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Water Deficit Irrigation of Robusta Coffee Under Nursery Conditions in Sultan Kudarat, Philippines

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Abstract. Robusta Coffee (*Coffea canephora*) is sensitive to water deficit, and its production is increasingly vulnerable to climate change, requiring the selection of drought-tolerant varieties. The study aimed to evaluate the growth response of four "France de Torino" clones (FRT 07, FRT 11, FRT 23, FRT 65) developed by Nestlé's Research and Development facility and three farmer-selected varieties (FRV-B, FRV-SNA, FRV-K) under stress conditions by withholding irrigation for 7, 14, and 21 days using a completely randomized design (CRD) with factorial treatment combinations. Growth responses were assessed based on leaf scorching, plant height, stem girth, number of leaves, soil moisture content, percentage of plant recovery, and biomass accumulation. Temperature and relative humidity (RH) were monitored to assess microclimatic effects. Results showed that prolonged drought stress reduced plant height (from 43.78 ± 4.21 cm at 7 days to 29.88 ± 3.42 cm at 21 days) and number of leaves (from 28.6 ± 3.4 to 15.8 ± 2.2), and increased leaf scorching (from 5.12 ± 1.38 to 21.32 ± 2.94). Among clones, FRT 23 had the highest average plant height (27.44 cm) under stress, while FRV-SNA exhibited the most incredible resilience across metrics, including the highest recovery rate (91.67%) and biomass accumulation (wet: 37.33 g; dry: 17.83 g). ANOVA revealed that drought stress significantly affected the growth parameters ($p < 0.0001$), while clone type influenced stem girth and recovery rate. Environmental monitoring revealed that inside the screenhouse, temperature reached a mean of 34.09°C, with relative humidity averaging 67%. Pearson's correlation showed strong inverse relationships between RH and inside screenhouse temperature ($r = -0.9279$, $p < 0.001$). Regression analysis indicated that temperature explained 86.1% of RH variability (Adj $R^2 = 0.8605$). Plants under 50% shade netting experienced moderated microclimates, supporting better growth under stress. The results were essential to improve the variety selection and water management strategies, ensuring long-term productivity and resilience of coffee in drought-prone areas.

Keywords: Drought stress; Irrigation; Robusta coffee; Water management; Water deficit.

1.0 Introduction

The adaptability of plants to environmental stresses has been a primary focus of plant ecology and adaptation studies (Yang et al., 2009). Plants have developed various strategies to survive diverse ecological challenges, such as resource competition, predation, climate variations, and habitat changes (Satake et al., 2015). Drought is among the most critical environmental stressors, significantly affecting crop productivity, particularly in agriculture. Drought stress induces physiological and biochemical changes in plants (Sadak et al., 2021), including reductions in plant height, stem diameter, and leaf number, and visible damage such as wilting and scorching (Farooq et al., 2009). Water scarcity has long been recognized as one of the leading causes of crop yield losses, surpassing the impacts of other environmental factors due to the severity and duration of its effects.

In response to these stressors, plants exhibit various survival mechanisms, including minimizing water loss, enhancing water uptake through deep root systems, and adjusting their leaf structure to reduce transpiration. Drought resistance mechanisms are complex and encompass physiological adaptations, such as increased osmolyte production, photosynthetic process alterations, and metabolic pathway adjustments. Lawlor and Tezara (2009) elaborate on how different plant species and varieties exhibit varied responses to drought, emphasizing changes in growth parameters such as biomass production, leaf folding, and recovery rates after stress. Such responses are influenced by water availability, temperature, and humidity, which further complicate plant reactions to drought.

In coffee production, Robusta coffee (*Coffea canephora*), a highly cultivated variety in tropical and subtropical regions, has been subject to growing concerns over its ability to tolerate drought stress, particularly in areas where water availability is a limiting factor. The introduction of newly developed Robusta coffee clones, such as those from Nestlé's Research and Development facility (FRT 07, FRT 11, FRT 23, FRT 65), presents an opportunity to examine the drought tolerance of specific clones and their growth responses under various water regimes. Despite previous studies on the effects of drought stress on coffee plants, a gap remains in understanding the specific reactions of different Robusta clones to withholding irrigation at various stages of growth, particularly in regions like Sultan Kudarat, where the climate presents unique challenges.

Previous studies have demonstrated that drought stress induces significant morphological, physiological, and biochemical changes in plants, including reductions in plant growth, leaf area, and overall biomass production. Farooq et al. (2009) reported that water deficit influences photosynthesis by reducing stomatal conductance, leading to decreased photosynthetic efficiency. Similarly, studies by Lawlor & Tezara (2009) highlighted how water deficit under high light conditions can impair metabolic processes, further exacerbating the adverse effects on plant growth. However, there is limited research on how specific Robusta coffee clones respond to drought conditions, particularly in terms of their morphological traits, such as plant height, stem diameter, and leaf number, as well as their ability to recover after stress (Ullah et al., 2021).

This study aims to fill this gap by determining the growth response of various Robusta coffee cloned cuttings and seedlings, focusing on their morphological changes and recovery rates under drought stress conditions. By examining the effects of withholding irrigation for 7, 14, and 21 days, this research will provide significant insights into the drought tolerance of these clones, contributing to the selection of more resilient varieties for cultivation in drought-prone areas. Additionally, this study aims to evaluate the impact of environmental factors, such as relative humidity and temperature, on drought stress indicators in Robusta coffee.

The significance of this study determines its potential to guide decision-making in the coffee industry and agricultural sector. As drought becomes an increasingly pressing issue due to climate change, understanding the drought resiliency of different Robusta coffee clones is crucial for improving the sustainability of coffee production. The findings will benefit nursery operators by providing guidelines for selecting drought-resistant varieties, ultimately enhancing water conservation, reducing labor costs, and ensuring a more stable supply of high-quality coffee seedlings. Furthermore, the study can support government and non-government programs to promote sustainable coffee farming, ensuring farmers access high-quality, drought-tolerant planting materials. This research will also contribute to the broader scientific understanding of plant adaptation to water stress, specifically within coffee cultivation.

2.0 Methodology

2.1 Research Design

This study utilized an experimental research design to evaluate the growth responses of Robusta coffee cloned cuttings and seedlings under drought stress. A completely randomized design (CRD) (Gomez, K. 1983) with three replicates of 28 factorial treatment combinations (4 water regimes × 7 Robusta coffee clones and seedlings) was used within a controlled nursery shed environment. Each factorial treatment had six plant samples, totalling 504 plant samples. Factor A represented different levels of withheld watering, while Factor B comprised various Robusta coffee clones and seedlings. The water regimes included well-watered (control) and withholding irrigation for 7 days, 14 days, and 21 days. The Robusta coffee varieties included FRT 07, FRT 11, FRT 23, FRT 65, FRV-B, FRV-SNA, and FRV-K.

2.2 Research Locale
The study was conducted in Sultan Kudarat, Philippines, from December 3, 2023, to March 7, 2024. This location was chosen for its relevance to Robusta coffee cultivation and its exposure to the studied climatic conditions, making it an ideal site for assessing drought stress in Robusta coffee.

2.3 Research Instrument
The planting materials included 288 cloned cuttings of Robusta coffee (FRT 07, 11, 23, and 65) and 216 seedlings from farmer-selected varieties (FRV-B, FRV-SNA, and FRV-K) placed in a nursery shed (or screenhouse) that was constructed using a 150-micron ultraviolet (UV) sheet, a 70%-80% shading garden net, and 6-mil agricultural plastic film, following the Uganda Coffee Development Authority's guidelines to control the shading variability. Also, they were carefully sourced to ensure consistency in experimental outcomes. The cloned cuttings (FRT 07, 11, 23, and 65) were obtained from recognized quality and locally produced in Cotabato, Philippines. In contrast, the FRV cuttings were sourced from Nestlé rejuvenation areas in Sultan Kudarat, Philippines. Other materials included a chicken net (2-inch mesh), a hygrothermograph (HTC-2), a digital weighing scale, a soil pH and moisture tester (Takemura DM-15), a ruler/meter stick, a Vernier caliper (Ingco HDCP 16150), a garden hose for irrigation, and standard recording tools such as pens, signage, and a record book.

On the other hand, the experimental setup was elevated approximately one foot from the ground to ensure that the drought stress conditions were accurately simulated and not influenced by external water sources such as rainfall. This elevation served to prevent surface water intrusion during unexpected weather conditions. Additionally, transparent cellophane was wrapped around the perimeter of the planting area, creating a controlled microenvironment. However, intentional gaps were left at the bottom and top sections of the enclosure to allow for proper air circulation and vapor exchange, thereby preventing excessive heat buildup and ensuring that the plants could still transpire normally.

Furthermore, the experiment was strategically scheduled during months with no forecasted La Niña events, based on data and advisories from PAGASA (Philippine Atmospheric, Geophysical and Astronomical Services Administration). This precaution was taken to eliminate confounding factors such as above-average rainfall, ensuring that the stress imposed on the plants could be attributed solely to heat and moisture deficit. Thus, the experiment accurately assessed the drought tolerance of the coffee clones and seedlings.

2.4 Care and Maintenance of Robusta Coffee Seedlings
The seedlings were arranged according to the experimental layout in a screen house. The nursery shed (screenhouse) was designed with proper ventilation and shading, incorporating UV sheets and garden nets. The flooring was elevated to avoid direct contact with the ground, and a transparent plastic cover film was used to protect the plants. A hygrothermograph was used to monitor temperature conditions inside the shed three times daily.

Watering frequency and management were crucial in assessing the plants' growth under different water regimes. The treatments included varying intervals of withholding water (7, 14, and 21 days), which helped simulate drought stress and observe the coffee plants' adaptation mechanisms. Shading with garden nets was also used to control light intensity and protect seedlings from excessive sunlight. The gradual removal of the net allowed the seedlings to acclimate to full sunlight, ensuring they were not exposed to harsh conditions too quickly.

Weed management was emphasized to prevent competition for water, nutrients, and light, especially in the nursery setting. Weeding was conducted regularly, every 2 to 3 weeks, to ensure that the Robusta coffee seedlings received the necessary resources for optimal growth and development. The study followed recommendations to reduce the impact of weeds, which could hinder seedling development during the early growth stages.

Fertilization was carried out to promote seedling growth, with a balanced fertilizer (14-14-14) applied weekly during the final 30 days of the study. The amount of fertilizer was carefully controlled to prevent over-fertilization, particularly since water regimes were also a factor in the experiment. This approach helped ensure that the seedlings received adequate nutrients while minimizing the risk of nutrient overload, potentially harming plant development.

2.5 Data Gathering Procedure

Leaf Scorching

Leaf scorching was quantified weekly by visual scoring between 11:00 am and 2:00 pm, with values ranging from 1 to 5 based on leaf folding, wilting, and damage, as described by Rosario et al. (1992), Anim-Kwapong et al. (2011), and Tesfaye et al. (2013). Each plant was visually rated, and the scores were averaged per factorial treatment in each replication. The proportion of plants exhibiting wilting symptoms was also manually counted every week.

Plant Height, Plant Girth, Number of Leaves

Plant height was measured every seven days using a precision meter stick from the soil interface to the apical meristem. Plant girth was measured using Vernier calipers at 0.5 inches above the soil surface, providing insights into the plant's structural integrity, which is sensitive to changes in water availability and temperature. The number of leaves was manually counted weekly, representing the plant's photosynthetic capacity and overall growth.

Temperature and Soil Moisture

Temperature data were recorded three times daily (8:00 a.m., 12:00 noon, and 4:00 p.m.) using a hygrothermograph. The daily average temperature was then calculated for analysis. Soil moisture was measured on the first day post-irrigation and subsequently recorded every seven days at 7:00 a.m. using a soil moisture meter. Soil moisture and pH levels were assessed using a Takemura DM-15 tester. This approach ensured that the measurements accurately reflected the available water content without the influence of recent irrigation events.

Plant Recovery and Rate of Biomass Accumulation

Plant recovery was assessed by counting viable plants, and the recovery percentage was calculated based on surviving plants relative to the total initial sample. Biomass accumulation, both wet and dry weight, was measured to quantify plant productivity. Wet weight was recorded immediately after removing soil and detritus, while dry weight was obtained after drying the plant material for 20 hours under controlled conditions. These parameters were carefully monitored to understand the plants' response to drought stress and their overall growth and survival under varying conditions.

2.6 Data Analysis

Collected data were analyzed using Analysis of Variance (ANOVA) to determine significant differences among treatments, followed by the Least Significant Difference (LSD) test for pairwise comparisons. Regression and correlation analysis were used to determine the relationships between growth parameters and environmental factors, providing insights into factors affecting plant performance. All analyses were performed using STATA 17 (Boston & Sumner, 2003; Gutierrez, 2010).

3.0 Results and Discussion

3.1 Leaf Scorching

Table 1 presents the extent of leaf scorching, including leaf folding, wilting, and damage, observed in various Robusta coffee clones and seedlings subjected to differing drought stress treatments. Visual scoring methods, as outlined by Rosario et al. (1992) and Anim-Kwapong et al. (2011), were employed to assess the impact of withholding irrigation across four treatment levels (Factor A). The Analysis of Variance (ANOVA) revealed statistically significant differences among the treatments.

The data show a clear progression of stress-related symptoms corresponding to the duration of irrigation withholding. Specifically, plants under well-watered conditions (A1) exhibited the lowest mean leaf scorching score (1.19), indicating minimal signs of drought stress. In contrast, plants exposed to 21 days without irrigation (A4) exhibited the highest mean score (2.69), suggesting a marked increase in drought-induced foliar damage. The trend across watering regimes reveals a consistent and gradual increase in leaf scorching as water availability decreases. This progression from A1 to A4 highlights the sensitivity of Robusta coffee plants to prolonged water deficit. These results align with previous studies by Maestri et al. (1995) and Meinzer et al. (1992), documenting the osmotic adjustment in maintaining leaf turgor under drought conditions. Similarly, Pugnaire et al. (1999) emphasized that visible symptoms such as wilting and necrosis are manifestations of impaired water relations at the cellular level, typically following prolonged water deprivation.

Table 1. *Average Rate of Leaf Scorching (Extent of Leaf Folding/Wilting and Damage) of Different Robusta Coffee Cloned Cuttings and Seedlings to Drought Stress. Sultan Kudarat, Philippines. December 2023 – March 2024*

Factor B. Clones/ Seedlings	Factor A. Withhold Watering				Clones/ Seedlings Mean^{ns}
	A1 Well-watered every 2 days	A2 Withhold irrigation for 7 days	A3 Withhold irrigation for 14 days	A4 Withhold irrigation for 21 days	
B1- FRT 07	1.19	1.70	2.50	2.50	**1.97**
B2- FRT 11	1.16	1.81	1.85	2.56	**1.84**
B3- FRT 23	1.41	1.95	1.89	2.68	**1.98**
B4- FRT 65	1.20	1.75	2.21	2.82	**1.99**
B5- FRV-B	1.17	1.58	2.30	2.75	**1.95**
B6- FRV-SNA	1.09	1.76	2.14	2.74	**1.93**
B7- FRV-K	1.09	1.72	2.22	2.78	**1.95**
Mean	**1.19^{a}**	**1.75^{b}**	**2.16^{c}**	**2.69^{d}**	

C.V.% = 0.2989

1/ Treatment means with the same letter are not significantly different at a 5% level of significance using LSD

ns is not significantly different at a 5% level of significance.

There are differences in leaf scorching responses that appear relatively small. Among the clones, FRT 11 had the lowest overall mean (1.84), while FRT 65 had the highest (1.99). FRV-SNA showed the lowest mean (1.93) among the farmer-selected seedlings, closely followed by FRV-B and FRV-K (both at 1.95). Although these values suggest slight variation in drought response, the magnitude of the difference is limited. Notably, the seedlings FRV-SNA and FRV-K showed the lowest individual mean values under well-watered conditions, at 1.09, indicating minimal stress symptoms when water was not limiting. Conversely, the highest individual score was observed in clone FRT 65 under the 21-day withholding treatment (2.82), indicating greater susceptibility to prolonged drought. While all genotypes displayed increased leaf scorching under extended water stress, the differences in average severity among clones and seedlings were minimal. Several factors may explain this relative uniformity. First, the genetic material used in the study may possess similar drought response mechanisms, such as stomatal regulation and osmoprotectant accumulation, which can lead to broadly comparable phenotypic outcomes (Farooq et al., 2009; Verslues & Juenger, 2011). Second, the controlled environment of the nursery may have reduced environmental variability that would otherwise amplify genotypic differences, as environmental heterogeneity is a known driver of phenotypic differentiation under stress conditions (Poorter et al., 2012) third, while a practical method, visual scoring may lack the resolution needed to detect subtle physiological differences among genetically similar plant materials (Begg & Turner, 1970; Kramer & Boyer, 1995). These limitations likely contributed to the non-significant discrepancies observed in the analysis.

Figure 1. *Effect of leaf scorching (extent of leaf folding and wilting) of different robusta coffee cloned cuttings and seedlings to drought stress*

Despite the absence of significant discrepancies among genotypes, the progression of leaf scorching with increased drought stress supports its utility as an early indicator of water deficit which is consistent with findings by Tesfaye et al. (2013b) and Anim-Kwapong et al. (2011), who demonstrated that leaf scorching is a reliable proxy for drought impact, correlating negatively with growth parameters such as plant height and biomass accumulation. While this parameter alone may not capture the full complexity of drought tolerance, it remains a valuable, cost-effective screening tool for early-stage evaluation of drought response in coffee seedlings and clones.

3.2 Plant Height

Table 2 shows that all Robusta coffee clones and seedlings experienced a reduction in height as drought stress intensified. The well-watered control group (A1) achieved the best mean height (44.29 cm). In comparison, the 21-day irrigation withholding treatment (A4) resulted in the lowest (31.39 cm), illustrating the fundamental role of moisture in supporting cell elongation, nutrient transport, and metabolic activity, which are critical for vertical growth in coffee plants (Taiz & Zeiger, 2006).

Table 2. *Average Plant Height of Different Robusta Coffee Cloned Cuttings and Seedlings under Drought Stress. Sultan Kudarat, Philippines. December 2023 – March 2024*

Factor B. Clones/ Seedlings	Factor A. Withhold Watering				Clones/ Seedlings Mean
	A1 Well-watered every 2 days	**A2 Withhold irrigation for 7 days**	**A3 Withhold irrigation for 14 days**	**A4 Withhold irrigation for 21 days**	
B1- FRT 07	32.34	27.85	25.59	22.69	**21.11^{a}**
B2- FRT 11	24.99	22.59	20.80	19.26	**21.91^{b}**
B3- FRT 23	32.33	29.14	25.37	22.92	**27.44^{a}**
B4- FRT 65	31.82	29.86	25.10	21.32	**27.03^{a}**
B5- FRV-B	59.89	62.92	55.47	45.13	**55.85^{c}**
B6- FRV-SNA	65.62	61.83	58.21	46.96	**58.15^{d}**
B7- FRV-K	63.07	57.77	54.08	41.44	**54.09^{c}**
Mean	**44.29^{a}**	**41.71^{b}**	**37.80^{c}**	**31.39^{d}**	

C.V.% = 0.9203

$^{1/}$ Treatment means with the same letter are not significantly different at a 5% level of significance using LSD

^{ns} is not significantly different at a 5% level of significance.

Farmer-selected seedlings outperformed cloned cuttings consistently across all stress levels. FRV-SNA maintained the tallest mean height (58.15 cm), followed by FRV-B (55.85 cm) and FRV-K (54.09 cm). Despite the 29% reduction in FRV-SNA's height from the well-watered condition to the most severe stress, it remained the tallest genotype at every drought level. In contrast, the cloned cuttings, notably FRT 07 (21.11 cm) and FRT 11 (21.91 cm), showed considerably lower growth, with FRT 07 exhibiting the greatest vulnerability to drought-induced height suppression. The superior height retention in farmer-selected varieties may be attributed to enhanced water-use efficiency, better-developed root systems, or more effective stomatal regulation mechanisms commonly associated with drought resilience in Coffea species. These varieties will likely have undergone natural or farmer-driven selection in local environments, promoting adaptation to intermittent water stress (DaMatta & Ramalho, 2006; Vieira et al., 2020).

Furthermore, this genotypic variation aligns with findings by Zhou et al. (2017), who demonstrated that drought-tolerant coffee cultivars maintain shoot growth through improved water-use efficiency and hormonal signalling that preserves meristem activity under stress. The significant interaction between clone type and irrigation regime ($p < 0.0001$) further supports that genotype-specific responses to water stress play a critical role in growth outcomes. Although clones like FRT 23 showed better height performance among cuttings, they still fell well below the farmer-selected seedlings, suggesting limited adaptive plasticity under water-limited conditions. Farmer-selected seedlings grew taller as water availability declined, while cloned cuttings showed reductions. These findings align with the work of Avelino et al. (2015), who emphasized the value of pairing drought-resilient genotypes with water-saving nursery practices.

In practical terms, genotypes like FRV-SNA and FRV-B show strong potential for use in drought-prone environments. Their ability to retain shoot growth under water stress indicates early vigor, which is important for nursery success and field establishment. Integrating these clones into propagation programs can help reduce transplanting losses and improve resilience in coffee production systems facing climate variability.

3.3 Plant Girth

Table 3 presents the average plant girth, or primary stem diameter, of Robusta coffee clones and seedlings under different drought stress treatments. The data show a subtle but consistent trend in which stem girth tends to decline with increased duration of irrigation withholding.

Table 3. *Average Plant Girth (Main Stem Diameter) of Different Robusta Coffee Cloned Cuttings and Seedlings under Drought Stress. Sultan Kudarat, Philippines. December 2023 – March 2024*

Factor B. Clones/ Seedlings	Factor A. Withhold Watering				Clones/ Seedlings Mean
	A1 Well-watered every 2 days	A2 Withhold irrigation for 7 days	A3 Withhold irrigation for 14 days	A4 Withhold irrigation for 21 days	
B1- FRT 07	0.13	0.12	0.11	0.10	**0.12**[a]
B2- FRT 11	0.12	0.11	0.10	0.09	**0.11**[a]
B3- FRT 23	0.14	0.13	0.13	0.20	**0.15**[b]
B4- FRT 65	0.13	0.11	0.12	0.09	**0.11**[a]
B5- FRV-B	0.22	0.23	0.19	0.19	**0.21**[c]
B6- FRV-SNA	0.24	0.21	0.20	0.19	**0.21**[c]
B7- FRV-K	0.22	0.19	0.19	0.17	**0.19**[c]
Mean [ns]	**0.17**	**0.16**	**0.15**	**0.15**	

C.V.% = 0.3390

[1/] Treatment means with the same letter are not significantly different at a 5% level of significance using LSD

[ns] is not significantly different at a 5% level of significance.

The highest mean girth was recorded under well-watered conditions (A1) at 0.17 centimeters, followed by 7 days of water withholding (A2) at 0.16 centimeters, and further decreased to 0.15 centimeters under both 14 and 21 days of water withholding (A3 and A4, respectively). These observations suggest that water availability supports stem thickening, although the magnitude of change across irrigation levels was limited. More pronounced differences were observed across the genotypes rather than the water treatments. Among the cloned cuttings, FRT 23 exhibited the highest mean stem girth at 0.15 centimeters, indicating slightly better performance under stress compared to FRT 07 (0.12 centimeters), FRT 11 (0.11 centimeters), and FRT 65 (0.11 centimeters). In contrast, the farmer-selected seedlings displayed consistently larger girths, with FRV-B and FRV-SNA each recording a mean of 0.21 centimeters, and FRV-K slightly lower at 0.19 centimeters. Notably, under well-watered conditions (A1), FRV-SNA had the most considerable stem girth at 0.24 centimeters, whereas under prolonged drought (A4), FRV 11 showed the lowest at 0.09 centimeters. These results reflect a clear advantage of farmer-selected genotypes in maintaining stem development under optimal and stressed conditions.

Genetic factors primarily influence stem girth rather than short-term variation in irrigation levels. This interpretation aligns with the findings of Roonprapanta et al. (2021), who reported that the genotype had a more substantial effect than water treatment on stem diameter in Robusta coffee grown under water-deficit conditions. Similarly, Arunyanark et al. (2022) demonstrated that drought-tolerant coffee varieties exhibit more stable stem girth even under limited water availability, a trait linked to structural resilience and internal water transport efficiency. Furthermore, the limited variation in stem girth across watering treatments may indicate that the thickening of the stem is less sensitive to short-term water stress compared to other parameters, such as plant height or leaf number. The drought duration in this study was insufficient to cause more pronounced reductions in stem diameter, particularly under controlled nursery conditions. This observation is consistent with the work of Omprakash et al. (2017), who noted that morphological reductions under drought tend to be more apparent in aboveground elongation than in stem thickness, especially during early stages of plant growth.

The ability of genotypes such as FRV-SNA and FRV-B to sustain larger stem girths across treatments suggests a potential for improved mechanical support, better vascular capacity, and enhanced nutrient transport under stressful conditions. This finding supports the conclusions of Dos Santos et al. (2023), who emphasized the value of stem girth as an indicator of overall plant vigor and drought resilience. Coffee plants with thicker stems are more likely to maintain physiological functions during drought and recover more efficiently when normal watering resumes.

3.4 Number of Leaves

The analysis of the average number of leaves across different Robusta coffee clones and seedlings under varying watering regimes, as presented in Table 4, reveals several significant trends. The results highlight that clone type (Factor A) and watering regime (Factor B) significantly affect leaf production, as evidenced by the statistical significance at a p-value of less than 0.01. However, the interaction between these two factors was not significant, indicating that their independent effects on leaf number do not lead to an outcome beyond what would be expected from their contributions.

Table 4. *Average Number of Leaves of Different Robusta Coffee Cloned Cuttings and Seedlings to Drought Stress. Sultan Kudarat, Philippines. December 2023 – March 2024*

Factor B. Clones/ Seedlings	Factor A. Withhold Watering				Clones/ Seedlings Mean
	A1 Well-watered every 2 days	A2 Withhold irrigation for 7 days	A3 Withhold irrigation for 14 days	A4 Withhold irrigation for 21 days	
B1- FRT 07	9.73	7.51	6.40	4.32	**6.99**[a]
B2- FRT 11	9.85	8.18	7.51	5.80	**7.84**[a]
B3- FRT 23	8.82	7.75	7.53	5.41	**7.38**[a]
B4- FRT 65	9.31	7.67	6.25	5.60	**7.21**[a]
B5- FRV-B	14.57	13.47	14.46	11.01	**13.38**[b]
B6- FRV SNA	15.54	12.41	16.08	9.01	**13.26**[b]
B7- FRV-K	12.90	11.51	13.33	9.61	**11.84**[c]
Mean	**11.53**[d]	**9.79**[b]	**10.22**[c]	**7.25**[a]	

C.V.% = 0.5558

1/ Treatment means with the same letter are not significantly different at a 5% significance level using LSD; ns is not significantly different at a 5% significance level.

The data demonstrate that the average number of leaves varies across the clones and seedlings under different watering treatments. Among the clones, FRT 11 exhibited the highest mean number of leaves for cloned cuttings, followed by FRT 23, FRT 65, and FRT 07, with average leaf numbers of 7.38, 7.21, and 6.99, respectively. FRV-B displayed the highest mean number of leaves among the seedlings, followed by FRV-SNA and FRV-K, with average leaf counts of 13.38, 13.26, and 11.84, respectively.

For Factor B (withhold watering), seedlings such as FRV-SNA and FRV-B generally yielded more leaves than the coffee-cloned cuttings. Regarding Factor A (watering regimes), the control group (A1—well-watered every two days) consistently produced the highest average number of leaves, with a mean of 11.53 leaves, followed by A2 (7 days of irrigation withholding), A3 (14 days of irrigation withholding), and A4 (21 days of irrigation withholding), which yielded progressively fewer leaves. Specifically, A4 resulted in the lowest mean leaf count of 7.25 leaves, highlighting the negative impact of prolonged irrigation withholding on leaf production.

Selecting appropriate clones and maintaining regular watering schedules to optimize leaf production (de Souza et al., 2024). In particular, FRT 11 among clones and FRV-B among seedlings demonstrated superior leaf production, even under varying watering conditions. The results suggest that genetic factors, such as inherent drought resilience and growth patterns, significantly contribute to the ability of coffee plants to sustain leaf production under stress (Chekol et al., 2023; de Souza et al., 2024). The coefficient of variation of 0.5558 indicates that approximately 55.58% of the variation in leaf number can be explained by the combined effects of clone type and watering levels. This value underlines the importance of both factors in influencing foliar development. Consistent irrigation, particularly in the form of frequent watering (A1), was found to support optimal leaf growth, while withholding irrigation for extended periods (A4) detrimentally affected leaf retention (Silva et al., 2013).

These findings suggest that selecting drought-tolerant clones with superior leaf production potential and consistent irrigation practices can improve plant resilience and overall productivity (Teixeira et al., 2021). Such strategies will enhance the sustainability of coffee production, particularly under water-limited conditions, by ensuring that plants maintain healthy foliage, which is essential for photosynthesis and overall plant vitality (Pinheiro et al., 2005).

3.5 Soil Moisture

The data in Table 5 indicated apparent differences in soil moisture content, which can significantly influence plant growth and productivity. The findings demonstrate that soil moisture levels are highest under the well-watered condition (A1), with a mean of 7.76%. This supports the idea that consistent irrigation promotes optimal hydration for plant physiological functions, such as nutrient uptake and photosynthesis. This aligns with studies by Vu et al. (2018), emphasizing the importance of sufficient water availability for maintaining growth parameters such as plant height and leaf expansion in coffee plants. Prolonged withholding of irrigation led to a progressive decrease in soil moisture, with the lowest moisture content (5.03%) observed under the 21-day irrigation withholding condition (A4).

Table 5. *Average Soil Moisture of Different Robusta Coffee Cloned Cuttings and Seedlings under Drought Stress. Sultan Kudarat, Philippines. December 2023 – March 2024*

Factor B. Clones/ Seedlings	Factor A. Withhold Watering				Clones/ Seedlings Mean
	A1 Well-watered every 2 days	A2 Withhold irrigation for 7 days	A3 Withhold irrigation for 14 days	A4 Withhold irrigation for 21 days	
B1- FRT 07	7.80	6.91	6.29	5.14	**6.54**[c]
B2- FRT 11	7.74	6.99	6.32	4.98	**6.51**[c]
B3- FRT 23	7.76	6.92	6.16	4.98	**6.46**[b]
B4- FRT 65	7.75	6.95	6.23	4.98	**6.48**[b]
B5- FRV-B	7.78	6.37	6.29	5.01	**6.36**[a]
B6- FRV-SNA	7.74	6.40	6.18	5.13	**6.36**[a]
B7- FRV-K	7.75	6.43	6.22	5.01	**6.35**[a]
Mean	**7.76**[d]	**6.71**[c]	**6.24**[b]	**5.03**[a]	

C.V.% = 0.6873

[1/] Treatment means with the same letter are not significantly different at a 5% level of significance using LSD

[ns] not significantly different at a 5% level of significance.

This decline reflects the impact of drought stress, which could limit essential processes for plant growth, such as nutrient absorption and cell expansion, ultimately leading to reduced plant vigor and productivity (Ramirez-Builes et al., 2024). The comparison of soil moisture among the coffee clones (Factor B) reveals that clone selection does not significantly influence moisture retention, with mean values ranging from 6.54% for FRT 07 to 6.35% for FRV-K. The narrow range of values across clones suggests that the effects of irrigation frequency (Factor A) outweigh the influence of genetic variation among the clones on soil moisture dynamics. This result contrasts with findings from studies by Chekol et al. (2023) and de Souza et al. (2024), which found genetic differences in drought resistance among coffee clones. Their studies suggest that specific clones may exhibit enhanced tolerance to water stress, which may confer advantages in soil moisture retention under drought conditions. However, in this study, the primary factor influencing soil moisture retention is the irrigation regime, rather than genetic factors.

The results show that water deficits reduce growth, yield, and quality. Research indicates that coffee plants, particularly Arabica and Liberica species, are susceptible to significant reductions in growth under water stress (Vu et al., 2018). While also affected by drought, Robusta coffee generally demonstrates more resilience to water shortages than other coffee species. Despite potential variations in genetic characteristics, irrigation practices are more influential in mitigating drought stress and maintaining soil moisture.

3.6 Percentage of Plants Recovered

Table 6 presents the mean percentage recovery of various Robusta coffee clones and seedlings subjected to different irrigation withholding periods. The results indicate apparent differences among clones in their ability to recover from drought stress, as well as among the irrigation treatments. The recovery percentage measures resilience and physiological capacity to survive and regain growth after water stress of plants, thus it is a reliable indicator of drought tolerance. Among the clones, FRV-SNA (B6) exhibited the highest overall recovery (91.67%), followed closely by FRV-K (B7) and FRV-B (B5), both with mean recovery values of 86.11%. These results suggest that these three clones possess intense drought adaptive traits, likely due to more efficient water-use strategies or better root system architecture, which facilitate rapid physiological recovery after rehydration. In contrast, FRT 07 (B1) and FRT 65 (B4) had the lowest recovery percentages, 40.28% and 41.67%, respectively, indicating poor drought resilience. The significant differences among clones reflect genotypic variation in stress response mechanisms, which align with earlier findings by Worku et al. (2021), who reported that clone-specific physiological traits greatly influence drought recovery in Coffea species.

Table 6. *Percentage Recovery of Different Robusta Coffee Cloned Cuttings and Seedlings Subjected to Drought Stress. Sultan Kudarat, Philippines. December 2023 – March 2024*

Factor B. Clones/ Seedlings	Factor A. Withhold Watering				Clones/ Seedlings Mean
	A1 Well-watered every 2 days	A2 Withhold irrigation for 7 days	A3 Withhold irrigation for 14 days	A4 Withhold irrigation for 21 days	
B1- FRT 07	66.67	33.33	55.56	5.56	**40.28**[a]
B2- FRT 11	72.22	38.89	61.11	38.89	**52.78**[b]
B3- FRT 23	83.33	50.00	77.78	11.11	**55.56**[b]
B4- FRT 65	66.67	33.33	55.56	11.11	**41.67**[a]
B5- FRV-B	94.44	100.00	94.44	55.56	**86.11**[c]
B6- FRV-SNA	100.00	88.89	100.00	77.78	**91.67**[d]
B7- FRV-K	100.00	94.44	83.33	66.67	**86.11**[c]
Mean	**83.33**[d]	**62.70**[b]	**75.40**[c]	**38.10**[a]	

C.V.% = 0.7102

[1/] Treatment means with the same letter are not significantly different at a 5% level of significance using LSD

[ns] not significantly different at a 5% level of significance.

Means across irrigation treatments (Factor A), regular irrigation (A1), resulted in the highest recovery rate of 83.33%, confirming the positive influence of consistent water availability on plant recovery. As the duration of irrigation withholding increased, the recovery percentage significantly declined. At 7- and 14-day withholding (A2 and A3), the recovery percentages were 62.70% and 75.40%, respectively, while the 21-day withholding (A4) produced the lowest recovery at 38.10%. This trend supports the understanding that prolonged water stress severely compromises the plant's ability to recover, likely due to irreversible physiological damage such as leaf senescence, xylem cavitation, or impaired root function (Pinheiro & Chaves, 2011).

Moreover, clones such as FRV-SNA (B6) maintained high recovery even under 21 days of water withholding (77.78%), outperforming all others under the same stress. In contrast, FRT 07 (B1) showed only 5.56% recovery at A4, indicating its inability to withstand prolonged drought. These findings are consistent with the study of DaMatta et al. (2003), which emphasized genotypic differences in drought acclimation, particularly in Robusta coffee. Specific clones exhibit better osmotic adjustment and maintain stomatal conductance under stress, which may explain the superior recovery seen in FRV-SNA and FRV-K. Due to their high recovery rates and apparent resilience, FRV-SNA, FRV-K, and FRV-B have the potential for drought-prone environments. On the other hand, clones such as FRT 07 and FRT 65 may require more frequent irrigation or be better suited for regions with stable water availability. This aligns with the findings of Avelino et al. (2007), who emphasized the importance of genotype selection as a key strategy in climate-resilient coffee production systems.

3.7 Rate of Biomass

As presented in Table 7, biomass accumulation strongly correlates with watering frequency, with significantly higher wet and dry weights observed under well-watered conditions (A1). Clones receiving irrigation every two days exhibited optimal biomass production, with FRV-K (B7) and FRV-SNA (B6) recording the highest mean wet and dry weights, at 60.67 g and 27.33 g, respectively. Conversely, extended water deprivation (A4) resulted in pronounced reductions in biomass accumulation, with the lowest values recorded for FRT 07 (B1), demonstrating the adverse effects of prolonged drought stress on plant growth.

Among the clones, FRV-SNA (B6) and FRV-K (B7) demonstrate the highest mean biomass production, with FRV-SNA recording 37.33 g (wet) and 17.83 g (dry), and FRV-K closely following with 37.17 g (wet) and 16.83 g (dry). These results suggest a strong genetic capacity of these clones to maintain growth and physiological function under reduced water conditions. In contrast, FRT 11 (B2) and FRT 07 (B1) exhibit the lowest biomass accumulation, particularly under extended drought, with FRT 07 averaging only 16.17 g (wet) and 7.33 g (dry). The comparatively poor performance of these clones under stress suggests a lower adaptive capacity to water-limited environments. The observed trend is consistent with earlier findings by Tesfaye et al. (2013), who reported considerable variation in biomass accumulation among Robusta genotypes under drought conditions. Their study emphasized that specific clones exhibit enhanced water-use efficiency and can sustain biomass production even under moisture-deficient conditions. Similarly, Silva et al. (2013) noted that Robusta coffee clones with efficient stomatal regulation and favorable biomass partitioning tend to perform better under drought stress, owing to enhanced photosynthetic capacity and carbon assimilation.

Table 7. *Rate of Biomass (Wet and Dry Weight) of Different Robusta Coffee Cloned Cuttings and Seedlings under Drought Stress. Sultan Kudarat, Philippines. December 2023 – March 2024.*

Category	Factor B. Clones/ Seedlings	Factor A. Withhold Watering				Clones/ Seedlings Mean
		A1 Well-watered every 2 days	A2 Withhold irrigation for 7 days	A3 Withhold irrigation for 14 days	A4 Withhold irrigation for 21 days	
Wet	B1- FRT 07	28.00	17.33	13.33	6.00	**16.17**[b]
Dry		13.33	8.67	5.33	2.00	**7.33**[b]
	B2- FRT 11	23.33	10.00	14.00	7.33	**13.67**[a]
		10.67	5.33	5.33	2.00	**5.83**[a]
	B3- FRT 23	26.67	17.33	17.33	7.00	**17.08**[b]
		10.00	8.67	7.33	3.00	**7.25**[b]
	B4- FRT 65	30.67	19.00	18.00	6.00	**18.42**[b]
		12.67	9.00	6.67	2.00	**7.59**[b]
	B5- FRV-B	54.00	48.00	24.67	15.33	**35.50**[c]
		25.33	23.33	12.00	8.67	**17.33**[c]
	B6- FRV-SNA	57.33	46.00	31.33	14.67	**37.33**[c]
		28.00	21.33	14.00	8.00	**17.83**[c]
	B7- FRV-K	60.67	42.00	34.00	12.00	**37.17**[c]
		27.33	18.67	15.33	6.00	**16.83**[c]
Wet	**Withhold**	**40.10**[a]	**28.52**[b]	**21.81**[b]	**9.76**[c]	
Dry	**Watering Mean**	**18.19**[a]	**13.57**[a]	**9.43**[b]	**4.52**[c]	

C.V.% = 0.8697 (Wet); 0.7897 (Dry)

[1/] Treatment means with the same letter are not significantly different at a 5% level of significance using LSD

[ns] not significantly different at a 5% level of significance.

Additionally, the greater reductions in dry weight compared to wet weight across clones suggest that drought stress affects plant water content and structural biomass integrity. Dry weight is generally a more stable indicator of plant productivity, reflecting the actual accumulation of organic matter. The performance of FRV-SNA reveals potential for drought-resilient nursery propagation. Its ability to maintain biomass under deficit conditions may confer a survival advantage during transplanting and early field establishment, where water stress is constant.

3.8 Temperature

Temperature is important in modulating the physiological and biochemical responses of Robusta coffee (*Coffea canephora*) clone cuttings and seedlings under drought stress. These environmental factors influence the plant's ability to maintain homeostasis, affecting key processes such as photosynthesis, transpiration, and stomatal regulation.

Table 8. *Temperature and Relative Humidity under Different Shading Conditions in Robusta Coffee Clone Cuttings and Seedlings to Drought Stress from December 2023-March 2024.*

Variable	Condition	Mean	Median	Standard Deviation	Minimum	Maximum
Inside temperature (°C)	80% Garden Net Shade	34.28	34.28	2.36	32.27	38.05
	50% Garden Net Shade	33.37	33.09	0.94	32.42	34.5
	No Garden Net Shade	33.58	33.44	0.28	33.38	33.93
	No Garden Net Shade (Recovery)	33.58	33.84	1.22	32.23	34.68
Outside temperature (°C)	80% Garden Net Shade	32.2	32.58	2.06	30.37	35.28
	50% Garden Net Shade	32.09	32.26	1.2	30.97	33.88
	No Garden Net Shade	32.39	32.57	0.6	31.71	32.9
	No Garden Net Shade (Recovery)	32.27	32.39	0.61	31.6	32.83
Relative humidity (%)	80% Garden Net Shade	66.28%	64.17%	8.54%	58.48%	78.33%
	50% Garden Net Shade	69.50%	70.29%	5.12%	62.05%	74.38%
	No Garden Net Shade	67.94%	67.95%	1.83%	66.10%	69.76%
	No Garden Net Shade (Recovery)	65.76%	67.43%	8.55%	56.52%	73.33%

Influence of Temperature on Physiological Responses

Temperature significantly affects the metabolic activities of Robusta coffee plants, with optimal growth typically occurring between 24°C and 30°C. When temperatures exceed this range, particularly under low shading conditions, the plants experience thermal stress. Elevated temperatures can induce the overproduction of reactive oxygen species (ROS), leading to cellular damage, disruption of chloroplast integrity, and a decline in photosynthetic efficiency (Taiz & Zeiger, 2006). Moreover, high temperatures accelerate evapotranspiration, exacerbating drought stress by depleting soil moisture, reducing leaf turgor, and limiting CO_2 uptake, ultimately inhibiting growth and development (Jones, 2014). The recorded temperatures under 50% garden net shade suggest that moderate shading effectively buffers against extreme temperature fluctuations, thereby minimizing heat-induced stress and promoting stable growth under water-limited conditions.

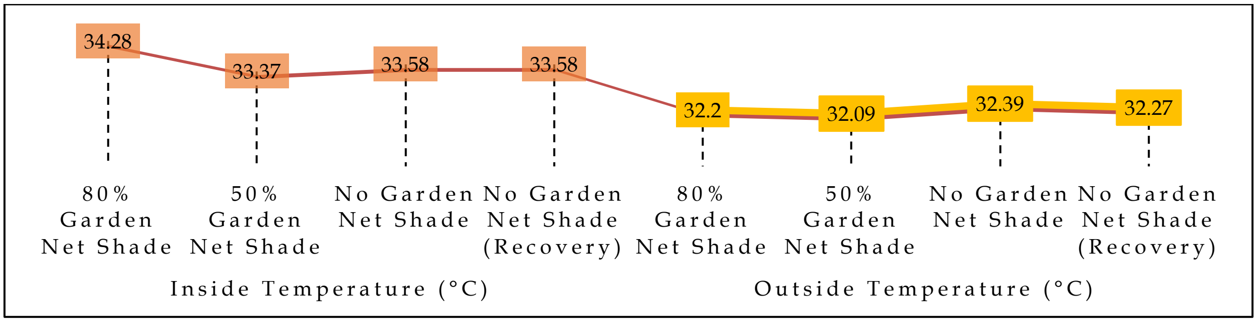

Figure 2. *Mean Temperature Observed under Different Shading Conditions in Robusta Coffee Clone Cuttings and Seedlings to Drought Stress from December 2023-March 2024*

Relative Humidity and Water Use Efficiency

The data illustrated in Figure 3 depict the relative humidity (RH) trend during the drought stress period across different shading treatments in Robusta coffee clone seedlings. The analysis shows variation in RH levels, with the highest percentages recorded under 80% garden net shade and the lowest in the no-shade treatment. Relative Humidity levels remained consistently elevated, creating a microenvironment with reduced vapor pressure deficit (VPD). This lower VPD reduces transpiration by narrowing the gradient between the internal moisture of the leaf and the surrounding air. Suppressing water loss through transpiration helps sustain cell turgor and prolong physiological activity during limited water availability, improving water use efficiency. This outcome supports the conclusions of Larcher (2003), who emphasized the importance of RH in maintaining water balance and cellular function in plants under stress conditions.

Conversely, RH dropped substantially without shade, especially during peak daylight hours. The lower RH under full sun increases VPD, intensifying transpiration and accelerating soil moisture depletion. This rapid water loss limits the plant's ability to maintain turgor pressure, resulting in the earlier onset of wilting, reduced stomatal conductance, and impaired photosynthetic activity. These physiological responses align with the observations of Kramer and Boyer (1995), who reported that plants exposed to low RH environments under drought stress are more likely to experience severe metabolic disturbances and reduced productivity.

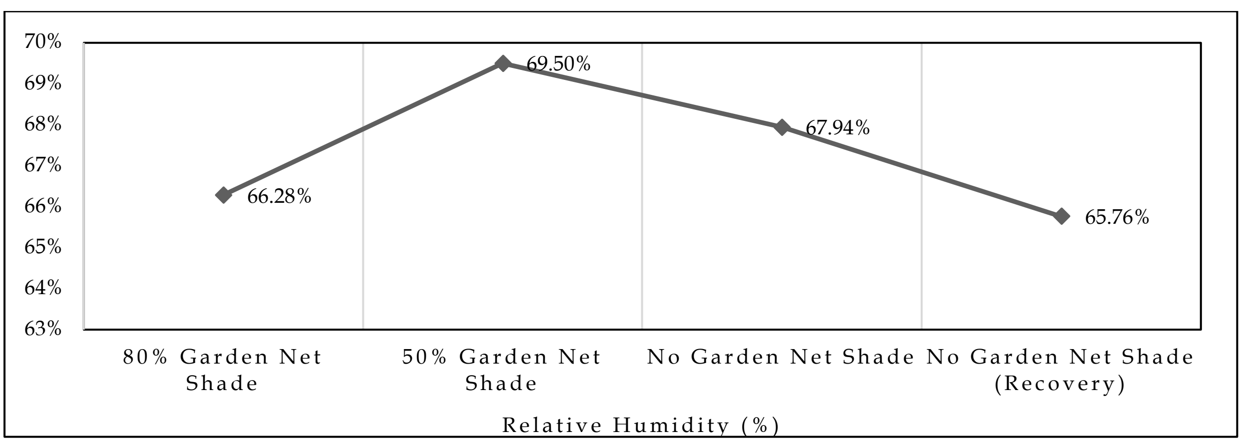

Figure 3. *Percentage of Relative Humidity During the Period of Drought Stress in Robusta Coffee Clone Seedlings*

The findings support shade management as an effective strategy to enhance water use efficiency and drought resilience in Robusta coffee. By increasing relative humidity, shade helps reduce water loss and delay drought effects. However, excessive moisture may hinder cooling and cause heat stress, highlighting the need to tailor shading levels to local climate conditions.

Temperature-RH Interaction and Drought Tolerance Mechanisms

Table 9 showed that the average relative humidity across all observations was 67%, with a low standard deviation of 0.15, suggesting relatively stable RH conditions during the study period. The mean inside screenhouse temperature (34.09°C) was slightly higher than the outside temperature (32.36°C), which may initially seem counterintuitive. However, this can be attributed to the heat retention effect of shading materials, which may trap heat during the day while reducing radiation stress on leaves (Lin, 2007).

Table 9. *Summary of Descriptive Statistics, Correlation, and Regression Analysis for Temperature and Relative Humidity (RH) under Varying Shading Conditions*

Analysis	Variable(s)	Value (Results)	Interpretation
Descriptive	RH	Mean ± SD 0.67 ± 0.15	Moderate RH under experimental conditions
	IST	Mean ± SD 34.09°C ± 3.97	Slightly elevated temperatures under shading materials
	OST	Mean ± SD 32.36°C ± 3.32	Lower temperatures in ambient (unshaded) conditions
Correlation	RH vs. IST	r = -0.9279, ($p < 0.001$)	Strong negative correlation: RH decreases as the IST rises
	RH vs. OST	r = -0.8124, ($p < 0.001$)	Significant inverse relationship with ambient temperature
	IST vs. OST	r = 0.8631, ($p < 0.001$)	Strong direct relationship between IST and OST
Regression	RH ~ IST	R^2 = 0.8610, Adj R^2 = 0.8605	Inside temperature explains 86.1% of RH variability
		β (Intercept) = 1.87, ($p < 0.001$)	Baseline RH when the inside temperature is zero
		β (IST) = -0.04, ($p < 0.001$)	1°C increase leads to a 0.04 decrease in RH
Regression	RH ~ IST+OST	R^2 = 0.8615, Adj R^2 = 0.8605	No significant improvement over RH ~ IST
		β (OST) = -0.00, (p = 0.31)	Not statistically significant

Note: IST = Inside Screenhouse Temperature, OST = Outside Screenhouse Temperature, RH = Relative Humidity

Correlation analysis revealed a strong and statistically significant inverse relationship between RH and both inside screenhouse temperature (r = -0.9279, $p < 0.0001$) and outside screenhouse temperature (r = -0.8124, $p < 0.0001$). These findings align with basic atmospheric physics: as temperature increases, the capacity of the air to hold moisture increases, thereby lowering relative humidity (Taiz & Zeiger, 2006). Notably, the stronger correlation with inside temperature suggests that microclimatic conditions within the screenhouse or under shade have a more immediate and pronounced effect on plant physiological environments.

Regression analysis further supported these relationships. The model using inside temperature alone explained 86.1% of the variance in RH (Adjusted R^2 = 86.05%), with each 1°C increase in temperature associated with a 0.04 unit decrease in RH. The second model, which added outside temperature as a predictor, showed only a marginal improvement in R^2 (86.15%) and revealed that outside temperature was not a statistically significant predictor of RH ($p = 0.3095$). This emphasizes the dominance of screenhouse-level microclimate in determining humidity conditions, confirming that shading interventions influence plant stress environments more than broader ambient temperature shifts. These results support physiological studies that describe how high temperatures coupled with low RH trigger drought responses such as increased abscisic acid (ABA) production, stomatal closure, reduced CO_2 assimilation, and decreased photosynthetic efficiency (Chaves et al., 2009). On the other hand, moderate shading creates a more favorable balance by moderating both temperature and RH, enabling osmotic adjustment and improved water-use efficiency, thereby enhancing drought resilience and post-stress recovery (DaMatta & Ramalho, 2006).

The results align with Lin (2007), who highlighted the benefits of shading in moderating climate extremes and enhancing plant performance. Campanha et al. (2004) also found that improved RH under shade led to higher stomatal conductance and photosynthesis. However, Vaast et al. (2006) cautioned that excessive shading may reduce light availability and limit yields, underscoring the need to optimize shade levels for stress reduction and productivity.

3.9 Impact of Drought Stress on Growth Responses of Robusta Coffee Clone

Table 10 presents the growth responses of Robusta coffee clones under varying levels of drought stress. The statistical analysis reveals significant variation across parameters, highlighting how drought duration, clone type, and their interaction influence different growth aspects. Leaf scorching, characterized by necrotic lesions and browning of leaf margins, is a visible and early indicator of drought-induced physiological stress. In this study, the extent of leaf scorching was significantly influenced by drought duration (p = 0.0000). However, it was not affected by clone type or the interaction between drought and clone ($p > 0.05$), indicating that drought severity, rather than genotype, primarily drives leaf tissue damage under stress.

Table 10. *Growth Responses (Mean ± Standard Deviation) of Robusta Coffee Clones and Seedlings under Different Drought Stress Conditions*

Growth Parameter	Drought Stress (Mean ± SD)	Clone Type (Mean ± SD)	Drought × Clone Interaction	Significance Summary
Leaf Scorching	7 Days: 5.12 ± 1.38 14 Days: 13.45 ± 2.27 21 Days: 21.32 ± 2.94	No significant differences among clones	Not Significant (NS)	Drought stress is significant ($p = 0.0000$) Clone and interaction are not significant
Plant Height (cm)	7 Days: 43.78 ± 4.21 14 Days: 37.66 ± 3.80 21 Days: 29.88 ± 3.42	FRV-B: 41.90 ± 3.95 FRV-K: 30.40 ± 2.88	Significant ($p < 0.0001$)	All effects are significant ($p < 0.0001$)
Plant Girth (mm)	7 Days: 8.24 ± 0.66 14 Days: 7.98 ± 0.61 21 Days: 7.86 ± 0.59	FRV-B: 8.75 ± 0.50 FRV-K: 7.12 ± 0.43	Not Significant (NS)	Clone significant ($p < 0.0001$) Drought ($p = 0.0955$) Interaction NS
No. of Leaves	7 Days: 28.6 ± 3.4 14 Days: 21.4 ± 2.7 21 Days: 15.8 ± 2.2	FRV-SNA: 27.1 ± 2.6 FRV-K: 16.3 ± 1.9	Not Significant (NS)	Drought and Clone are significant ($p < 0.0001$) Interaction NS
Soil Moisture (%)	7Days: 28.1 ± 2.9 14 Days: 18.4 ± 2.6 21 Days: 12.7 ± 2.3	No significant differences among clones	Not Significant (NS)	Drought was significant ($p < 0.0001$), Clone and interaction were NS

As water availability declines, plants continue to transpire until they can no longer maintain turgor, resulting in stomatal closure and eventual cellular breakdown (Chaves et al., 2003). This process is visually manifested as leaf scorching. The increase in scorching, from 5.12 ± 1.38 at 7 days to 21.32 ± 2.94 at 21 days, emphasizes how prolonged drought exacerbates foliar damage. The absence of significant clone-based variation in scorching suggests it may be a non-genotype-specific stress response. This uniformity implies that visual symptoms emerge after plants cross a critical threshold of water deficit, regardless of genotype (Hsiao, 1973). Consequently, leaf scorching alone may be insufficient to assess drought tolerance unless paired with physiological or biochemical markers. These findings align with Wahid et al. (2007), who linked drought-induced leaf damage to oxidative stress and impaired water transport processes across genotypes. While leaf scorching is helpful for early stress detection, additional parameters such as stomatal conductance, chlorophyll content, or leaf retention offer more reliable indicators of drought resilience in breeding contexts.

In contrast, plant height shows significant effects of both drought stress ($p < 0.0001$) and clone type ($p < 0.0001$), along with a strong interaction between the two factors ($p < 0.0001$). These results imply that while water deficiency generally suppresses vertical growth, specific clones exhibit better height retention under stress, pointing to inherent drought resilience mechanisms. Clones like FRV-B and FRV-SNA maintained comparatively greater heights under 21 days of water withholding, likely due to better stomatal regulation or osmotic adjustment, mechanisms well-documented by Zhou et al. (2017). Correlation analysis supports this finding: plant height is highly correlated with the number of leaves ($r = 0.879$, $p < 0.01$) and plant girth ($r = 0.829$, $p < 0.01$), indicating that taller plants generally sustain better overall growth structure (see Table 11).

Plant girth was significantly influenced by clone type ($p < 0.0001$), but not by drought stress ($p = 0.0955$) or the interaction between clone and stress level ($p = 0.319$), indicating that stem development is predominantly under genetic control and remains relatively stable during short-term drought conditions, supported by regression analysis, which revealed a weak explanatory model, with environmental variables accounting for only 1.73% of the variance in girth and no significant predictors identified ($p = 0.233$). The consistently greater stem girth observed in clones such as FRV-B and FRV-K suggests that their genetic characteristics may enhance structural integrity and hydraulic conductivity under water-limited conditions.

The number of leaves was significantly influenced by both drought stress and clone type ($p < 0.0001$), with their interaction approaching statistical significance ($p = 0.0541$), suggesting that while drought generally reduces leaf production, the extent of reduction differs among clones. FRV-B and FRV-SNA maintained higher leaf counts under stress, indicating their potential to sustain photosynthetic activity under water-limited conditions. Correlation analysis reinforces this finding, revealing a strong positive relationship between leaf number and plant height ($r = 0.879$, $p < 0.01$), and a moderate correlation with biomass ($r = 0.650$, $p < 0.05$), highlighting the importance of leaf retention in overall plant productivity under drought stress (see Table 11). As expected, soil moisture content significantly declined under increasing drought stress ($p < 0.0001$). At the same time, clone type and interaction effects were not significant ($p > 0.05$), reaffirming that external water input is the dominant determinant of soil moisture availability (O'Geen, 2013). Regression modelling for soil moisture revealed that relative humidity (p = 0.001) had a significant positive influence, with a parameter estimate of 6.03, while inside temperature negatively impacted moisture levels (estimate = -0.32).

Table 11 presents the relationships between growth traits and environmental factors. Strong positive correlations were found among growth traits, especially between plant height and number of leaves (r = 0.879) and between leaves and biomass (r = 0.816), indicating interdependence. Soil moisture and pH were moderately correlated with biomass and leaf traits. In contrast, temperature showed negative correlations with relative humidity and soil moisture, illustrating its role in shaping drought conditions.

Table 11. *Pearson Correlation Matrix of Growth Parameters and Environmental Factors in Robusta Coffee under Drought Stress*

Variable 1	Variable 2	Correlation Coefficient (r)
Plant Height	Number of Leaves	0.879*
Plant Height	Plant Girth	0.829*
Plant Height	Biomass	0.754*
Number of Leaves	Biomass	0.816*
Soil Moisture	Biomass	0.510*
Soil pH	Biomass	0.546*
Inside Temperature	Relative Humidity	-0.775*
Outside Temperature	Relative Humidity	-0.731*
Soil Moisture	Number of Leaves	0.470*
Soil Moisture	Soil pH	0.501*
Soil pH	Number of Leaves	0.438*
Soil Moisture	Plant Height	0.285*
Soil pH	Plant Height	0.334*
Outside Temperature	Soil Moisture	-0.323*
Inside Temperature	Soil Moisture	-0.386*
Inside Temperature	Soil pH	-0.276**
Outside Temperature	Soil pH	-0.229**
Relative Humidity	Soil pH	0.226**

R coefficients with * are significantly different at a 1% level of significance using Pearson's Correlation
R-squared coefficients with ** are significantly different at a 5% level of significance using Pearson's Correlation

Table 12 shows that plant height, biomass, and girth were only slightly influenced by temperature and humidity. Plant height was moderately affected by inside and outside temperatures and RH ($p = 0.021$), though no single factor was dominant. Biomass had a moderate positive correlation with soil moisture ($r = 0.510$, $p < 0.05$), emphasizing the importance of water availability for growth.

Table 12. *Regression Analyses Between Growth Parameters and Environmental Factors (Temperature and Relative Humidity)*

Growth Parameters	Environmental Factors	p	R^2 (%)
Plant Height	IST, OST, RH	.021	17.76
Biomass	None	.332	2.33
Plant Girth	None	.233	1.73
Soil Moisture	RH, IST	<0.01	51.30

Note: IST = Inside Screenhouse Temperature, OST = Outside Screenhouse Temperature, RH = Relative Humidity
None = No environmental factors (IST, OST, RH, etc.) were significantly correlated or predictive of those growth parameters.

Environmental factors affect Robusta coffee growth but are not the main drivers of key traits like plant height, stem girth, and biomass. Genetic traits, particularly for stem girth, appear to play a more dominant role. Selecting drought-tolerant clones with stable growth for improved productivity under water-limited conditions and maintaining adequate irrigation and soil moisture. Combined correlation and regression analyses show that plant height and leaf number are more sensitive to environmental stress, while stem girth is largely genetically determined. Clones like FRV-B and FRV-SNA, which exhibited strong growth and stress tolerance, are promising candidates for breeding drought-resilient Robusta varieties for climate-affected regions.

4.0 Conclusion

This study contributes to climate-resilient agriculture by identifying drought-tolerant Robusta coffee clones suitable for regions increasingly affected by climate variability, particularly in the Philippines, a major coffee-producing nation highly vulnerable to El Niño and prolonged droughts. By simulating water deficit conditions in a controlled nursery environment, the research demonstrated that drought stress reduces plant growth parameters such as plant height, stem girth, number of leaves, and biomass. However, the distinct responses of clones, especially the superior performance of FRV-SNA and FRV-B in biomass accumulation and plant recovery, and FRV-K in height retention, underline the genetic variation in stress adaptation.

The study's contribution is a science-based framework for selecting and propagating drought-resilient Robusta clones, which can strengthen nursery management practices and inform government-supported coffee rehabilitation and climate adaptation programs, integrating morphological, physiological, and environmental indicators. The implications are substantial as prioritizing resilient clones can reduce the risk of seedling loss during water shortages, lower production costs, and ensure more stable supply chains in the coffee industry. This means more confidence in planting materials, even under increasingly unpredictable rainfall patterns for coffee farmers and nursery operators. For policymakers, it offers evidence to support targeted interventions, such as promoting localized varietal selection and drought-aware extension services.

Further studies should examine the long-term field performance of these promising clones under actual farming conditions, including soil variability, pest pressures, and multi-season drought cycles. Research into physiological and molecular mechanisms, such as root architecture, osmotic adjustment, and stress-responsive gene expression, could further enhance our understanding of drought resilience in Robusta coffee. Additionally, integrating this data into predictive climate-smart decision-support tools can aid in scaling up adaptation strategies across similar agroecological zones. This study offers evidence-based insights that enable stakeholders to develop a more resilient and sustainable coffee sector amid climate change.

5.0 Contributions of Authors

All the authors were responsible for the conceptualization of the study. Rhealiza C. Evasco conducted and collected the necessary data, analyzed the study, and drafted the manuscript. Junito P. Marcelino provided technical guidance, supervised the research process, and reviewed and edited the manuscript.

6.0 Funding

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7.0 Conflict of Interest

The author declares no conflicts of interest, financial or otherwise, that could have influenced the study's findings or conclusions.

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9.0 References

Anim-Kwapong, E., Padi, F. K., & Danquah, E. Y. (2011). Variation and association among characters genetically related to yield and yield stability. Journal of Plant Breeding and Crop Science, 3(12), 311–320. https://doi.org/10.5897/JPBCS11.054

Arunyanark, A., Roonprapant, P., Sridokchan, W., Pakoktom, T., & Chutteang, C. (2022). Effect of water deficit and propagation methods on physiological responses of robusta coffee (Coffea canephora) varieties. Agriculture and Natural Resources, 56(6), 1123–1134. https://doi.org/10.34044/j.anres.2022.56.6.07

Avelino, J., Cristancho, M., Georgiou, S., Imbach, P., Aguilar, L., Bornemann, G., Läderach, P., Anzueto, F., Hruska, A. J., & Morales, C. (2015). The Coffee Rust Crisis in Colombia and Central America (2008–2013): Impacts, plausible causes and proposed solutions. Food Security, 7(2), 303–321. https://doi.org/10.1007/s12571-015-0446-9

Begg, J. E., & Turner, N. C. (1970). Water potential gradients in field tobacco. Plant Physiology, 46(2), 343–346. https://doi.org/10.1104/pp.46.2.343

Boston, R. C., & Sumner, A. E. (2003). STATA: A statistical analysis system for examining biomedical data. In J. A. Novotny, M. H. Green, & R. C. Boston (Eds.), Mathematical modeling in nutrition and the health sciences (Vol. 537, pp. 191–202). Springer. https://doi.org/10.1007/978-1-4419-9019-8_23

Campanha, M.M., Santos, R.H.S., de Freitas, G.B., Martinez, H.E.P., Muniz, J.A., & Finger, F.L. (2004). Growth and yield of coffee plants in agroforestry and monoculture systems in Minas Gerais, Brazil. Agroforestry Systems, 63(1), 75–82. https://doi.org/10.1023/B:AGFO.0000049435.22512.2d

Chekol, H., Warkineh, B., Shimber, T., Mierek-Adamska, A., Dąbrowska, G. B., & Degu, A. (2024). Drought stress responses in arabica coffee genotypes: Physiological and metabolic insights. Plants, 13(6), 828. https://doi.org/10.3390/plants13060828

de Souza, G. A., Baroni, D. F., Bernado, W., Santos, A. R., Barcellos, L. C., Barcelos, L. F., Correia, L. Z., de Almeida, C. M., Verdin Filho, A. C., Rodrigues, W. P., Ramalho, J. C., Rakočević, M., & Campostrini, E. (2025). Leaf to root morphological and anatomical indicators of drought resistance in Coffea canephora after two stress cycles. Agriculture, 15(6), 574. https://tinyurl.com/2aa7rrnh

dos Santos, C. S., de Freitas, A. F., da Silva, G. H., Pennacchi, J. P., Figueiredo de Carvalho, M. A., Santos, M., Junqueira de Moraes, T. S., de Rezende Abrahão, J. C., Pereira, A. A., Carvalho, G. R., Botelho, C. E., & Silva, V. A. (2023). Phenotypic plasticity index as a strategy for selecting water-stress-adapted coffee genotypes. Plants, 12(23), 4029. https://doi.org/10.3390/plants12234029

Farooq, M., Wahid, A., Kobayashi, N., Fujita, D., & Basra, S. M. A. (2009). Plant drought stress: Effects, mechanisms and management. Agronomy for Sustainable Development, 29(1), 185–212. https://doi.org/10.1051/agro:2008021

Gomez, K. A., & Gomez, A. A. (1983). Statistical procedures for agricultural research (2nd ed.). John Wiley and Sons.

Gutierrez, R. (2010). Competing-risks regression. Stata Conference, Boston, July 15–16. StataCorp.
Kramer, P.J. & Boyer, J.S. (1995). Water relations of plants and soils. Academic Press, San Diego.
Larcher, W. (2003). Physiological plant ecology: Ecophysiology and stress physiology of functional groups (4th ed.). Springer-Verlag Berlin Heidelberg
Lawlor, D. W., & Tezara, W. (2009). Causes of decreased photosynthetic rate and metabolic capacity in water-deficient leaf cells: A critical evaluation of mechanisms and integration of processes. Annals of Botany, 103(4), 561–579. https://doi.org/10.1093/aob/mcn244
Lin, B.B. (2007). Agroforestry management as an adaptive strategy against potential microclimate extremes in coffee agriculture. Agricultural and Forest Meteorology, 144(1–2), 85–94. https://doi.org/10.1016/j.agrformet.2006.12.009
Maestri, M., DaMatta, F. M., Regazzi, A. J., & Barros, R. S. (1995). Accumulation of proline and quaternary ammonium compounds in mature leaves of water-stressed coffee plants (Coffea arabica and C. canephora). Journal of Horticultural Science, 70, 229–233.
Meinzer, F. C., Saliendra, N. Z., & Crisosto, C. H. (1992). Carbon isotope discrimination and gas exchange in Coffea arabica during adjustment to different soil moisture regimes. Australian Journal of Plant Physiology, 19(2), 171–184.
O'Geen, A. T. (2013). Soil water dynamics. Nature Education Knowledge. https://tinyurl.com/y27czzp2
Poorter, H., Bühler, J., van Dusschoten, D., Climent, J., & Postma, J. A. (2012). Pot size matters: A meta-analysis of the effects of rooting volume on plant growth. Functional Plant Biology, 39(11), 839–850. https://doi.org/10.1071/FP12049
Pugnaire, F. I., Serrano, L., & Pardos, J. (1999). Constraints by water stress on plant growth. In M. Pessarakli (Ed.), Handbook of plant and crop stress (pp. 271–283). Marcel Dekker.
Ramirez-Builes, V. H., Küsters, J., Thiele, E., & Lopez-Ruiz, J. C. (2024). Physiological and agronomical response of coffee to different nitrogen forms with and without water stress. Plants, 13(10), 1387. https://doi.org/10.3390/plants13101387
Rosario, D. A., Ocampo, E. M., Sumague, A. C., & Paje, M. C. M. (1992). Adaptation of vegetable legumes to drought stress. In C. G. Kuo (Ed.), Adaptation of food crops to temperature and water stress: Proceedings of an international symposium (pp. 360–371). Asian Vegetable Research and Development Center (AVRDC).
Roonprapant, P., Arunyanark, A., & Chutteang, C. (2021). Morphological and physiological responses to water deficit stress conditions of robusta coffee (Coffea canephora) genotypes in Thailand. Agriculture and Natural Resources, 55(3). https://doi.org/10.34044/j.anres.2021.55.3.18
Sadak, M. S., Tawfik, M. M., & Bakhoum, G. S. (2021). Role of chitosan and chitosan-based nanoparticles on drought tolerance in plants: Probabilities and prospects. In Role of chitosan and chitosan-based nanomaterials in plant sciences (pp. 475–501). Elsevier. https://doi.org/10.1016/B978-0-323-85391-0.00013-7
Satake, A., Sakurai, G., & Kinoshita, T. (2015). Modeling strategies for plant survival, growth, and reproduction. Plant and Cell Physiology, 56(4), 583–585. https://doi.org/10.1093/pcp/pcv041
Silva, P. E. M., Cavatte, P. C., Morais, L. E., Medina, E. F., & DaMatta, F. M. (2013). The functional divergence of biomass partitioning, carbon gain, and water use in Coffea canephora in response to the water supply: Implications for breeding aimed at improving drought tolerance. Environmental and Experimental Botany, 87, 49–57.
Tesfaye, S. G., Ismail, M. R., Kausar, H., Marziah, M., & Ramlan, M. F. (2013). Plant water relations, crop yield, and quality in coffee (Coffea arabica L.) as influenced by partial root zone drying and deficit irrigation. Australian Journal of Crop Science, 7(9), 1361–1368.
Ullah, I., Mao, H., Rasool, G., Gao, H., Javed, Q., Sarwar, A., & Khan, M. I. (2021). Effect of deficit irrigation and reduced fertilization on plant growth, root morphology, and water use efficiency of tomato grown in soilless culture. Agronomy, 11(2), 228. https://doi.org/10.3390/agronomy11020228
Vaast, P., Bertrand, B., Perriot, J., Guyot, B., & Génard, M. (2006). Fruit thinning and shade improve bean characteristics and beverage quality of coffee (Coffea arabica L.) under optimal conditions. Journal of the Science of Food and Agriculture, 86(2), 197–204. https://doi.org/10.1002/jsfa.2338
Verslues, P. E., & Juenger, T. E. (2011). Drought, metabolites, and Arabidopsis natural variation: A promising combination for understanding adaptation to water-limited environments. Current Opinion in Plant Biology, 14(3), 240–245. https://doi.org/10.1016/j.pbi.2011.04.006
Vu, N. T., Park, J. M., Tran, A. T., Bui, T. K., Vu, D. C., & Jang, D. C. (2018). Effect of water stress on the growth and physiology of coffee plants. Journal of Agricultural Life and Environmental Sciences, 2018, 121–130.
Worku, M., & Astatkie, T. (2010). Growth responses of arabica coffee (Coffea arabica L.) varieties to soil moisture deficit at the seedling stage at Jimma, Southwest Ethiopia. Journal of Food, Agriculture and Environment, 8(1), 195–200.
Yang, S., Lan, S., & Gong, M. (2009). Hydrogen peroxide-induced proline and metabolic pathway of its accumulation in maize seedlings. Journal of Plant Physiology, 166(15), 1694–1699. https://doi.org/10.1016/j.jplph.2009.04.006
Zhou, R., Yu, X., Ottosen, C.-O., Rosenqvist, E., Zhao, L., Wang, Y., Yu, W., Zhao, T., & Wu, Z. (2017). Drought stress had a predominant effect overheat stress on three tomato cultivars subjected to combined stress. BMC Plant Biology, 17, 24. https://doi.org/10.1186/s12870-017-0974-x