Perimeter (Central-East, Ivory Coast)

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Abstract

The low nitrogen content of soils in the rice-growing area of M'Bahiakro requires optimized fertilization to improve yields while minimizing environmental impacts. This study proposes an intelligent model based on backpropagation neural networks (BPNN) to predict the nitrogen requirements of rice using seven physico-chemical soil parameters (K, P, Norg, OM, θpf, CEC, and Kc). The model was trained using the Levenberg-Marquardt algorithm, with a sigmoid transfer function for the hidden layer and a linear function for the output layer. Model performance was evaluated using the coefficient of determination ($R^2 = 0.98$) and the mean squared error (MSE = 0.001), indicating high predictive accuracy. Results show that rice yield no longer improves significantly beyond 118 kg N·ha^{-1}, with R^2 and MSE values stabilizing around 98% and 0.007, respectively. This threshold therefore represents an optimal nitrogen dose, enabling a balance between agricultural productivity and the preservation of natural resources, particularly by reducing soil degradation and groundwater contamination. However, to strengthen the model's robustness, further investigations are essential in the irrigated area of M'Bahiakro, especially during the dry season. Expanding the study to include other rice varieties, soil types, and cultivation practices would not only broaden the model's applicability but also reinforce its role as a decision-support tool in sustainable nitrogen fertilization strategies.

Keywords

Irrigated Perimeter, Artificial Neural Networks, Rice, Nitrogen Fertilization, Soil Conservation, M'Bahiakro

1. Introduction

Irrigated production provides around 75% of the world's rice requirements [1] and plays a particularly important role in global food security. Irrigated crops produce around 40% of total agricultural output and have a major economic and social role to play in terms of consumption, marketing, and the fight against poverty [2].

Of all the nutrients required for rice production, nitrogen is the most restrictive. It is one of the essential constituents of the fundamental molecules of living organisms (nucleic acids, peptides, and proteins). Soil nitrogen availability is a key factor in rice development, growth, and performance [3]. Only mineral forms of nitrogen, such as ammonium and nitrate, can be taken up by the roots of most crop plants, with a preference for nitrate [4]. These elements may already be present in the soil through the degradation of organic matter, either naturally present or supplied in the form of fertilisers. However, it is common to supply an additional quantity directly as a mineral fertiliser. According to [5], the use of these fertilisers in the second half of the 20th century led to an increase in rice yields. However, the excessive use of chemical fertilisers in irrigated rice production is beginning to threaten soil quality and, by extension, reduce yields [6].

In Côte d'Ivoire, rice has become the staple food for the vast majority of the population, both in urban centres and in rural areas [7]. Over the years, national rice consumption has increased from 30 kg/hbt/year in 1960 to 60 kg/hbt/year in 1992, reaching 68 kg/hbt/year in 2002 and over 85 kg/hbt/year in 2015 [8]. However, national production has fallen considerably despite the use of chemical fertilisers. In fact, [9] noted a drop in rice yield from around 7.3 to 6.0 $t \cdot ha^{-1}$ in the Natiokobadara irrigated perimeter (Korhogo in northern Ivory Coast) over the period 2007 to 2013. This drop in rice yield, which is related to the decline in soil fertility, is thought to be due to the excessive use of chemical fertilisers. [6] also reported a downward trend in irrigated rice yields from 3.2 to 2.6 $t \cdot ha^{-1}$ in the irrigated lowlands of Gagnoa (west-central Ivory Coast), probably due to the effects of chemical fertilisers.

The town of M'Bahiakro, the subject of this study, is no exception to this observation. In fact, M'Bahiakro is home to one of Côte d'Ivoire's vast irrigated rice development programmes, with an estimated 450 ha of irrigable land and significant water availability via the N'Zi river [10]. The development of the M'Bahiakro irrigated perimeter includes a 5 m high inflatable dam on the N'Zi with a water retention capacity of 2.76 million m^3, which will remove all constraints on rainfed rice production subject to climatic hazards [11]. However, a concern linked to the sustainability of this irrigated production system relates to the quality of the irrigation water and the production capacity of the soil over time. In fact, in the process of increasing rice production, inputs are often used in excess of nutrient exports to the plots, either through over-fertilization or poor assimilation of the fertiliser by the plants. This could lead to a deterioration in soil and water quality in the M'Bahiakro irrigated area. According to [12], around 0.1% of the inputs used by farmers reach the target organisms, with the remainder contaminating the surrounding environment. Thus, inputs that reach the soil can alter soil microbial diversity and microbial biomass, eventually leading to a disruption of the soil ecosystem and a loss of soil fertility [13]. In addition, excessive concentrations of inputs not recovered by crop plants end up either reaching groundwater through infiltration or watercourses, sometimes causing pollution and eutrophication problems [14].

Furthermore, an increase in the quantity of nutrients in the soil does not necessarily mean an increase in yield in the same proportion. According to Mitscherlich's law, when increasing doses of a fertiliser are applied to the soil, we find that as the quantities applied increase, the yield increases obtained become smaller and smaller ([15] [16]).

In this context, artificial intelligence methods using artificial neural networks (ANNs) offer an advantage in optimising nitrogenous fertilisers to meet the needs of rice in terms of water and soil planning and management. In the field of artificial intelligence, ANNs represent an organised set of interconnected neurons, enabling complex problems to be solved at lower cost. According to [17], ANNs develop self-learning models for exploring the neighbourhood of objects by looking for similarities between objects. In the field of agriculture, these models have the ability to compare the farmer's data with that from a set of similar cases in order to predict the optimal dosage of fertiliser and the associated yield, thus reducing the uncertainties in the fertilisation decision. The models run so far using RNA methods in several research studies have proved to be fairly informative for assessing yield and dosage in support of precision fertilisation ([18] [19]). According to this research, ANN models generate site-specific optimal doses and can verify the stability of these doses under various assumptions, such as climate change or a change in practice.

In our case, nitrogen doses should not only be adjusted as closely as possible to the needs of the rice crop, but should also be synchronised with the development cycle of the rice crop so that soil nitrogen fertilisation is carried out at the right time with the appropriate dose to meet the targeted objectives, thereby reducing soil and groundwater contamination. It is within this framework that this study was initiated, the main objective of which is to optimise the supply of nitrogen fertiliser in the face of the intensification of irrigated rice growing. The importance of this optimisation is to be able to maintain good rice production in the irrigated perimeter of M'Bahiakro while preserving the quality of the soil and water. To the best of our knowledge, no such work has been done to date on the M'Bahiakro irrigated perimeter in central-eastern Ivory Coast. In the course of this work, the general knowledge of the study area and the main theoretical aspects necessary for understanding neural networks.

In the optimization of nitrogen quantity, the processes are described. The optimum amount of nitrogen is then presented and discussed. A conclusion followed by an outlook will mark the end of the work.

2. Methodology

2.1. Location of the Irrigated Perimeter

The study site is an irrigated perimeter located in the Iffou region, in the department of M'Bahiakro in central-eastern Ivory Coast. It lies between longitudes 4018' and 4020' West and latitudes 7026' and 7031' North and includes the first hydro-agricultural inflatable dam in Ivory Coast [10] (**Figure 1**).

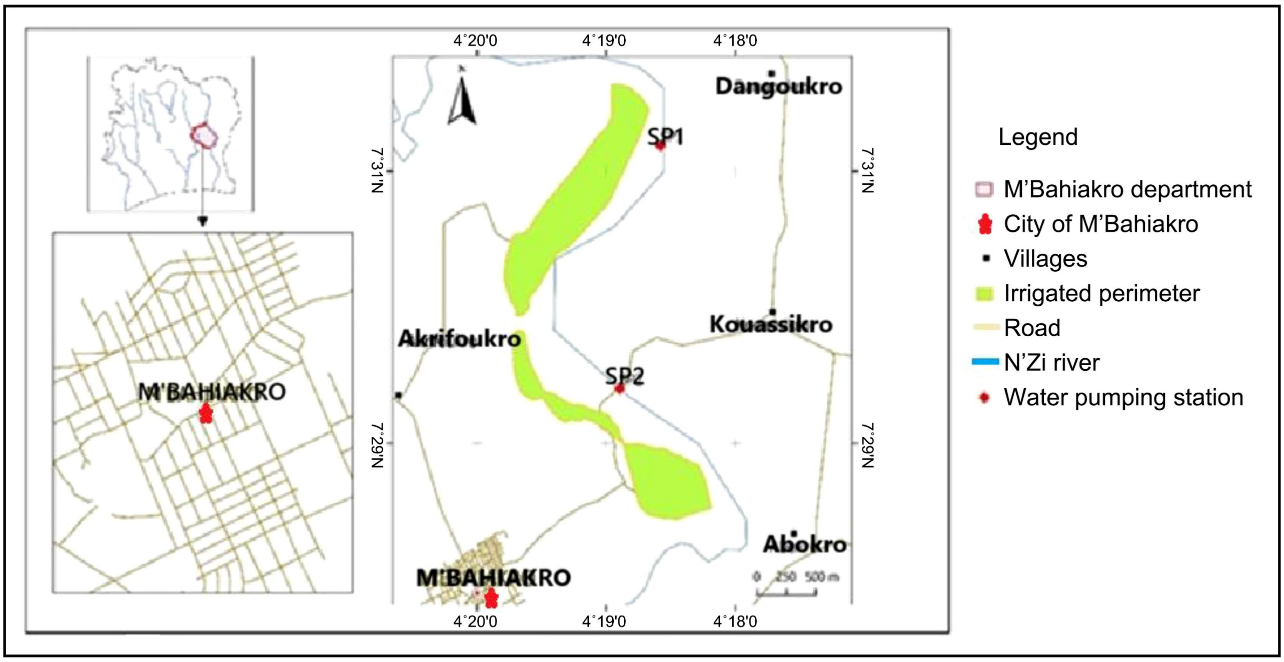


Figure 1. Presentation of the study area.

2.2. Description of the Irrigated Area

The rice-growing perimeter, divided into two sectors, covers an area of 450 ha and is 9 km long and 1 km wide [11]. The irrigation system is gravity-fed, with open canals and two water storage towers. The hydraulic districts are grouped into twelve zones or blocks, with six (06) blocks per sector and two (02) water pumping stations (**Figure 2**). The soils in the irrigated perimeter generally have a clay-loam texture (70%) with hydraulic conductivities varying between 10^{-4} and 10^{-3} m/s

[10]. The drainage porosity of the soil in the irrigated area varies between 40% and 60%. The highest soil porosity values are observed to the north of the irrigated perimeter, with a maximum average value of around 54%.

Figure 2. First water pumping station in the M'Bahiakro irrigated area.

2.3. Data Collection

2.3.1. Physico-Chemical Data for Irrigation Water in the Irrigated Perimeter

The physico-chemical parameters of the water, in particular pH, temperature (T˚C) and electrical conductivity (EC), were measured in situ using a HANNA type HI 9828 portable multiparameter calibrated according to the study season. At the same time, three water samples for nitrogen analysis (nitrites, nitrates, and ammonium) were taken the following day between five and six in the morning. The water samples were taken using three 500 mL polyethylene bottles immersed directly in the water of the dam by means of a rope. Each bottle was rinsed three times with the water to be sampled, then filled to the brim and hermetically sealed before being stored in a cooler. The bottles containing the water samples were stored at a temperature of 4˚C, as indicated by a thermometer in the cooler. This temperature of 4˚C maintained in the cooler with the aid of ice accumulators is useful for maintaining the stability of all the nitrogenous elements in the bottles. The preserved water samples were taken to the laboratory on the day of sampling. In the laboratory, nitrogen parameters were analyzed within twelve hours of sampling, using a flame molecular absorption spectrophotometer in accordance with [20].

2.3.2. Physico-Chemical Data from the Surface Layer of the Soil

Soil samples were taken using an auger at 20 points spread across the study area. The twenty samples were taken to a depth between 0 and 30 cm of soil, equivalent to the organic horizon of the soil. This is also the soil zone (0 - 30 cm) most affected by farming activities [2]. The collection and transport of the twenty soil samples and the analysis of their chemical parameters were carried out in accordance with the protocols defined by the French standards agency (AFNOR). The methods used to analyze the chemical parameters of the soil are summarized in **Table 1**. In addition, physical data relating to fine soil density (Dt), moisture at field capacity (θcc), moisture at the permanent wilting point (θpf), and the cultural coefficient (Kc) at the irrigated perimeter were determined in situ.

Table 1. Methods for analyzing soil parameters.

Parameters	Methods	Standards
Organic matter (OM)	Walkley and Black method	NF ISO 10694
Total nitrogen (Norg)	Kjeldahl digestion method	NF ISO 13878
pH	Electrometric method	NF ISO 10390
Cation exchange capacity (CEC)	Metso method	NF X31-130
Phosphorus (P)	Olsen method	NF ISO 11263
Potassium (K)	Fluoro-nitro perchloric method	NF X31-108

As part of this study, the values of the crop coefficient (Kc) were established in accordance with the recommendations of [21], as presented in FAO Irrigation and Drainage Paper No. 56. These coefficients take into account the different phenological stages of rice, distributed over twelve ten-day periods covering the entire vegetative cycle. Their variation allows for a more accurate estimation of water requirements at each stage of crop development and contributes to optimal irrigation planning (**Table 2**).

Table 2. Rice crop coefficients ([21]).

Decade	1	2	3	4	5	6	7	8	9	10	11	12
Kc	0.6	0.8	1.0	1.0	1.0	1.0	1.05	1.05	1.0	1.0	0.9	0.9

2.3.3. Rice Yield Data as a Function of Increasing Doses of Nitrogen

To obtain data on rice yields as a function of increasing doses of nitrogen, a 1-hectare area of the irrigated perimeter was set aside for rice experimentation with increasing doses of nitrogen. The experiment was carried out over 6 months (from August to February 2020) and consisted first of dividing the 1 hectare of the cleared area into four equal parts of 2500 m^2 each. Three parts of the 1 hectare each received 70 kg·N·ha^{-1}, 90 kg·N·ha^{-1} and 140 kg·N·ha^{-1} of nitrogen, and the fourth part, with no nitrogen applied, was chosen as the control according to **Figure 3** below. The doses applied were the result of a synthesis of the nitrogen doses applied to each experimental plot from the soil preparation phase through to the ripening of the rice plants. The rice yield results obtained following this experiment were reported for each quantity of nitrogen applied to the different plots.

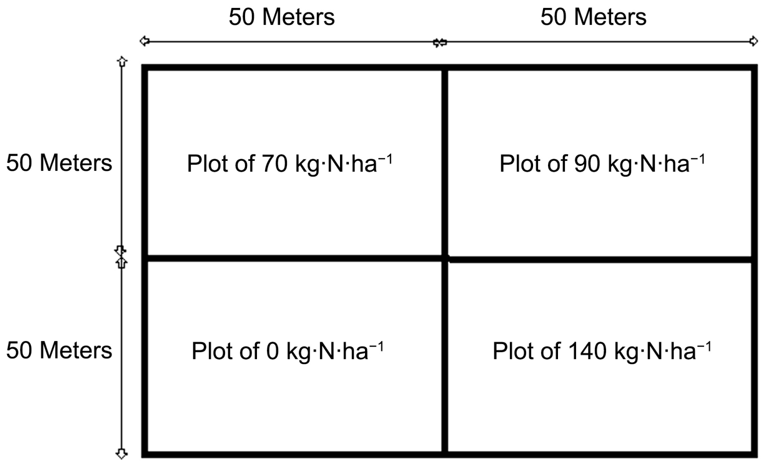


Figure 3. Rice experimentation with increasing doses of nitrogen.

2.4. Model Development Process

This section briefly describes artificial neural networks, in particular, the gradient back-propagation neural network (BPNN) used in this study.

2.4.1. Artificial Neural Networks

Artificial neural network methods are statistical tools used to estimate complex phenomena. Their specificity lies in their ability to estimate non-linear systems. These methods are particularly suitable for reproducing agricultural and hydrological processes and are therefore widely used in soil and water quality modelling ([17] [18] [22]). Among neural models, Multilayer Perceptron models are inspired by the architecture and functioning of the human brain, where the brain attempts to learn from signals coming from its environment in order to provide a response or action to be taken. This type of neural model is made up of interconnected neurons which, following an input signal represented by explanatory variables, produce an output signal, which can only be the variable being modelled. The choice of input variables is generally based on current knowledge of the processes involved. However, when the relationships between the different variables are not well known, a stepwise approach can be used. The stepwise (constructivist) approach consists of testing each of the variables individually in a reference network and combining the variables that obtain the best result for the chosen performance criterion [22].

Typically, the Multilayer Perceptron consists of three types of layers. Each of the variables in the input layer is connected to each of the neurons in the hidden layer(s), which are in turn connected to the neurons in the output layer(s). The connected neurons operate in a specific way and perform a weighted sum of the variables of the previous layer, following the free parameters (weights and biases) initialized beforehand with random values. Then, using a linear or non-linear activation function, they generate a result according to a well-defined algorithm [23].

2.4.2. Error Gradient Back-Propagation Algorithm

The Back Propagation Neural Network (BPNN) algorithm is the most widely used neural network method and determines the optimal weighting of features by iteratively modifying the hidden nodes and the learning rate while calculating the relative weights of the input variables between the neurons in the different layers of the neural network. In statistics, BPNNs are techniques known as classical gradient-based error correction algorithms. This principle forms the basis of gradient algorithm methods, which are effectively used in Multilayer Neural Networks (MLNs) [24]. The aim of the gradient algorithm is to converge iteratively towards an optimized configuration of weights and biases.

The weights and biases used in the model design are given by Equations (1) and (2).

$$w_{ij} = w_{ij} - \alpha\left(\frac{d_{(MES)}}{d_{w_{ij}}}\right), \tag{1}$$

$$b_{j0} = b_{j0} - \alpha\left(\frac{d_{(MES)}}{d_{b_{j0}}}\right), \tag{2}$$

where alpha (α) is the learning rate. The process of forward propagation, cost calculation, and backward propagation is repeated for a fixed number of iterations or until the cost function converges. MES is the mean squared error.

Furthermore, the optimal choice of network parameters, such as the number of layers and hidden nodes in a layer required to achieve a particular objective, is not easy to achieve. Clearly, there is no analytical tool for determining the ideal number of hidden neurons. In this situation, some authors have proposed a few rules. [25] suggest that, in the majority of applications, the optimal number of hidden neurons should be less than or equal to the number of inputs. [26] suggests that the following limit should not be exceeded, depending on the number of inputs according to Equation (3). However, these rules of thumb depend on the nature of the data used and the noise in the data. They cannot, therefore, be generalized. For the optimal choice of network parameters, it is therefore necessary to adopt a "trial-and-error" approach according to [22].

$$m \le 2\beta + 1, \tag{3}$$

where m is the number of hidden neurons and β is the number of input variables.

2.4.3. Learning BPNN Neural Model

In general, a neural network must be capable of performing a particular function in a given environment. This capability is acquired through the learning algorithm adopted by the neural model. This is the first phase in the life cycle of a neural network (passage from a state of ignorance to a state of knowledge). In the event of a change in function or external environment, this phase must be repeated to adapt the behavior of the neural network to the new parameters (transition between two states of knowledge). Learning a neural network involves subjecting the system to a set of iterative stimuli. By intuition, the network will become better and better informed about the input set. With each learning iteration (feeding the neural network with a stimulus), the neurons in the network adapt their processing to meet the needs of the targeted function [27].

In the majority of existing neural networks, the behavior of a neuron depends on the weights and the activation threshold associated with it. These values, known as the free parameters of the neural model, define the behavior of the neural network on all the inputs. It is therefore difficult, and even impossible, to predict the values of the free parameters during the design phase. Hence, the need to go through the learning phase. During this phase, the free parameters will be modified in order to reduce the error in the system's response to the examples presented at its input and to experience. After a certain number of learning iterations, the margin of error decreases so that it is tolerated by the system. At this point, the neural network no longer needs to learn. Consequently, we can say that the neural network is capable of analyzing real examples from its external environment as an expert. At this point, the decision phase, often called the recall phase, begins [28].

In our case, the neural network is trained by trial and error according to equations 5 and 6 defined above until the best intelligent model is obtained. The intelligent model obtained at the end of training was evaluated according to the performance criteria chosen, namely the coefficient of determination (R2, closer to 1) and the mean square error (MSE, smaller). These performance criteria (MSE and R2), described by Equations (4) and (6), present the best values for testing the performance of a model for optimizing the application of quantities of a chemical fertilizer.

$$\text{MSE} = \frac{\sum_{i=1}^{n}\left(N_{observed,i} - N_{simulated,i}\right)^2}{n}, \tag{4}$$

$$R = \sqrt{1 - \frac{\sum_{i=1}^{n}\left(N_{observed,i} - N_{simulated,i}\right)^2}{\sum_{i=1}^{n}\left(N_{observed,i} - \bar{N}\right)^2}}, \tag{5}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(N_{observed,i} - N_{simulated,i}\right)^2}{\sum_{i=1}^{n}\left(N_{observed,i} - \bar{N}\right)^2}, \tag{6}$$

where n is the number of measurement points, $N_{observed,i}$ is the observed value of nitrogen, $N_{simulated,i}$ is the predicted amount of nitrogen, and $\bar{N}$ is the mean value of $N_{observed,i}$.

The output value giving rise to the quantity of nitrogen supplied, depending respectively on the number of input nodes, hidden nodes, and output nodes, is given by Equation (7).

$$y_k = f_0\left[\sum_{i=1}^{m} W_{kj} \times f_n\left(\sum_{i=1}^{n} W_{ij} x_i + b_{j0}\right) + b_{k0}\right], \tag{7}$$

where y_k are the output values of the *k*th neuron at the nth iteration and x_i are the input values of the network, m and n are the numbers of neurons in the hidden and output layers respectively; W_{ij}, the connection weights between the input layer and the hidden layer; W_{jk}, the connection weights between the hidden layer and the output layer; b_{j0} and b_{k0} are respectively the bias of the *j*th hidden neuron and the bias of the kth output neuron; f_n and f_0 are respectively the transfer function of the hidden neuron and the output neuron.

For this purpose, the MATLAB simulation code was run to find the optimal model according to fixing criteria defined as follows: the maximum number of iterations fixed at 1000, the target error MSE and the minimum performance gradient fixed at 10^{-3} and 10^{-5}, respectively. Levenberg-Marquardt (LM) convergence was used, and logarithmic and linear sigmoid activation functions were used, respectively, for the hidden and output layers.

2.4.4. Database Construction

Nitrogen optimization was carried out following the simulation of rice yield as a function of increasing nitrogen doses. This simulation was carried out using all the data and physico-chemical parameters of the soil and irrigation water obtained during the rainy season (April). The justification for choosing this period was inspired by the work of [29] in France and [30] in Belgium, where the fertilizer requirements of rice would be relatively much more significant for their growth. The data set consists of fine soil density (dt, $g \cdot cm^{-3}$), moisture at field capacity (θcc, %), moisture at wilting point (θPF, %), organic nitrogen content of the layer studied (Norg, $kg \cdot ha^{-1}$), cation exchange capacity (CEC, $Cmol \cdot kg^{-1}$), physico-chemical soil parameters (pH, K, P, OM, TOC), rice cropping coefficient (Kc), rice yields as a function of increasing nitrogen doses (Rd, $kg \cdot ha^{-1}$), irrigation water parameters (SO_4^{2-}, Mg^{2+}, Ca^{2+}, Na^+, NH_4^+, $mg \cdot L^{-1}$), rice water requirement (Be, m^3). The input variables were selected using the focused Principal Component Analysis (fPCA) method under R 3.1.3 software. A correlation analysis was carried out in order to identify the variables in the dataset showing significant correlations with rice yields (Rd, $kg \cdot ha^{-1}$) for a selected significance threshold of $p < 0.05$. Thus, compared with the work of [22], parameters that were highly correlated ($1 \geq |r| > 0.5$) with yield (Rd) were retained as explanatory variables for the construction of the model.

Finally, in order to reduce the complexity of the network and accelerate its convergence, pre-processing was carried out, mainly concerning the normalization of input and target data, based on the Min-Max method. This involves transforming the values of the input parameters and the values of the data into the range 0 to 1 according to Equation (8), given by

$$\overline{X} = \frac{X - X_{\min}}{X_{\max} - X_{\min}}, \tag{8}$$

where $\overline{X}$: normalized value, X: raw analyzed value, $X_{\min}$: minimum value, and $X_{\max}$: maximum value.

3. Results

3.1. Physico-Chemical Parameters of Irrigation Water

Table 3 presents the physico-chemical characteristics of irrigation water from the N'Zi river for the July 2021 season at M'Bahiakro. Analysis of this table shows that the irrigation water is acidic and has an average temperature between 25˚C and 26˚C, with an average acidic pH value of around 6.82. Electrical conductivity (EC) remains below irrigation water standards (<3000 µs/cm). Apart from ammonium (NH_4^+), the irrigation water complies with irrigation standards for nitrite (NO_2^- < 3 mg/L) and nitrate (NO_3^- < 30 mg/L).

Table 3. Values of physicochemical parameters of irrigation water.

Physico-chemical parameters	Min.	Max.	Mean ± Sd	Standards [31]
pH	6.74	6.86	6.82 ± 0.07	6.5 - 8.4
T˚C	25.00	26.00	25.6 ± 1.04	35.0
EC (µs/cm)	129.20	155.60	142.1 ± 13.20	3000
NO_3^- (mg/L)	0.400	1.20	0.77 ± 0.06	30.0
NO_2^- (mg/L)	0.00	0.00	0 ± 0.01	3.0
NH_4^+ (mg/L)	0.81	2.60	1.57 ± 0.07	0.5

3.2. Chemical Parameters of the Surface Layer of the Soil (0 - 30 cm)

The results of analyses carried out on soil samples from the irrigated perimeter are shown in Table 4. The pH values obtained indicate slightly acidic soils with average levels ranging from 5.42 to 7.02, within the optimum growth range for rice species (5.5 ≤ pH ≤ 7.5). The average levels of total organic carbon (TOC) and assimilable phosphorus (P) were higher than the reference standards, with average values of 2.71% and 532.3 ppm, respectively. The average levels of organic matter (OM) (4.63%), cation exchange capacity (CEC) (12.93 Cmol/kg), and potassium (K) (1.17 Cmol/kg) are within the normative range. Furthermore, in all the soil samples studied, the average nitrogen content (0.07%) is generally low compared with the reference range, which is between 0.2% and 0.25%. Nitrogen supplementation would therefore be essential for improving rice production in the M'Bahiakro irrigated perimeter.

Table 4. Values of soil physico-chemical parameters.

Physico-chemical parameters	Min.	Max.	Mean ± Sd	Standards according to [32]
pH	5.42	7.02	6.38 ± 0.46	5.5 - 7.5
K (Cmol/kg)	0.78	1.68	1.17 ± 0.28	0.15 - 0.25
OM (%)	3.89	5.34	4.63 ± 0.48	3.6 - 6.5
CEC (Cmol/kg)	9.23	18.26	12.93 ± 3.44	10 - 25
COT (%)	2.26	3.1	2.71 ± 0.29	1.26 - 2.5
Norg (%)	0.05	0.08	0.07 ± 0.01	0.2 - 0.25
K (ppm)	409	721	532.30 ± 97.48	134 - 179

3.3. Physical Parameters of the Surface Layer of the Soil (0 - 30 cm)

The results of the physical soil parameters used in this study are summarized in Table 5. At the perimeter, the density of fine soil (Dt) between 0 and 30 cm depth averaged 70%. Moisture at field capacity and moisture at the point of permanent wilting were 17.57% and 30.6%, respectively. The crop coefficient for the irrigated perimeter averaged 0.8.

Table 5. Parameters of the soil layer (0 - 30 cm).

Parameters	Details	Mean values
Dt (%)	Density of fine soil	70.00
θcc (%)	Field capacity humidity	17.57
θpf (%)	Humidity at the wilting point	30.60
Kc	Rice crop coefficient	0.80

3.4. Rice Yields as a Function of Increasing Nitrogen Doses

The yields obtained from rice production experiments at M'Bahiakro are summarized in Table 6 below. The application of nitrogen doses to irrigated rice crops in M'Bahiakro indicates an average yield of around 4406 kg·ha^{-1} for increasing doses of nitrogen varying between 70 kg·ha^{-1} and 140 kg·ha^{-1}. The yield responses of rice following application of doses of 70 kg·ha^{-1}, 90 kg·ha^{-1}, and 140 kg·ha^{-1} were 4150 kg·ha^{-1}, 4500 kg·ha^{-1}, and 4570 kg·ha^{-1}, respectively.

Table 6. Rice yields as a function of increasing nitrogen doses.

Nitrogen doses applied (kg·ha^{-1})	Rice yield (kg·ha^{-1})
70	4150
90	4500
140	4570

3.5. Choice of Variables

The choice of input variables for the simulation model of the response of rice to increasing doses of nitrogen was made using the fPCA method (**Figure 4**). This method was used to highlight the relationships between rice yields (Rd) and the physico-chemical parameters of the water and soil studied. **Figure 4** thus shows that Rd is significantly negatively associated with K, P, Norg, OM, θcc ($-1 > r \geq -0.8$) and positively with CEC, Kc ($1 > r \geq 0.8$). These significant correlations reveal the contribution of these different physico-chemical parameters (K, P, Norg, OM, θpf, CEC and Kc) to rice production yield at M'Bahiakro. These parameters are therefore used to design the simulation model.

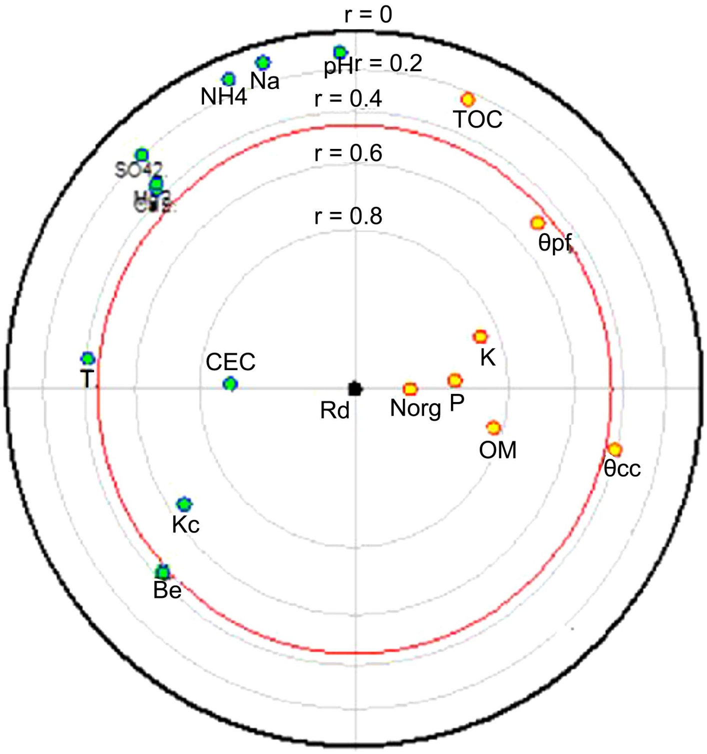


Figure 4. Correlation between explanatory variables and rice yield.

Yellow dots indicate negative correlation values with the dependent variable in the center; green dots indicate positive correlation values with the dependent variable in the center. The red circle indicates the significance threshold ($p < 0.05$); the points inside indicate significant correlations with the score of interest located at the center of the focused PCA.

3.6. Architecture and Performance of the BPNN Model

The BPNN neural model specified by the constructive approach, with seven (7) input variables, one (1) hidden layer of six (6) neurons, and rice yield as the only (1) output variable, is illustrated in **Figure 5**. **Figure 5** defines the architecture of the BPNN model for the season under study. This architecture also shows the weights (wij) generated on the network arrows and the bias (bj) corresponding to variable i and neuron j in the model (Table 7). Minimum values of these free parameters (weights, bias) tend to make the models more coherent and efficient. The weights of these different parameters towards the hidden layer vary between −2.15 and 3.20. From the hidden layer to the output layer, they vary between −1.78 and 2.27. The table also highlights the biases at the level of the six neurons in the hidden layer, which are between −2.77 and 2.72, and the bias at the level of the neuron in the output layer, which is around 0.753. The results of these free parameters were used to simulate rice yields.

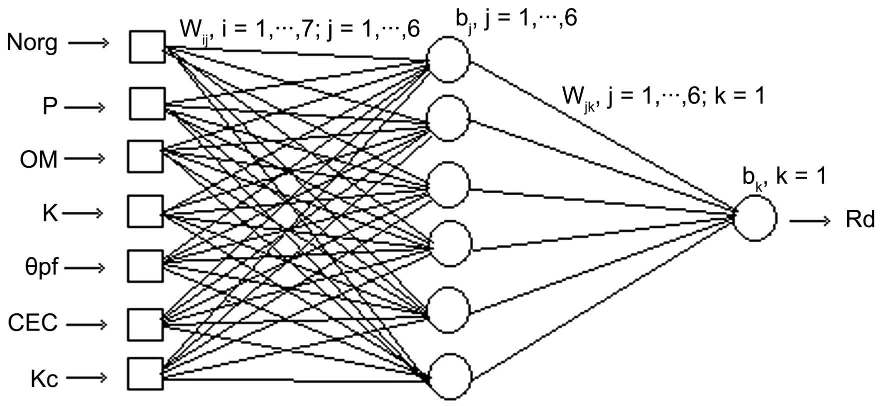
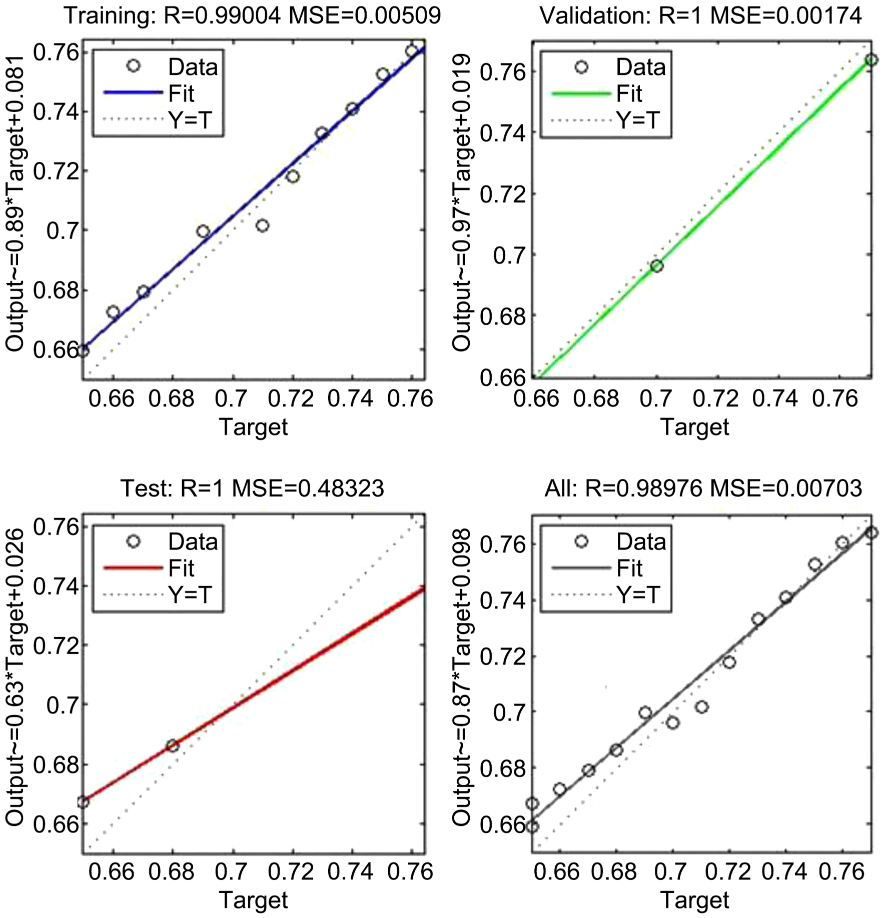


Figure 5. Architecture of the BPNN model developed.

Table 7. Weights and biases of the final training of the BPNN model.

Weight (w_{ij}) of input parameters in the hidden layer						
$w_{1,1} = -2.1411$	$w_{2,1} = -0.5830$	$w_{3,1} = -0.6873$	$w_{4,1} = 0.3036$	$w_{5,1} = 1.4505$	$w_{6,1} = -1.7453$	$w_{7,1} = 0.1412$
$w_{1,2} = 0.8336$	$w_{2,2} = -0.8515$	$w_{3,2} = 2.1763$	$w_{4,2} = 0.6385$	$w_{5,2} = -2.7559$	$w_{6,2} = -1.7348$	$w_{7,2} = -0.3839$
$w_{1,3} = 2.9713$	$w_{2,3} = -0.1183$	$w_{3,3} = -0.0134$	$w_{4,3} = 0.1927$	$w_{5,3} = -0.5977$	$w_{6,3} = 0.6710$	$w_{7,3} = -1.1590$
$w_{1,4} = -0.5140$	$w_{2,4} = 1.2520$	$w_{3,4} = -0.6916$	$w_{4,4} = 2.0591$	$w_{5,4} = 1.6958$	$w_{6,4} = 1.7783$	$w_{7,4} = 0.4111$
$w_{1,5} = 0.3349$	$w_{2,5} = 0.5399$	$w_{3,5} = 0.7842$	$w_{4,5} = 1.3813$	$w_{5,5} = -0.9460$	$w_{6,5} = -0.1066$	$w_{7,5} = -0.3485$
$w_{1,6} = 3.1919$	$w_{2,6} = -1.4355$	$w_{3,6} = -2.1736$	$w_{4,6} = -2.1377$	$w_{6,6} = 1.4527$	$w_{6,6} = 1.5430$	$w_{7,6} = 0.4014$
Weight (w_{jk}) between hidden neurons and the output layer						
$w_{1,1} = 1.3010$	$w_{2,1} = 2.2671$	$w_{3,1} = -1.5012$	$w_{4,1} = -1.7745$	$w_{5,1} = 2.1580$	$w_{6,1} = 2.4241$	$w_{7,1} = 1.6418$
Bias (b_j) in hidden neurons						
$b_1 = 2.7104$	$b_2 = -2.5734$	$b_3 = -1.1307$	$b_4 = -2.7694$	$b_5 = -0.4560$	$b_6 = -0.1230$	$b_7 = 0.6165$
Bias (b_k) in the output layer						
$b = 0.7525$						

The indices relating to the R and MSE values obtained during the learning phase of the BPNN model (**Figure 6**) indicate the performance of the proposed model. Analysis of the results obtained shows that, for the season studied, the R coefficients are relatively high and greater than 0.90. In addition, the MSE values obtained for this BPNN model are clearly satisfactory (MSE around 0.001 fixed). According to the performance criteria, the BPNN model developed with the input variables Norg, P, OM, K, CEC, *θ*pf, and Kc performs well with R and MSE values ranging from 90% to 100% and from 0.48323 to 0.00174, respectively.


Training: R=0.99004 MSE=0.00509

Validation: R=1 MSE=0.00174

Test: R=1 MSE=0.48323

All: R=0.98976 MSE=0.00703

Figure 6. BPNN model learning phase.

3.7. Simulation of Rice Response

Table 8 shows the observed and simulated rice yields for the BPNN model developed. The simulated yields are obtained by varying the nitrogen doses in the model while setting the values of the other input parameters and the free parameters of the model following the learning process. These yields represent the response of the rice to increasing doses of nitrogen.

The difference between the observed and simulated yields is relatively small in relation to the MSE error values close to zero. In general, 80% of the MSE values obtained are satisfactory, with values relatively lower than 0.5. The architecture of the BPNN model developed would therefore confirm the performance of the 7-6-1 configuration neural network in calculating rice yields, with good superposition of the values observed experimentally and those simulated overall, with the exception of the yield obtained for 0 kg·ha^{-1} of Nitrogen (MSE = 0.687 > 0.5). Furthermore, the association between observed and simulated rice yields given by the linear regression line (**Figure 7**) indicates the reliability of the model developed, with a high coefficient of determination R2 of the order of 98%.

Table 8. Rice yields from the BPNN model.

Nitrogen doses applied (kg·N·ha^{-1})	Rice yield Observed (kg·ha^{-1})	Predicted rice yield (kg·ha^{-1})	MSE
0	-	454.5524	0.6869632*
70	4250	3989.11932	0.1010789**
90	4500	4412.79346	0.0184000***
140	4570	4624	0.0765579****

Error ≤ 0.05 (Excellent), 0.05 < Error ≤ 0.5 (Good), Error > 0.5 (Poor).

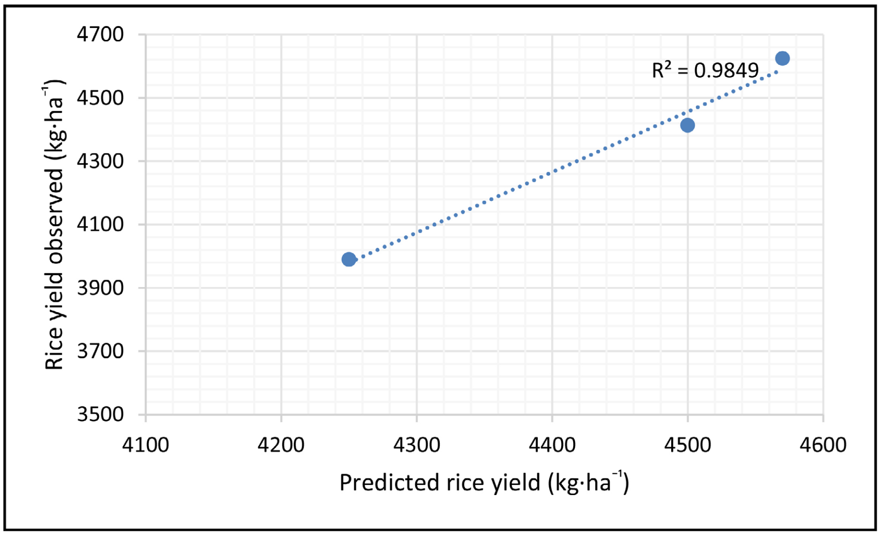


Figure 7. Correlation diagram.

3.8. Nitrogen Optimization

The quadratic regression from the BPNN model illustrates the response of rice to increasing doses of nitrogen (**Figure 8**). An increase in yield is observed, followed by a stabilization of yield with increasing doses of nitrogen. In the absence of nitrogen, the rice yield is estimated at 454 kg·ha^{-1}. This production increases with an application of 70 kg·ha^{-1} of nitrogen and would reach a yield of around 3989 kg·ha^{-1}. Beyond the dose of 70 kg·N·ha^{-1} of nitrogen, production would stabilize at around 4500 kg·ha^{-1} in terms of yield, whatever the dose of nitrogen applied. Furthermore, the derivative of the equation $y = -0.3364x^2 + 79.405x$ ($y' = -0.6728x$

+ 79.405) cancels out at a value of 118. The biophysical recommendation of nitrogen would then be capped at 118 kg·N·ha^{-1} nitrogen in the irrigated plots of M'Bahiakro.

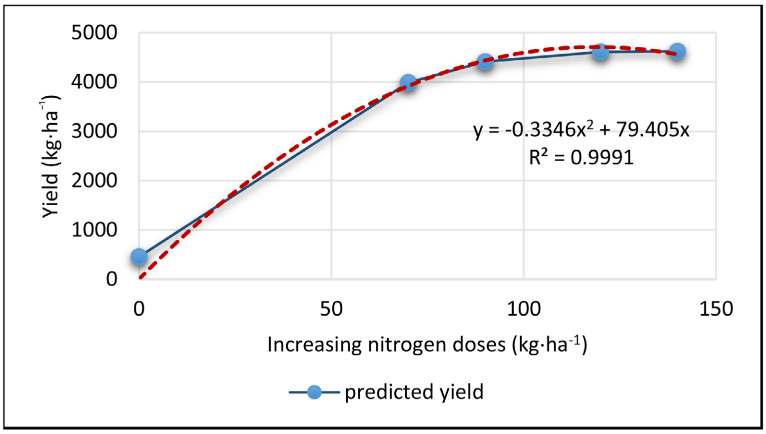


Figure 8. Nitrogen optimization.

4. Discussion

Nitrogen (N) is an essential nutrient for rice growth and development. Due to the low nitrogen content in the cultivated soils of the M'Bahiakro rice-growing area [10], the application of nitrogen fertilizers has become a necessary practice to increase yields. However, rational management of these inputs is required to balance agricultural productivity with environmental sustainability. In this context, a comparative analysis of artificial neural networks, according to [22], revealed that the best results were obtained with an architecture comprising six neurons in the hidden layer, tailored to the agroecological conditions of M'Bahiakro. The developed BPNN (Backpropagation Neural Network) model showed promising performance, with a mean squared error (MSE) of approximately 0.001, a correlation coefficient ($R \geq 0.90$), and a high coefficient of determination ($R^2 = 0.98$).

The effect of removing each input variable on the model's performance was also analyzed using the correlation index (r) within a targeted principal component analysis (PCA). This analysis indicated that rice yield (Rd) is associated with seven physicochemical parameters: K, P, Norg, OM, θpf, CEC, and Kc. Including these variables led to a satisfactory nitrogen optimization model. Compared to other studies, the nitrogen mineralization model in prairie soil proposed by [33], which includes five input variables (clay content, C, N, P, and pH), showed an R^2 of 0.78. This model appears less effective, as it considers fewer variables than the seven used in our case.

Numerous studies have demonstrated the impact of selected parameters on crop performance, particularly organic matter fractions ([34] [35]), organic nitrogen stock [36], and soil moisture [37]. These variables, which are relatively easy to obtain, provide accurate indications of the optimal nitrogen quantity to apply in the irrigated area of M'Bahiakro. The model's performance confirms its ability to accurately predict nitrogen requirements, paving the way for precise fertilizer optimization in irrigated rice systems. Yields varied significantly depending on the nitrogen application levels. They increased with the amount of nitrogen applied, but the yield gain plateaued beyond 118 kg·N·ha^{-1}. These results align with those of [30], who showed that residual soil nitrogen at harvest remains acceptable at 55 kg·N·ha^{-1} but becomes excessive beyond 152 kg·N·ha^{-1}. The work of [38], using a random forest regression algorithm, also identified an average optimal economic dose of 150 kg·N·ha^{-1} for most canola production scenarios during the test year. In our case, nitrogen efficiency decreases when the applied dose exceeds the optimal threshold of 118 kg·ha^{-1}.

However, several recent studies present contrasting or complementary findings. [39] demonstrated that fertilization ranging from 250 to 350 kg·ha^{-1} can reduce yield losses under heat stress by improving leaf hydraulic conductivity. Similarly, [40] reported a significant increase in yield and quality of hybrid rice with a combined nitrogen/potassium application up to 225 kg·ha^{-1}. Furthermore, [41] showed that differentiated nitrogen inputs, even beyond 150 kg·ha^{-1}, promote the formation of quality tillers and grain filling. These observations are reinforced by an analysis by [42], which indicates that innovative management strategies such as deep fertilization, slow-release fertilizers, or targeted split applications can maintain or even improve yields, even with doses exceeding 150 kg·ha^{-1}. Thus, although 118 kg·ha^{-1} appears to be the optimal dose under the agroecological conditions of M'Bahiakro, the literature suggests that higher doses may be beneficial in certain contexts, depending on pedoclimatic factors, cultivation techniques, rice genotypes, and nitrogen application methods.

Furthermore, although the nitrogen requirement prediction model developed in this study demonstrated high performance under the agroecological conditions of M'Bahiakro, its effectiveness can be significantly influenced by external climatic factors. Indeed, interannual climate variability and extreme events (heat waves, droughts, heavy rainfall) simultaneously affect soil nitrogen dynamics and rice physiology, which can lead to a divergence between the theoretical optimal dose and the actual agronomic response of crops. The work of [10], carried out on the irrigated perimeter of M'Bahiakro, highlighted a low nitrogen concentration during the dry season, compared to the rainy season, when levels can be significantly higher. This difference can be explained by reduced mineralization activity during the dry season, when soil samples were taken (December 2018). The study of mineralization dynamics showed that after a phase of microbial inactivity induced by dry conditions, the first rains strongly stimulate microbial processes. This reactivation results in significant mineralization flows, leading to a significant increase in the available nitrogen content in the soil ([43] [44]). This phenomenon clearly illustrates the impact of climate variability on nitrogen dynamics. From this perspective, the nitrogen requirement prediction model could be improved by integrating dynamic climate variables. Adjusting doses according to the seasons and weather forecasts would make it possible to anticipate losses linked to climatic hazards and optimize fertilization efficiency. Such an approach would strengthen the resilience of irrigated rice systems to environmental fluctuations.

5. Conclusions

This study established an optimal nitrogen dose of 118 kg/ha for rice cultivation in the irrigated perimeter of M'Bahiakro, based on a machine learning model of the BPNN type (Backpropagation Neural Network). The model incorporates seven key input variables (K, P, Norg, OM, θpf, CEC, and Kc), a hidden layer composed of six neurons, and a single-neuron output layer. It demonstrated robustness and efficiency, outperforming conventional approaches in agronomic prediction.

The results highlight the potential of intelligent modeling tools for more precise and environmentally responsive nutrient management. Beyond its scientific contribution, this advancement offers concrete prospects for agricultural practice and input governance. It serves as a strategic reference for local policymakers engaged in developing evidence-based agricultural policies, while providing a solid technical foundation for extension services to guide farmers toward more rational fertilization practices.

For producers, the optimal dose of 118 kg/ha represents a practical benchmark for adjusting cultivation practices to optimize yields, reduce input costs, and minimize environmental impacts. The modeling approach based on machine learning has proven to be a relevant strategy for optimized nutrient management, contributing to sustainable agriculture that is more resilient to environmentally induced abiotic stresses.

However, integrating climatic data into BPNN-type neural networks could enhance the model's robustness and adaptability in the face of climatic uncertainties. The development of hybrid models combining artificial intelligence, agroclimatic sensors, and spatial analysis would not only improve the accuracy of nitrogen fertilization recommendations but also strengthen the role of these tools as decision-support instruments. Such an approach would promote more proactive, sustainable, and climate-resilient input management.

Conflicts of Interest

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

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Fragipan Remediation Using Annual Ryegrass Cover Crop

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Abstract

Field experiments were conducted involving annual ryegrass with and without several surface-applied amendments. The results suggest a significant degradation effect of annual ryegrass on the fragipan horizon. Annual ryegrass (ARG) used as a cover crop was found to degrade previously compacted sections of fragipan, with its roots penetrating through the upper part of the fragipan by first exploring inter-prismatic gray veins and eventually invading adjacent compacted zones, thus creating avenues for additional crop root penetration and utilization of additional water and nutrients. The fragipan structure degradation increased with each (ARG) planting season, resulting in an increasingly deeper soil suitable for crop utilization. Significant crop yield responses of soybean and corn to these soil matrix improvements were observed after the fourth year of using (ARG) as a cover crop and continued to increase yearly thereafter. The yearly addition of sodium, potassium or calcium nitrate fertilizer, or humate additive, did not result in a significant synergistic crop yield effect, but the observed trend in rooting depth warrants further study.

Keywords

Fragipan Soil Horizons, Plant Root Restriction, Degradation of Compacted Sections, Effect of Ryegrass, Root Penetration, Effect of $CaNO_3$, $NaNO_3$, KNO_3, Lime and Humate Surface-Applied Amendments, Soybean-Ryegrass and Corn-Ryegrass Rotations

1. Introduction

The fragipan is a naturally occurring restrictive soil horizon that virtually stops water movement and root growth through the soil. Fragipans occur in more than 20 million hectares in the United States [1]. They are commonly located 45 - 60 cm below the soil surface. The dense nature of these layers is due to cementation and binding of the soil particles with a silicate-rich amorphous aluminosilicate, sometimes in association with iron (Fe) or manganese (Mn). These binding agents seal the pores and pack the soil particles close together [2].

Fragipans usually reduce plant available water holding potential to about one-half of that observed in many other crop producing soils [3]-[6]. They commonly cause over-saturation with water above the fragipan layer during the winter and spring, which results in adverse soil conditions for the crops growing during this time [7]. However, by far the biggest production problem for corn and soybeans grown on these soils, which under normal soil conditions can extend their rooting systems below 100 cm, is the limited water holding capacity and nutrient uptake at critical growth stages. Plant water and nutrient deficits at reproductive and grain-fill periods may reduce yields by at least 20% - 25% [8]-[10].

Although there are many studies on the nature and characteristics of fragipans, there have been very few attempts to find methods that would accelerate fragipan degradation and remediation [7]-[12]. Karathanasis *et al.* [13] used a slaking method and found 3 amendments in addition to annual ryegrass (ARG) that could degrade fragipan clods. Also, Matocha *et al.* [14] reported reduced bulk densities and tensile strengths in fragipan aggregate matrices in fields with a ryegrass (ARG) cover crop compared to those without cover. Murdock *et al.* [10] used an *in-situ* greenhouse method, using intact soil columns, found annual ryegrass (ARG), festulolium and 4 additional amendments that could partially degrade and remediate the fragipan matrix. Previous greenhouse trials with intact undisturbed columns in greenhouse experiments proved that ARG could grow roots into compacted fragipan sections and degrade root-restrictive zones with multiple plantings [15].

In this research approach, ARG was planted in field trials as a cover crop in rotation with a corn and soybean crop. Different past proven amendments [10]-[13] were added to the soil surface to evaluate any possible synergistic effect when used in combination with ARG.

The purpose of this study was to determine the effectiveness and rate of change of ARG and other surface-applied amendments to degrade the fragipan and increase the crop-accessible rooting volume of the soil and its productivity.

2. Materials and Methods

Three studies were established from 2013 to 2015 and were active for 6 to 8 years at the University of Kentucky Research and Education Center in Caldwell County at Princeton, Kentucky. The climate is humid subtropical with about 125 cm of annual rainfall. The studies were conducted on a Zanesville silt loam fragipan soil (fine-silty, mixed, active mesic, oxyaquic fragiudalf) with a 0% - 2% slope. The site was selected because it has a strongly developed fragipan horizon beginning at about 60 cm below the soil surface and is about 50 cm thick. All plot areas were soil sampled yearly to a depth of 15 cm, and fertilizers and lime were added according to the University of Kentucky recommendations found in AGR-1 [16] for the crops grown that year. The organic matter content ranged from 2.6% to 3.0%. Corn (Zea mays) and soybean (Glycine max) were the warm season grain crops and were no-till planted in early May about 4 cm deep at the rate of 75K seeds/ha for corn and 370K seeds/ha for soybeans. The ARG cover crop was no-till planted about the last week in September one cm deep at the rate of 22 kg/ha. The Bounty variety was used the first 3 years, with Marshall being used the remaining years. Weeds were controlled in corn and soybean by preemergent herbicides and multiple in-season applications of glyphosate. ARG was killed in the spring using glyphosate when the ARG was 25 to 30 cm in height and when the weather conditions favored maximum herbicide effectiveness.

The yield response with and without annual ryegrass was analyzed using the Proc GLM (General Linear Modeling) method in SAS Studio (SAS 9.4 Web Browser) (SAS Institute Inc., Cary, NC, USA). Mean separation was performed using the Tukey-Kramer method. The response of soil properties to annual ryegrass treatment was analyzed using a randomized block design with a Mixed procedure in SAS Studio.

The depth to the fragipan in the plot areas was determined prior to the experimental trials using a soil penetrometer, with an average of 27 readings per plot. A 105 cm long hydraulic probe with a 5 cm diameter was used in succeeding years to more closely observe and measure root growth and degradation of the fragipan after the treatments were applied. The plot size in all three trials was 3 m wide and 12 m long. The table below shows some of the measured variability in the depth to the fragipan found in a randomly selected 4.5 m transect within the plot area.

Table 1. Variability of depth to the fragipan from the soil surface along a (short) 4.5-meter transect.

Transect Distance (M)	Fragipan Depth (cm)	Transect Distance (M)	Fragipan Depth (cm)	Transect Distance (M)	Fragipan Depth (cm)
0	60	1.65	57.5	3.30	57.5
0.15	55	1.80	50.0	3.45	67.5
0.30	52.5	1.95	60.0	3.60	50.0
0.45	42.5	2.10	52.5	3.75	60.0
0.60	55.0	2.25	45.0	3.90	65.0
0.75	52.5	2.40	50.0	4.05	62.5
0.90	55.0	2.55	55.0	4.20	57.5
1.05	50.0	2.70	57.5	4.35	65.0
1.20	50.0	2.85	67.5	4.50	67.5
1.35	52.5	3.00	80.0		
1.50	52.5	3.15	75.0		

Range of Depth – 42.5 cm to 80 cm; Average of All Readings – 56.6 cm.

Table 1 shows the significant variance in fragipan depth from the soil surface that occurs naturally on an uneroded soil. The deepest fragipan depth (80 cm) was nearly twice the depth of the shallowest site (42 cm). Measurements to the fragipan depth along a transect of greater length (61 m), also within the plot area, revealed an even greater range of 0.42 m - 0.95 m. The deeper readings tended to occur in clusters. This natural variability should definitely be noted because it will require greater treatment differences to achieve statistical significance for measurements of yield, rooting depths, and depth of fragipan degradation.

Experiment 1: Effect of ARG Cover Crop on Fragipan Degradation and Rooting Depth into the Fragipan for 8 Years

Annual Ryegrass (ARG) has been found to cause matrix degradation in laboratory and greenhouse experiments [9] [10] [13]-[15]. There are no reported scientific studies on the degradation of the fragipan in field trials using ARG as a cover crop. Soil health improvements have been reported on some individual fields [12]. In this scientific study, the main treatment, (ARG), was no-till planted and grown as a cover crop each year prior to the no-till planting of either corn or soybeans. Details of the method are found in the Materials and Methods section. A no cover crop comparison was exactly the same without a cover crop. The study had 5 replications and the treatments were repeated each year for 8 years. Cores (3) were taken from each plot within 5 and 8 years of treatment to observe and record any fragipan degradation, depth to unaltered fragipan, and rooting depth.

Table 2 shows the average depth to the unaltered, consolidated fragipan at the beginning of the trial and 5 and 8 treatment years later. The average depth range of the unaltered fragipan in the untreated control for each of the 3 measurement years is common due to the natural variability as shown in **Table 1**. The average depth to the fragipan in the ARG-treated plots increased with each year increment, indicating a degradation of the fragipan by the ARG with each treatment year. The measured rate of degradation during the first 5 years was 1.4 cm per year. However, it increased to 3 cm per year over the last 3 years. This increased rate of degradation with increased time was found in other unpublished studies.

Table 2. Average depth to non-degraded fragipan with and without ARG growth over a period of 8 years at three different time periods.

Years of Treatment	Average Rooting and Non-Degraded Fragipan Depth (cm)		
	Treatment		
	ARG	None	P
0	56 a	56 a	NS (0.05)
5	63 b	54 a	0.05
8	72 b	59 a	0.05

Table 3 shows the average minimum and maximum depth to the non-degraded fragipan and rooting in the ARG and non-ARG treatments. Three cores were taken

in each plot of the 5 replications for a total of 15 cores. The first measurements were taken prior to beginning ARG treatments. The measure of variability (difference) at the (0 year) trial would be due to the natural variability in depth to the fragipan. The increase in difference (53 cm) associated with the ARG treatments would be due to the uneven degradation of the fragipan by the ARG. The increased variability in depth to the fragipan is probably caused by increased and uneven rooting depth into the inter-prismatic gray veins of the fragipan due to more rapid disintegration (**Figure 1**). Previous research by Murdock *et al.* [15] found deeper and more extensive changes in the inter-prismatic gray veins that were associated with deeper and more extensive rooting. Two of the 15 measurements (13%) had maximum depths greater than the probe depth (105 cm) in the 8-year measurements. At these 2 sites, the soil found in the last few centimeters was of silt loam texture and subsoil characteristics and color, with no fragipan prism fragments, indicating the fragipan at these 2 locations may have been completely degraded. Therefore, the variability of the measurements after 8 years is greater than the 53 cm shown, since the depth of the soil profile without the fragipan is unknown.

Table 3. Maximum and minimum depths to the non-degraded fragipan and rooting depth at three different times over eight years with and without an ARG cover crop in 30 measurements over five replications.

Treatment Year	Rooting and Non-Degraded Fragipan Depth (cm)					
	Treatment					
	ARG			None		
	Minimum	Maximum	Difference	Minimum	Maximum	Difference
0	40-	80	40	42-	85	43
5	42-	95	53	40-	82	42
8	52-	105*+	53+	47-	90	43

No fragipan was found at two core sites, and 105 was the maximum length of the probe.

Figure 1. An exposed fragipan soil showing the inter-prismatic gray veins that separate the consolidated, impermeable prismatic matrix.

Table 4 shows the effect of the cumulative degradation of the fragipan over the 6 years on the yearly yields. Soybeans were grown most years due to the ease of management. However, corn was rotated into the summer crop position occasionally. There were two replicated comparisons within the same approximately 4 ha field. Summer crops were not planted or harvested the 7th year due to a tornado that destroyed the infrastructure and equipment at the Research Center (UKREC). Fall planting of the ARG was able to continue for two additional years.

Table 4. Yield of soybeans and corn with and without annual ryegrass (ARG) cover crop with an increasing number of yearly treatments during the first 6 years.

Years of Treatment	Crop	Yield		P	Difference (%)
		ARG	None		
1	Soybean	64.1	63.8	NS	+0.5
1	Soybean	62.4	62.0	NS	+0.6
1					Average +0.6
2	Soybean	45.8	50.2	NS	−8.8
2	Soybean	68.2	65.5	NS	+4.1
2					Average −2.4
3	Corn	139.1	142.9	NS	−2.7
3	Soybean	60.6	58.3	NS	+3.9
3					Average +1.2
4	Soybean	50.4	47.2	NS	+6.8
4	Soybean	44.2	42.3	NS	+4.5
					Average +5.7
5	Soybean	60.8	57.6	NS	+5.6
5	Soybean	53.9a	47.9b	0.08	+12.5
5					Average +9.1
6	Soybean	49.1	46.3	NS	+6.6
6	Soybean	66.2a	58.7b	0.02	+12.8
6					Average +9.4

The amount of yield in any circumstance is dependent on many contributing factors such as rainfall, temperature, diseases, insects, management capabilities, and others. Depth of rooting is a significant factor, especially in rainfed conditions. Large differences in rooting depth often overshadow the other contributing factors due to higher amounts of plant-available water. This effect is evident in Table 4. There are few differences in yields between treatments with ARG as a cover crop and no cover crop in the first 3 years. There was a small numerical separation in the 4th year. Yield differences in years five and six demonstrate the increased yield potential of the deeper rooting depth. The change in rooting depth is shown in **Table 2**. The fragipan, although deeper, is still present throughout all the plots with the exception of a small area in 2 plots found in the 8th year. The potential yield increase after a drastic degradation of the fragipan is reported in AGR 250 [9]. Two on-farm measurements where ARG has been grown as a cover crop for 10 to 15 years resulted in yield increases between 25% and 60%, depending on the year and crop. In both cases, the rooting depth had increased from about 60 cm to the 1 to 1.2 meter range (unpublished data).

As seen in **Table 5**, the ARG cover crop significantly increased the organic matter in the top 15 cm of the soil. The small numerical increases below 15 cm were not significant and indicate that the additional rooting mass of the ARG cover crop was much less at deeper soil depths, but it was effective in breaking down parts of the compacted fragipan matrix.

Measurements of phosphorus, potassium, calcium, and magnesium made at the same depths as the organic matter in **Table 5** also indicate no accumulation of these nutrients above that found with no cover crop treatment.

Table 5. Effect of 7 years of ARG cover crop on the soil organic matter content at increasing depths.

Depth (cm)	Organic Matter (5)		
	ARG	None	P*
0 - 15	3.01b	2.87a	0.05
15 - 30	2.75a	2.21a	NS
30 - 45	2.00a	1.99a	NS
45 - 60	1.93a	1.93a	NS

*Significance at 0.05 level or less.

Experiment 2: Effect on ARG and Some Common Agricultural Fertilizers on Fragipan Degradation in Field Trials after Seven Growing Cycles Using ARG as a Cover Crop with a Soybean or Corn Rotation

ARG, sodium nitrate ($NaNO_3$), and materials that raise pH, such as finely ground calcium carbonate, have been reported to partially degrade the fragipan when placed in direct contact with the fragipan [9] [10] or when $NaNO_3$ is placed on the soil surface with a growing ARG cover crop in the greenhouse [15]. One objective of this experiment was to determine any synergistic effects of these fertilizers on changing the brittle fragipan matrix when placed on the soil surface while growing ARG as a cover crop and a corn or soybean summer crop under field conditions. Another objective was to evaluate if some basic nitrate (NO_3)-based fertilizers would leach sufficiently to raise the pH of the fragipan layer and provide a more favorable rooting growth environment under rainfed field conditions. All crops and cover crops were planted using no-tillage.

The fertilizer treatments used were sodium nitrate ($NaNO_3$), potassium nitrate (KNO_3), and calcium nitrate ($CaNO_3$). Urea was used as the nitrogen source in the control treatment, which had no cover crop and only the corn or soybean summer crop. Nitrogen was not applied to the ARG cover crop, but 224 kg/ha of N was applied to the summer crop (corn or soybeans) and used as a control treatment. Seven complete cycles were completed over seven years. Each treatment had four replications.

Using ARG as a cover crop, plus the three different fertilizer treatments, resulted in an average of 11.4 cm increase in depth of rooting and soil depth above the hard unaltered fragipan (**Table 6**). These are very similar to the yearly depth increases found in Experiment 1. There appears to be no synergistic effect by any one fertilizer over the others in the rate of fragipan degradation. The synergistic effect of adding $NaNO_3$ to an ARG cover crop rotation reported by Murdock [15] using intact complete soil profile cores in the greenhouse was not apparent in this field study.

Table 6. Average rooting and non-degraded fragipan depth (cm) after 7 years of ARG cover crops and selected fertilizer treatments.

Treatment	Depth (cm)
Control (urea)	59.5b**
Sodium Nitrate + ARG	72.0a
Potassium Nitrate + ARG	69.8a
Calcium Nitrate + ARG	70.1*a

*One site had only remnants of the fragipan remaining; **Probability of significance was 0.05 or less.

Except for the 0 - 15 cm depth, the pH was similar for all nitrogen sources at each sampling depth (**Table 7**). The lower pH in the 0 - 15 cm depth in the control was probably due to the acidifying effect of the nitrification of the ammonium that develops from urea.

Table 7. Effect of soluble nitrate fertilizers on the soil pH of the top 45 cm after 7 years of additions of nitrogen at the rate of 225 kg/ha per year.

Treatment	Soil pH					
	Depth (cm)					
	0 - 15	P*	15 - 30	P*	30 - 45	P*
Control	5.8a	0.05	6.6a	NS	5.0a	NS
Sodium Nitrate	6.4b	0.05	6.6a	NS	5.1a	NS
Potassium Nitrate	6.6b	0.05	6.8a	NS	5.3a	NS
Calcium Nitrate	6.4b	0.05	6.5a	NS	5.3a	NS

*Probability sensitivity at the 0.05 level.

The lack of synergistic effects in the field trials compared to the greenhouse experiments, involving intact soil cores encased in plastic tubes, may be attributed to some leakage occurring along the edge of the soil/core-plastic interface under greenhouse conditions. The leaching is speculative but is a possibility, as noted by Murdock, author of citation [10]. Obviously, this leaching mechanism would not be available under natural soil conditions. Also, adding soluble nitrate nitrogen fertilizers without ammonium appeared to have little effect on the pH except in the surface 0 - 15 cm layer. Therefore, it would be difficult to have a synergistic effect on the fragipan degradation by planting ARG as a cover crop without using an amendment compound that would be capable of leaching through the soil profile at a relatively high rate.

Experiment 3: Effect of ARG and Menifee Humate on fragipan degradation in field trials after six growing cycles using an ARG cover crop with a soybean or corn rotation

Humates have been reported to degrade the fragipan when placed in direct contact with the fragipan [9] [10]. The objective of this trial was to determine the effectiveness of Menifee humate to degrade the fragipan when placed on the soil surface in a no-tillage environment. This humate was also evaluated for any synergistic effect it might have when placed on the soil surface with ARG as a cover crop. The Menifee humate is a sub-bituminous material commonly used as a soil conditioner. In this experiment, it was surface-applied just prior to the ARG planting each fall at the rate of 560 kg/ha. The trial was continued for six years. Each treatment had four replications.

Table 8. Average rooting and non-degraded fragipan depth (cm) after 6 years of ARG cover crop, humate, and combination treatment.

Treatment	Depth (cm)
Control	65.3b*
ARG	70.0a
Humate	66.0b
ARG + Humate	73.3a

*Significance at the 0.05 level or lower.

As seen in **Table 8**, the depth to the non-degraded fragipan and rooting depth in the control treatment and the humate treatment were almost identical. The ARG treatment and the ARG + Humate treatment were statistically the same, even though the combination of ARG and humate was numerically greater. This indicates that the surface-applied humate was probably not able to move through the profile over a six-year period to have any significant effect on the degradation of the fragipan. This is further supported by the fact that there was little, if any, difference between the control treatment and the humate treatment. This trial further substantiates the effectiveness of ARG even without the addition of other amendments. Even the highly soluble sodium nitrate fertilizer used in Experiment 2 did not have sufficient leaching capabilities to substantially increase the rate of fragipan degradation above that of ARG alone.

3. Conclusion

The results of this study suggest that the use of ARG can effectively remediate the fragipan in field conditions, particularly over a period of several years. When ARG was used as a cover crop in rotation with corn or soybeans, the degrading effect of the ARG on the fragipan was a continuous process that occurred with each crop of ARG and averaged 1.4 cm per year for the first 5 years and increased to 3 cm per year for the last 3 years of the 8-year study. The result is a structural change of the fragipan from a nearly massive compacted matrix to a more porous, blocky, or granular structure, which is similar to a regular subsoil in structure and color. The rate of degradation appears to accelerate with time due to the increased rate of degradation in the inter-prismatic gray veins by the more vigorous ARG roots. The pressure applied by the ARG roots can break sections of the fragipan matrix into smaller segments. The crop roots can take advantage of those cracks to expand their rooting system, and when the ARG is not active, they use the openings created by their roots to extend theirs and improve water and nutrient uptake. The crop yields increase as the soil deepens with each additional annual grass cover crop. Breakdown was sufficient in 5 to 6 years to significantly increase yields of corn and soybeans by about 10 percent. The yields can increase by 30% or greater based on farm field measurements. Amendments ($NaNO_3$, KNO_3, $CaNO_3$, and humate), which had previously shown to potentially increase the degradation rate of the fragipan when applied to an ARG treatment in the greenhouse, were not effective under field conditions.

Conflicts of Interest

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

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