Kirkuk University Journal for Agricultural Sciences
ISSN:2958-6585
https://kujas.uokirkuk.edu.iq

RESEARCH ARTICLE https://doi.org. 10.58928/ku26.17208

Effect of Different Irrigation Periods and Methods on the Growth, Biomass, Nutrient Uptake and Physiological Traits of *Leucaena leucocephala (Lam.) De Wit* Saplings Planted in the Bardarash District, Kurdistan Region, Iraq

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Received:29/10/2025 **Revised: 25/12/2025** **Accepted: 07/06/2026** **Published: 08/06/2026**

ABSTRACT

Background: Irrigation management is one of the most crucial silvicultural practices in enhancing the growth and establishment of tree plantations in arid and semi-arid regions. Therefore, the present study evaluated the effects of different irrigation periods, methods and their interactions on the growth, biomass allocation, nutrient uptake, and physiological traits of Leucaena leucocephala saplings in Bardarash District, Kurdistan Region, Iraq.
Methods: A factorial randomized complete block design (RCBD) with two factors was conducted. The first factor was three irrigation periods (every 3, 6, and 9 days) and the second factor was three irrigation methods (surface irrigation, deep irrigation without wicks, and deep irrigation with wicks).
Results: Results displayed that growth and biomass traits were significantly influenced by irrigation periods. Saplings watered every three and six days revealed greater growth, biomass, and relative water content compared to those watered every nine days, which showed growth reduction due to drought. Irrigation methods showed that stem growth and root biomass were improved under surface irrigation, whereas leaf mass ratio enhanced under deep irrigation with wicks. Different nutrient uptake patterns were observed among treatments. The highest nitrogen content was under less frequent (9 day) deep irrigation without wicks, the best phosphorus content was under moderate (6 day) surface irrigation, and potassium under more frequent (3 days) wick irrigation. Physiological traits revealed that protein content, chlorophyll content, and water-use efficiency improved under moderate and less irrigation frequency (6–9 days), while relative water content enhanced under more frequent irrigation (3 days). Irrigation techniques revealed that protein content and relative water content declined under subsurface irrigation with wicks.
Conclusion: The results showed that using surface or deep non-wick irrigation every six days maximizes water savings without compromising sapling development and nutrient efficiency. The findings enhanced knowledge about irrigation management for afforestation and reforestation programs in semi-arid regions.

***Keywords*:** Leucaena leucocephala, Irrigation periods, Irrigation methods, Growth performance, Biomass allocation, Nutrient uptake, Water use efficiency, Relative water content, Protein content.

INTRODUCTION

Leucaena leucocephala (Lam.) de Wit is a multipurpose, fast-growing leguminous tree that is widely distributed in tropical and subtropical regions. Reaching a height of 7-18 meters, this thornless perennial plant has bipinnate leaves composed of 6-8 pairs of pinnae containing 11-23 pairs of leaflets. The tree produces cream-colored, globular inflorescences that develop into brown, flat pod clusters that contain 15–30 seeds [1].

Because of its ability to grow and thrive in almost any environment, its capability to grow quickly, and its high ability to fix nitrogen from the atmosphere into the soil, *L. leucocephala* is heavily used in afforestation and reforestation, agroforestry systems, and also as construction, paper pulp, fuelwood, and fodder sources [2 ,3, 4]. It is also used as timber to make supports for climbing crops, as well as in light construction, while its leaves provide an important protein and nutrient supplement for ruminant livestock [2].

Given the species' potential, foresters should plant it for afforestation and reforestation projects. The plantation projects have employed a number of silvicultural treatments to enhance the survival, growth, quality and health of the trees. Availability of water is one of the most crucial factors in the establishment, growth, biomass accumulation, nutrient uptake, and physiological performance of trees, particularly under the climatic variability of dryland forestry systems [5]. Studies that manipulate irrigation interval or the amount delivered commonly report that shorter intervals increase growth and biomass and early establishment vigor of Leucaena, while longer intervals or reduced water reduced shoot growth but often increase root: shoot ratio and certain drought- response traits. These responses are consistent across pot and field experiment [6]. The water requirement of any species depends on its morphological traits, growth stage, and environmental conditions. Irrigation frequency and technique have been shown to significantly influence the survival, growth, and productivity of fast-growing forest tree seedlings, such as *L. leucocephala*. Regular irrigation often promotes growth and survival, but prolonged irrigation intervals significantly reduce biomass, plant height, root length and survival rate [7]. The shoot and root growth of *L. leucocephala* have also been shown to be affected by irrigation regimes; moderate irrigation has been found to be the most successful in maintaining growth and water-use efficiency [8].

When water is scarce, a variety of irrigation methods are also required for seedling establishment. The common method of irrigation is surface irrigation due to its simplicity and low cost. However, it causes increasing water loss due to high evaporation if it is not managed properly [9]. In addition, subsurface irrigation techniques such as wick and non-wick-based irrigation are an innovative watering method that have been developed to enhance deeper root development and promote water-use efficiency. Wick irrigation delivers water to the root zone gradually and steadily, it also increases seedling establishment and minimizes water loss in dry and semi-arid environments [10].

The establishment of *L. leucocephala*, a tree species of ecological and commercial significance, depends heavily on irrigation management. Therefore, further research is required to determine the best irrigation intervals and techniques to improve its survival, growth and development in semi-arid environments. This study aims to evaluate the effects of irrigation frequency and method on the growth, biomass allocation, nutrient uptake, and physiological traits of *L. leucocephala* saplings in Bardarash District, Kurdistan Region, Iraq.

Materials And Methods

1. The species under study:

For this study an adequate number of *Leucaena leucocephala* (Lam) de wit seedlings were bought in a private nursery in Mosul city on the first of July. The average stem height, and diameter of the seedlings were approximately 68.42 ±2.37 cm and 5.11±0.17 mm respectively.

2. Location of the study:

The study was conducted in Barda-Rash Forest (36°29'23.3"N 43°35'09.0"E) in Barda-Rash region- Dohuk Governorate as shown in Figure 1, from the middle of July 2024 to the end of November 2024. Before conducting the experiment, a representative number of soil samples were taken from the upper 50 cm of the field soil and sent to the soil laboratory at the Agricultural Research Center- Erbil to analyze their physical and chemical properties as shown in Table 1. A hydrometer was used to determine the quantity of sand, silt and clay, a pH meter was used to the acidity and alkalinity of the soil, a Kjeldal apparatus was used to determine the total nitrogen content, a spectrophotometer was used to determine the extractable phosphorus content and a photometer was used to determine the soluble potassium content in the soil [11, 12]. Furthermore, during the experiment period, daily air temperature of the area was recorded using thermo-hygrograph equipment, then the mean of minimum, maximum and average of the air temperature for each month were discovered, as shown in Table 2.

Table 1: Some physical and chemical characteristics of the field soil which were examined in June 2024

Soil characteristics	Amounts	Units
Sand	69.9	%
Silt	12	%
Clay	18.1	%
Texture	Sandy Loam	
pH	7.92	
EC (Electrical Conductivity)	0.2	$dS.m^{-1}$
Nitrogen	0.011	%
Phosphorous	29	ppm
Potassium	100	ppm

Table 2: Air temperature of the study area from July to November 2024

Months (2024)	Air Temperature ˚C		
	Minimum	Maximum	Average
July	29.57	45.83	37.70
August	29.39	47.81	38.60
September	25.77	44.00	34.88
October	18.03	33.71	25.87
November	13.63	24.73	19.18

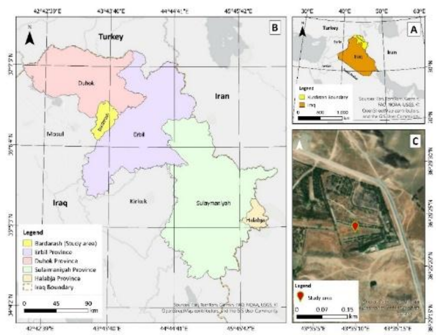

Figure 1: The map of the study area

3. Experimental Design

The experiment followed a factorial randomized complete block design (RCBD) with two factors. The first factor was three irrigation periods, which included every 3 days, every 6 days and every 9 days [6]. The second factor was three irrigation methods, which included the surface irrigation (SI), deep irrigation without wicks (DI-W) and deep irrigation with wicks (DI+W). Each treatment was replicated four times, so the total number of experimental units were 36 as shown in Figure 2. The required amount of water to reach full water field capacity of the soil was found as proceed by [13]. On this base, 18 L water was manually added for each irrigation treatment.

Every 3 Days Irrigation			Every 6 Days Irrigation			Every 9 Days Irrigation			
DI+W	SI	DI-W	SI	DI-W	DI+W	DI-W	DI+W	SI	Block 1
DI-W	SI	DI+W	DI+W	DI-W	SI	DI-W	SI	DI+W	Block 2
DI-W	DI+W	SI	DI+W	SI	DI-W	SI	DI-W	DI+W	Block 3
SI	DI-W	DI+W	DI-W	DI+W	SI	DI+W	DI-W	SI	Block 4

2M 2M 3M

Figure 2: Layout of the experiment

4. Land Preparation and Planting

In accordance with the experimental design, the area was first marked out plowed and prepared. After that planting holes with dimensions of 50 × 50 × 50 cm (depth × length × breadth) were dug out. The holes in the same irrigation periods were spaced 2 meters apart, whereas the holes in different irrigation periods were spaced 3 meters apart. Additionally, three techniques for irrigation (Figure 3) were used as following:

1) Surface irrigation: In accordance with the experimental plan, circular basins with an 18 L capacity were built around each seedling to make water application easier.
2) Deep irrigation without wicks: To enable subsurface water delivery, 18 L buckets were positioned next to the seedlings at a depth of about 12 cm below the soil surface and drilled at two locations close to the base.
3) Deep irrigation with wicks: 18 L buckets were equipped with wicks and pierced at two locations close to the base. Each wick was placed with one end in the root zone and the other end through the perforation. The buckets were buried beneath the soil's surface.

Water was manually applied over 80 seconds per irrigation event.

Figure 3: Irrigation methods, Surface irrigation (A), Deep irrigation without wicks (B), Deep irrigation with wicks (C), The buckets with or without wicks were buried beneath the soil's surface at 12 cm (D).

5. Studied parameters:

5.1. Growth parameters

Growth characteristics, which were stem height (cm), and stem diameter (mm), leaf number, and branch number at the start of the experiment were measured. Additionally, at the end of the trial, the aforementioned parameters were recalculated to find increment of stem height (cm), and stem diameter (mm), leaf number, and branch number.

5.2 Leaf area (LA- cm^2):

Three fully grown leaves from the top, middle, and bottom of the saplings were taken in each experimental unit to find the leaf area (cm^2) by using the Image J application, as described by [14].Then the average of leaf area per experimental unit was used to statistical analysis.

6.Biomass parameters

6.1 Biomass allocation

At the end of the experiment, three saplings from each treatment were randomly chosen and harvested. Their roots were gently washed to remove the soil. After that the saplings were divided into its constituent, which were stem, leaf, and root. Furthermore, the parts of the saplings were oven-dried at 60ºC for 72 hours in order to confirm a consistent dry weight.

6.2 Biomass ratio

From the biomass allocation parameters biomass ratios, were computed [15]. Among the biomass ratios are Stem mass ratio (STM) (stem dry weight (g)/ (total dry weight (g)), Leaf mass ratio (LMR) (leaf dry weight (g)/ (total seedling dry weight (g)), Root mass ratio (RMR) (root dry weight (g)/ (total dry weight (g)), Root to shoot ratio (R:S) (root dry weight (g)/ (shoot dry weight (g)).

7. Biochemical parameters

Leaf samples that had previously been dried and powdered were used to evaluate the macronutrient contents of nitrogen (N), phosphorus (P), and potassium (K). The micro-Kjeldahl digestion method was used to calculate the total nitrogen content (%), as explained by [11]. According to [12], the colorimetric method (V-1100 digital) was utilized to determine the total phosphorus (%) concentration using a spectrophotometer set at 410 nm. The total potassium content (%) of the leaves was determined using a flame photometric technique (BWB Technologies) as described by [12].

8. Physiological parameters

8.1. Chlorophyll Content:

For each sapling, three full mature leaves from different positions of canopy (bottom, middle, and top) were carefully chosen to detect chlorophyll content using a portable chlorophyll meter SPAD-502 (Konica Minolta, Japan) [16]. Additionally, the average of these three chlorophyll measurements were taken for each of the saplings.

8.2. Protein content (%):

Protein content was determined using the formula given by [17] and as follows:

Protein percentage = (N%) * 4.64.

N%: Nitrogen percentage.

4.64: The constant ratio.

8.3 Relative water content (%)

Three comparable fully developed leaves from each seedling were sampled in order to determine the relative water content (RWC) of the leaves. In order to get fresh weight, leaf samples were brought to the lab after being packed in plastic and kept above ice in a cooler. After that, the leaves floated on water for a full day in order to soak and determine their turgid weight. Turgid leaves were dried at 70°C until their weight remained constant [18]. RWC was computed using the following formula:

$$\mathrm{RWC} = \frac{(\mathrm{FW} - \mathrm{DW})}{(\mathrm{TG} - \mathrm{DW})} \text{ X } 100$$

FW: Sample fresh weight
DW: Sample dry weight
TW: Sample turgid weight

8.4. Water use efficiency (g/L)

Water use efficiency (WUE), is the ratio of total biomass produced to total water used in the process. It evaluates a plant's capacity to use water for growth and development. It is computed using the following formula [19]:

$$\text{Water Use Efficiency (g/L)} = \frac{\text{Total plant biomass (g)}}{\text{Total water used (L)}}$$

9. Data analysis:

The data of growth, biomass, biochemical, and physiological traits were submitted individually to Analysis of Variance (ANOVA) using SPSS software Version 26. The significant differences between treatment means were compared by Duncan Multiple Rang Test at $p \leq 0.05$ [20].

Results And Discussions

1. Influence of irrigation periods, irrigation methods and their interactions on growth parameters of *Leucaena leucocephala* saplings

Table 1 shows that the irrigation frequency significantly influenced all growth parameters of *Leucaena leucocephala* saplings ($P < 0.01$). Saplings irrigated every 3 days exhibited the highest stem height (143.50 cm), stem diameter (27.40 mm), leaf number (29,503), leaf area (7.80 cm²), and branch number (17). In contrast, saplings irrigated every 9 days showed the lowest values across these metrics, indicating drought-induced growth suppression. These patterns indicate that frequent watering helps maintain higher soil water potential, which supports sustained cell expansion, leaf development, and cambial activity [21]. However, no significant differences were observed between the 3-day and 6-day treatments for stem height, leaf number, and branch count, suggesting that a 6-day interval may be sufficient for maintaining growth under semi-arid conditions. These findings concur with prior researches that adequate irrigation frequency positively influenced growth performance. Conversely, extended irrigation periods negatively influenced the growth properties. Previous research on *Leucaena leucocephala* seedlings revealed similar gains in growth rate and root formation under more frequent watering, but longer intervals consistently reduced performance [22]. Studies on other species, like *Acacia nilotica*, *Dalbergia sissoo*, and *Paulownia tomentosa*, show that regular irrigation increases stem height, stem diameter, and leaf output whereas infrequent watering hinders growth. [23, 7, 16]. The decline in growth under extended irrigation periods in the current study may be connected to physiological limitations induced by drought stress. Decreased soil moisture reduces turgor pressure, a significant driver of cell development, thereby limiting vertical and horizontal growth of stems. The reduction in stem diameter under water stress could be the result of reduced water supply, which shrinks xylem channels and inhibits stem circular growth [24]. Additionally, plants cultivated in drought-prone environments typically have decreased stomatal conductance, which aids in water saving and maintaining an acceptable leaf water status. However, this also lowers photosynthesis and internal CO_2 concentration in the leaves, which in turn slows growth [25]. The concordance between the current data and previous studies generally supports the hypothesis that *Leucaena leucocephala* is highly responsive to irrigation scheduling, with shorter intervals encouraging optimal growth and longer intervals producing quantifiable physiological constraints.

Regarding the irrigation methods, the data demonstrated that all growth parameters except for stem height were not significantly affected by the irrigation methods. Where the highest stem height (138.92 cm) recorded in the surface irrigation, while the poorest value (107.58 cm) was observed in the deep irrigation with wicks. This suggests that stem height was the only variable to respond in a significant way between irrigation method; with surface irrigated saplings attaining greatest height whereas those receiving deep-wick treatments were the shortest. This result indicates that the root-zone moisture distribution in the upper rooting zone (the foremost region for nutrient absorption and growth regulation processes like cell elongation, hormone synthesis) has a critical impact on shoot extending about plant adjustment to drying soil conditions [26]. This pattern is consistent with known differences in soil wetting patterns among irrigation systems. Surface irrigation typically maintains a wider and shallower wetting front, supporting root proliferation in the upper soil layers where nutrient availability, oxygen supply, and hormonal signaling most strongly influence shoot elongation. In contrast, deep-wick irrigation preferentially hydrates deeper soil zones and can leave the upper root zone periodically dry. Even in the absence of soil-moisture measurements, this mechanism is well supported by prior work showing that drying of the upper root zone can trigger ABA-mediated inhibition of shoot growth, similar to the physiological response observed under partial root-zone drying (PRD) [27, 28]. By contrast, stem diameter and branching characteristics did not vary significantly among irrigation methods. These traits often integrate growth over a longer time span than height and are less sensitive to short-term fluctuations in surface moisture distribution. Similar insensitivity has been reported for structural growth parameters under varied irrigation systems in seedling cultivation and orchard crops [26, 29].

The interaction effect between irrigation periods and irrigation methods revealed that all growth parameters were not significantly influenced ($P > 0.05$) by the combination. In contrast, the Duncan's multiple range test showed that there were statistical differences among means of the studied parameters. The comparison among means showed that the best interaction was 3-day irrigation with the surface method, which achieved the highest stem height (163.5 cm), stem diameter (28.7 mm), number of leaves (33460), leaf area (8.08 cm²) and branch number (21). These results concur with Singh [30], who displayed that surface irrigation around seedlings in arid plantation guarantees effective establishment by keeping satisfactory root-zone moisture. The results of stem height, stem diameter, and leaf number showed that irrigation every 3 and 6 days with the three irrigation methods obtained statistically the same result, which means that it was possible to irrigate every 6 days instead of 3 days by any of the irrigation methods. This offers water savings without compromising productivity. On the other hand, the poorest growth performance was achieved under the combination of irrigation every 9 days and deep irrigation with wick, indicating that both long intervals and subsurface irrigation could lead to poor root-zone environment for plant growth. The current results can be interpreted by some environmental and physiological mechanisms described in the previous studies. The better growth at 3-day and 6-day irrigation intervals was due to the sufficient soil moisture content around fine feeder roots which allows cell elongation and maintains stomatal conductance as well as photosynthetic activities [31].The similar performance under 3- and 6-day treatments indicates that *Leucaena leucocephala* seedlings could tolerate moderate soil drying without reductions in air water potential, displaying adaptive plasticity for tree seedlings grown under semi-arid environments [31, 32]. When applied regularly, irrigation also enhanced nutrient availability by improving nitrogen and phosphorus solubilization and translocation hence leading to an increase in stem diameter and leaf formation [33]. In contrast, the lowest performance under 9-day deep irrigation with wick reflects the adverse impacts of water stress, which was attributed to a prolonged reduction in soil water potential that limited root water uptake and foliar development [34, 35]. Additionally, subsurface wick irrigation may bypass the shallow root zone where young saplings concentrate their feeder roots, resulting in an unfavorable root–water interface and inefficient uptake [26]. Furthermore, abscisic acid (ABA), which is produced as a result of prolonged water deprivation, promotes stomatal closure and reduces carbon uptake, ultimately restricting development [36]. These mechanisms explain why frequent surface irrigation encouraged optimal growth while extended intervals, particularly with wick-based systems, restricted seedling development.

Table 1. Influence of irrigation periods, irrigation methods and their interactions on growth parameters of *Leucaena leucocephala* saplings.

Irrigation Periods (Once every)	Irrigation Methods	Stem Height Increment (cm)	Stem Diameter Increment (mm)	Leaf Number Increment	Leaf Area (cm^2)	Branch Number
3 days		143.50±10a	27.40±2a	29503±2590a	7.80±0.2a	17.00±2a
6 days		130.67±13a	21.48±2b	27783±3563a	6.49±0.2b	13.58±1ab
9 days		97.67±11b	13.46±2c	10608±1404b	5.61±0.2c	10.42±1b
P-Value		0.001	0.00003	0.00001	<0.01	0.002
	SI	138.92±11a	21.95±2a	25882±3445a	6.55±0.4a	15.42±2a
	DI without W	125.33±11ab	21.26±2a	21810±3765a	6.60±0.3a	13.08±1a
	DI with W	107.58±14b	19.13±3a	20203±3691a	6.75±0.3a	12.50±1a
	P-Value	0.042	0.484	0.490	0.719	0.205
3 days	SI	163.50±11a	28.70±2a	33460±2950a	8.08±0.1a	21.00±2a
	DI without W	139.50±8ab	25.68±2ab	27100±4778a	7.52±0.4ab	15.50±3b
	DI with W	127.50±25ab	27.83±5ab	27950±5856a	7.79±0.4a	14.50±2b
6 days	SI	150.25±12ab	22.25±3abc	31440±5092a	6.33±0.2cd	14.25±2b
	DI without W	121.00±31ab	23.30±6abc	27670±8165a	6.37±0.4cd	13.00±3b
	DI with W	120.75±24ab	18.875±3bcd	24240±6196ab	6.79±0.3bc	13.50±2b
9 days	SI	103.00±20bc	14.90±3cd	12745±2989bc	5.26±0.1e	11.00±2b
	DI without W	115.50±12bc	14.80±2cd	10660±2045c	5.91±0.3cde	10.75±2b
	DI with W	74.50±22c	10.68±3d	8420±2334c	5.67±0.3de	9.50±2b
P-Value		0.541	0.802	0.977	0.352	0.581

Means within each column for each factor followed by the same letter are not significantly different from each other according to Duncan's Multiple Range Test at a 5% level. (S: Surface, I: Irrigation, D: Deep, W: Wicks).

2. Influence of irrigation periods, irrigation methods and their interactions on biomass allocation of *Leucaena leucocephala* saplings

The data presented in the Table 2 shows that the irrigation periods had a high significant effect ($p<0.01$) on all biomass allocation traits of the saplings. The highest mean value for stem dry weight (662.22 g), leaf dry weight (456.11 g), root dry weight (365g) and total dry weight (1483.33 g) were achieved from the irrigation every 3 days. In addition, there were no statistical differences between irrigation periods of 3 and 6 days in terms of all biomass allocations except leaf dry weight. On the other hand, the lowest biomass allocation parameters were observed under the irrigation every 9 days. This trend is consistent with conventional drought-growth response curves in woody plants, which demonstrate that when soil water becomes scarce, turgor-driven cell development first slows down (particularly in leaves). A gradual down-regulation of photosynthesis and stomatal conductance ensues, leading to a reduction in biomass and whole-plant carbon acquisition [37].

However, reduced photosynthesis and limited leaf expansion under prolonged water deficit restricted assimilate supply to all organs, and the 9-day irrigation interval exceeded the stress threshold, resulting in uniformly lower stem, root, and total biomass [38]. Shorter irrigation intervals help maintain mesophyll CO_2 diffusion and stomatal conductance (g□), supporting greater carbon assimilation and growth. In contrast, longer intervals trigger abscisic acid-induced stomatal closure, reduced leaf water potential, and impaired carbon metabolism, with leaf expansion and cambial activity being especially sensitive to water shortage [37]. Adequate water supply maintains higher photosynthetic efficiency and chlorophyll content, enhancing biomass accumulation, while water stress reduces chlorophyll and limits CO_2 assimilation [39]. Water availability is therefore a primary constraint to growth in arid regions. Insufficient water decreases carbohydrate supply, disrupts transport and metabolic processes, especially carbohydrate and amino-acid metabolism and ultimately reduces biomass [40]. Similar trends have been reported on *L. leucocephala* and other species. Empirical investigations on *L. leucocephala* also show higher dry matter yields with increased irrigation amount or frequency [41], and more frequent watering significantly enhanced stem, leaf, and root dry weights in *Paulownia tomentosa* seedlings [16].

The irrigation methods indicated that all the biomass allocation traits except for root dry weight were not significantly changed by different watering strategies. The best irrigation method to boost root dry weight (358.33 g) was surface irrigation, while the poorest root dry weight (244.89 g) was obtained under the deep irrigation with wicks. This research reveals how fine roots spontaneously shoot out in the top layers of soil, which are rich in nutrients and particularly sensitive to moisture on the surface [42, 43]. Wick -assisted deep irrigation, on the other hand, concentrates moisture in small, consistently wet areas that hinder oxygen transmission. This generates hypoxic conditions that slow down biomass synthesis and stem metabolism [44,45]. Other species have shown similar trends, with underground irrigation without enough air slowing root growth and systems with enough air speeding up root growth [46, 47]. Research conducted in vineyards and afforestation systems provide more evidence that the positioning of irrigation significantly influences root architecture. Surface irrigation adds fine-root biomass to shallow strata, while deep or wick-based methods may take it away if there isn't enough oxygen [48,49]. The higher RDW in this study's surface irrigation can be explained by a better balance between water distribution and oxygen availability in the rhizosphere, which encourages more fine-root growth, unlike wick-based deep irrigation.

The combination effect between irrigation periods and irrigation methods demonstrated that all biomass allocation parameters were not significantly influenced ($P > 0.05$) by the interaction. In contrast, The Duncan’s multiple range test revealed that there were statistical differences among means of the biomass parameters. The comparison among means showed that the best interaction techniques to produce the highest dry weight of stem (765 g), leaf (537 g), and total (1736.33 g) were 3-days irrigation with deep wick irrigation method. Moreover, the greatest root dry weight (422.33 g) was recorded under the combination between 6 days and surface irrigation. However, the lowest dry weight of the most parts of the saplings were observed under the combination between 9 days and deep irrigation with wicks. The results for most biomass allocation traits indicated that irrigation every 3 days using any irrigation method, and irrigation every 6 days using surface or subsurface methods without wicks, produced statistically similar outcomes. This suggests that under limited water availability, irrigation every 6 days using surface or subsurface methods without wicks can be a viable alternative to irrigation every 3 days. According to research indicating how subsurface moisture deprivation without appropriate aeration might impede root growth and metabolism, the drop in dry weights under wick irrigation at 9-day intervals also implies a mix of water stress and localized hypoxic conditions in the root zone [44,46]. These data show that irrigation frequency has a higher influence on overall biomass production than irrigation method, even when method-specific effects are visible in root allocation. Comparable findings of 6-day irrigation using surface or subsurface techniques without wicks and 3-day irrigation using either method show that intermediate intervals can support biomass formation well, reducing water usage without sacrificing yield. This is in consistent with prior study on *L. leucocephala* and other legumes, which demonstrated that moderate irrigation levels enhanced biomass, leaf area, and water-use efficiency whereas excessive and insufficient watering impaired performance [41 ,50] Practically speaking, surface irrigation every six days could offer a reasonable compromise between conserving water and expanding biomass, especially in semi-arid regions where water deficit is a serious limitation [51].In order to gain the finest fodder supply and long-term sapling establishment, it is required to alter irrigation schedules to balance shoot and root growth, as the interaction patterns so indicate. Water scarcity is currently a major global concern. To serve the food needs of the world's rising population, it is challenging to deliver fresh water sources using traditional irrigation techniques. Therefore, study, development, and implementation of appropriate irrigation systems as well as effective irrigation management plans are vital.

Table 2. Influence of irrigation periods, irrigation methods and their interactions on biomass allocation of *Leucaena leucocephala* saplings

Irrigation Periods (Once every)	Irrigation Methods	Stem Dry Weight Increment (g)	Leaf Dry Weight Increment (g)	Root Dry Weight Increment (g)	Total Dry Weight Increment (g)
3 days		662.22±67a	456.11±43a	365.00±38a	1483.33±135a
6 days		590.44±94a	332.89±41b	306.78±49a	1230.11±156a
9 days		217.67±51b	171.89±26c	178.78±27b	568.89±100b

P-Value		0.00	0.00	0.003	0.000
	SI	578.89±103a	338.11±48a	358.33±54a	1275.33±198a
	DI without W	453.00±92a	280.33±47a	247.33±27b	980.67±155a
	DI with W	438.44±99a	342.44±67a	244.89±47b	1026.33±204a
	P-Value	0.324	0.972	0.040	0.242
	SI	764.33±107a	471.33±48ab	404.33±69a	1640.00±248a
3 days	DI without W	457.33±87abc	324.00±66bc	292.33±18ab	1073.67±159abc
	DI with W	765.00±60a	573.00±6a	398.33±58a	1736.33±69a
	SI	644.67±214ab	341.67±63bc	422.33±113a	1408.67±385ab
6 days	DI without W	721.67±135ab	360.67±96bc	289.00±42ab	1371.33±235ab
	DI with W	405.00±87abc	296.33±77bc	209.00±47b	910.33±215bc
	SI	327.67±134bc	201.33±59c	248.33±58ab	777.33b±250bc
9 days	DI without W	180.00±42c	156.33±32c	160.67±26.08b	497.00±100c
	DI with W	145.33±37c	158.00±54c	127.33±26b	432.33±114c
P-Value		0.199	1.860	0.398	0.204

Means within each column for each factor followed by the same letter are not significantly different from each other according to Duncan's Multiple Range Test at a 5% level. (S: Surface, I: Irrigation, D: Deep, W: Wicks).

3. Influence of irrigation periods, irrigation methods and their interactions on biomass partitioning indices of *Leucaena leucocephala* saplings

Table 3 shows that irrigation periods had a highly significant effect (p<0.01) on all biomass partitions except leaf mass ratio of *Leucaena leucocephala*. The highest mean value of the stem mass ratio (0.468) was obtained from the irrigation every 6 days, while its minimum value was observed under the irrigation every 9 days. In contrast, the highest mean value of the root mass ratio (0.323) and the root to the shoot ratio were obtained from the irrigation every 9 days, while, their minimum value were recorded under the irrigation 3 and 6 days. These result mean that the saplings watered once every 3 and 6 days, significantly allocated more dry mass in stem part. However, when the saplings watered once every 9 days significantly allocated more dry mass in root system and root to shoot ratio also enlarged [16]. This phenomenon is considered as a good species mechanism of adapting to water stress situations. Similar outcomes were reported by the prior scholars [52, 53, 54, 55]. Actually, a general response to water stress is thought to be either a decrease in the shoot per root ratio or an increase in root growth [56]. This helps the seedlings to maximize their water intake from the soil to ensure their survival and growth [57].

The irrigation methods illustrated that all the biomass partitioning indices except of leaf mass ratio were not significantly influenced by different irrigation methods. The best irrigation method to enhance leaf mass ratio (0.331) was the deep irrigation with wicks, while the poorest value of the parameter (0.270) was recorded under the surface irrigation. These outcomes are in line with earlier research demonstrating that wick systems increase above-ground biomass by guaranteeing a constant supply of water [10] indicating that increased leaf allocation is favored by consistent water availability [58,36]. In general, wick irrigation seems to be a potential technique for enhancing *L. leucocephala* leaf growth and facilitating its establishment in arid and semi-arid environments.

Regarding the interaction, Table 3 displayed that all biomass partitioning indices of *Leucaena leucocephala* saplings were not significantly influenced (P > 0.05) by the combination between irrigation periods and irrigation methods. However, the Duncan's multiple range test revealed that the statistical differences had among means of the biomass partitions. The comparison among means displayed that the greatest stem mass ratio (0.52) observed under the irrigation every 6 days and deep irrigation without wicks methods, while the lowest value (0.34) was recorded under the irrigation every 9 days combined with deep wick irrigation methods. This implies that whereas extended periods of wick irrigation encouraged a decrease in stem allocation, moderately frequent irrigation encouraged above-ground biomass allocation, especially to stems. Similar results have been documented in other species, where extended stress decreased stem development but moderate irrigation improved stem allocation because of improved water availability [58,16]. On the other hand, the heights leaf mass ratio (0.35) was obtained from the saplings that watered once every 9 days with deep wick irrigation, while the lowest value (0.25) was identified from the saplings that watered once every 6 days with surface irrigation. This demonstrated that, even with long watering intervals, wick irrigation may maintain water availability in deeper soil layers, encouraging leaf retention and growth. This is congruent with research by Bainbridge [10], who showed that by supplying a steady capillary supply of water, wick irrigation increases above-ground biomass, especially leaf. Moreover, the greatest root mass ratio (0.34) and root to shoot ratio (0.51) were investigated from the saplings irrigated once every 9 days with surface irrigation, whereas the minimum value of them (0.22 and 0.28 respectively) were found under the irrigation every 6 days and deep irrigation without wicks methods. This supported the adaptive tactic of increasing biomass allocation to roots in order to optimize soil water extraction when water supply is low. These reactions align with known drought adaptation strategies in forest plants, where stress enhances root distribution to enhance survival [52, 53, 55]. Thus, the observed treatment differences show that *L. leucocephala* exhibits flexible biomass partitioning strategies.

Table 3. Influence of irrigation periods, irrigation methods and their interactions on biomass partitioning indices of *Leucaena leucocephala* saplings.

Irrigation Periods (Once every)	Irrigation Methods	Stem Mass Ratio	Leaf Mass Ratio	Root Mass Ratio	Root to Shoot Ratio
3 days		0.442±0.01a	0.307±0.03a	0.250±0.02b	0.338±0.03b
6 days		0.468±0.02a	0.280±0.02a	0.251±0.02b	0.343±0.03b
9 days		0.367±0.01b	0.310±0.02a	0.323±0.01a	0.483±0.03a
P-Value		0.00	0.181	0.00	0.005
	SI	0.437±0.01a	0.270±0.01b	0.291±0.02a	0.419±0.04a
	DI without W	0.433±0.02a	0.291±0.01b	0.276±0.02a	0.389±0.04a
	DI with W	0.406±0.02a	0.335±0.01a	0.258±0.02a	0.356±0.04a
	P-Value	0.354	0.006	0.360	0.361
	SI	0.468±0.01ab	0.293±0.02abc	0.240±0.02b	0.317±0.04c
3 days	DI without W	0.421±0.01bcd	0.297±0.01abc	0.281±0.03ab	0.397±0.06abc
	DI with W	0.439±0.02abc	0.331±0.01ab	0.229±0.03b	0.300±0.05c
	SI	0.445±0.03abc	0.255±0.02c	0.300±0.00ab	0.428±0.02abc
6 days	DI without W	0.522±0.02a	0.262±0.04bc	0.215±0.02b	0.276±0.03c
	DI with W	0.439±0.05abc	0.320±0.01abc	0.240±0.05b	0.326±0.08bc
	SI	0.401±0.04bcd	0.263±0.01bc	0.335±0.03a	0.511±0.06a
9 days	DI without W	0.356±0.02cd	0.314±0.00abc	0.330±0.02a	0.5496±0.05ab
	DI with W	0.338±0.01d	0.353±0.04a	0.303±0.02ab	0.442±0.05abc
P-Value		0.204	0.745	0.262	0.321

Means within each column for each factor followed by the same letter are not significantly different from each other according to Duncan's Multiple Range Test at a 5% level. (S: Surface, I: Irrigation, D: Deep, W: Wicks).

4. Influence of irrigation periods, irrigation methods and their interactions on nutrient uptake of *Leucaena leucocephala* saplings.

Table 4 shows that the irrigation periods had a significant influence on the absorption and fixation of nutrients in leaves of *Leucaena leucocephala* saplings. The highest percentage of nitrogen content (2.02%) and potassium content (0.443%) were found in leaves of the saplings irrigated every 9 days, while the lowest nitrogen content (1.66%) and potassium content (0.420%) were achieved from those irrigated every 3 and 6 days respectively. In contrast, the greatest phosphorus content (0.443%) was achieved from those watered every 6 days, whereas, the minimum phosphorus content (0.154%) was observed from those watered every 9 days. Given their disparate mobility and absorption methods, this result implies that various nutrients react differentially to soil moisture regimes. The mobility of these nutrients in soil solution and their reliance on mass flow for transfer to the root surface are the reasons for the higher nitrogen and potassium levels under longer irrigation intervals (9 days) [59, 60]. Longer periods of drying and rewetting may increase the concentration of solutes surrounding the roots, which will increase the efficiency of uptake when water becomes accessible again. [61] reported similar results, showing that nitrogen uptake efficiency was highly impacted by irrigation frequency, with less watering reducing water stress and boosting nitrogen use efficiency in Rhododendron grown in containers. But too frequent irrigation can cause mobile nutrients, especially nitrate, to drain, which would make them less available to roots [62]. The slightly lower N and K levels found in seedlings irrigated every three and six days are consistent with this. On the other hand, seedlings irrigated every six days had the maximum phosphorus level, while those irrigated every nine days had the lowest. Phosphorus is comparatively stationary in soil, unlike N and K, and its uptake depends on diffusion and tight contact between soil particles and roots [63 ,64]. Reduced soil moisture reduces P diffusion, destroys mycorrhizal connections, and diminishes root-soil contact during extended dry periods (9 days), all of which limit uptake. Conversely, overly frequent watering (3 days) may create conditions of high soil moisture, which limit root aeration and can lessen mycorrhizal activity, consequently diminishing P absorption efficiency [65].

The methods of irrigation also had a highly significant effect on the absorption of nutrients by *Leucaena leucocephala* saplings. The highest level of nitrogen uptake (2.05%) was achieved through the deep irrigation method without wicks, while the lowest content was recorded under deep irrigation with wicks. On the other hand, the highest phosphorus content (0.341%) and potassium (0.463%) were achieved through the deep irrigation with wicks, whereas the lowest of their contents (0.141% and 0.407%, respectively) were recorded through the deep irrigation methods without wicks. This contrast reflects differences in nutrient transport while nitrogen, which is mostly absorbed by mass flow, benefits from cycles of soil wetness and drying that promote transpiration-driven delivery, phosphorus and potassium, which rely more on diffusion, are preferred in conditions that are consistently moist [66 ,67]. The lower nitrogen under wick irrigation is likely due to reduced oxygen and nitrification in continuously wet macrozones, which limited nitrate availability and absorption efficiency [68]. However, by increasing phosphorus transport and likely promoting mycorrhizal activity, stable moisture around wick emitters increased P and K acquisition [68 ,69, 70, 71]. According to [61, 72 and 73] have reported comparable trade-offs between fruit trees and nursery crops. In some cases, frequent or subsurface irrigation reduced the accumulation of N by limiting mass flow from transpiration, but also boosted the intake of P and K. Overall, the results confirm previous findings that irrigation design influences root feeding patterns, soil moisture distribution, and oxygen status, which in turn alters nutrient dynamics [26 ,74].

Nutrient uptake in *Leucaena leucocephala* saplings was significantly influenced by the interaction of irrigation timing and method. These results highlight how soil moisture dynamics and delivery patterns jointly regulate nutrient acquisition. The combination of irregular watering and mass flow-driven nutrient transfer is reflected in the maximum nitrogen concentration (2.45%) under the 9-day interval and deep irrigation without wicks. Longer intervals probably caused drying-rewetting cycles, which elevated the demand for transpiration and concentrated nitrate in the soil, improving the efficiency of nitrogen intake [60, 61]. The lowest nitrogen (1.17%) seen during frequent (3-day) deep wick irrigation may be due to continuously moist macrozones that decreased soil aeration, decreased nitrification, and restricted nitrate mobility. This is consistent with findings that watering too much or continuously reduces N uptake [72, 67]. The importance of soil–root interaction and intermediate irrigation frequency is highlighted by the highest phosphorus content (0.592%) during the 6-day surface irrigation regime. Unlike nitrogen, phosphorus uptake is largely diffusion-driven and sensitive to moisture availability and mycorrhizal activity [63,68]. The 6-day technique most likely maintained sufficient soil hydration by avoiding the anoxic conditions of 3-day watering and the drought-induced diffusion limits of 9-day irrigation. With side water distribution in the topsoil, where labile phosphorus is concentrated, surface irrigation may have further improved P availability. This conclusion is consistent with other research that indicated that P absorption is boosted by moderate watering regimes that maintain mycorrhizal function and solubility [69,70]. The potassium uptake showed a significant trend during the three days of deep wick irrigation, culminating at 0.470 percent. Wick irrigation maintains constant moisture levels in active root zones, which is beneficial for potassium since it is a highly mobile cation and requires regular replenishment of soil solution [70,65]. Frequent watering may enhance root cation exchange activity and membrane transport, enhancing K absorption even in cases where nitrogen uptake is hindered. The lowest K content under 6-day deep non-wick irrigation highlights the likelihood of occasional drying in subterranean strata, which restricts root access and potassium mobility. Previous research indicates that subterranean irrigation maintains consistent moisture and ion transport channels, which improves K uptake [70, 75].

Table 4. Influence of irrigation periods, irrigation methods and their interactions on nutrient uptake of *Leucaena leucocephala* saplings.

Irrigation Periods (Once every)	Irrigation Methods	Nitrogen (%)	Phosphorus (%)	Potassium (%)
3 days		1.66±0.16c	0.206±0.03b	0.433±0.01ab
6 days		1.79±0.09b	0.443±0.07a	0.420±0.01b
9 days		2.02±0.12a	0.154±0.01c	0.443±0.01a
P-Value		0.01	0.01	0.035
	SI	1.86±0.10b	0.321±0.07b	0.427±0.01b
	DI without W	2.05±0.13a	0.141±0.01c	0.407±0.01c
	DI with W	1.56±0.11c	0.341±0.07a	0.463±0.004a
	P-Value	0.01	0.01	0.00001
3 days	SI	2.25±0.02b	0.186±0.002d	0.400±0.01d
	DI without W	1.56±0.01f	0.118±0.001g	0.430±0.01bcd
	DI with W	1.17±0.01g	0.313±0.001c	0.470±0.01a
6 days	SI	1.66±0.01e	0.592±0.001a	0.430±0.01bcd
	DI without W	2.15±0.01c	0.152±0.001e	0.370±0.01e
	DI with W	1.56±0.01f	0.584±0.001b	0.460±0.01ab
9 days	SI	1.66±0.03e	0.184±0.001d	0.450±0.01abc
	DI without W	2.45±0.05a	0.152±0.001e	0.420±0.01cd
	DI with W	1.96±0.01d	0.127±0.001f	0.460±0.01ab
P-Value		0.01	0.01	0.00

Means within each column for each factor followed by the same letter are not significantly different from each other according to Duncan's Multiple Range Test at a 5% level. (S: Surface, I: Irrigation, D: Deep, W: Wicks).

5. Influence of irrigation periods, irrigation methods and their interactions on Protein, Chlorophyll content, relative water content and water use efficiency of *Leucaena leucocephala* saplings.

Table 5 displays that irrigation periods had a significant effect on the protein, chlorophyll content, and relative water content of the *Leucaena leucocephala* saplings. Even though water use efficiency was not significantly affected by the irrigation intervals, the Duncan's multiple range test revealed statistical differences among means. The highest level of the protein (9.39%) and the chlorophyll content (54.67) were achieved through irrigation periods of every 9 days, while their lowest values (7.70%), (49.00) respectively were observed under the 3 days watering. In contrast, the greatest relative water content (71%) was recorded under more frequent irrigation (3 days), whereas, the lowest value (59%) was obtained from less frequent irrigation (9 days). Moreover, the saplings watered every 6 days had the best water use efficiency (2.85 g/l), while those watered every 3 days had the lowest water use efficiency (1.75 g/l). The substantial impacts of irrigation intervals on the protein, chlorophyll, and relative water content (RWC) of *Leucaena leucocephala* seedlings demonstrated the physiological responses to water availability. The levels of protein and chlorophyll peaked after nine days of irrigation, indicating that moderate water stress boosted the production of osmo-protectant proteins and the stability of chlorophyll, improving drought resistance. Yige et al., [76] published similar results, observing that *L. leucocephala* seedlings under controlled drought stress increased protective protein activity and chlorophyll modifications to preserve photosynthetic capacity. Following three days of irrigation, lower levels of protein and chlorophyll most likely result from dilution from excessive water and reduced stress signaling, which can prevent the synthesis of stress-related proteins and chlorophyll-maintenance mechanisms [77, 78]. RWC, on the other hand, benefited from consistent irrigation; the highest values (71%) were recorded following three-day watering, suggesting better turgor management and leaf hydration. Taiz et al., [79] showed similar results, highlighting the importance of regular watering in maintaining leaf water status. However, seedlings that received irrigation every nine days showed the lowest RWC, suggesting trade-offs between stress adaptation and hydration. It's interesting to note that total water use efficiency (WUE) was not considerably impacted, yet 6-day irrigation produced the greatest mean. This is consistent with research by Zegada-Lizarazu [80], who found that by balancing hydration and stress-induced efficiency mechanisms, intermediate irrigation intervals maximize biomass gain per unit water. As previously noted in leguminous species under well-watered regimes, excessive watering at 3-day intervals decreased WUE, most likely as a result of increased transpiration without corresponding biomass gains [81]. Overall, our findings indicate that acute water stress (6–9 days) enhances physiological efficiency through protein accumulation, chlorophyll stability, and improved WUE, whereas regular watering increases tissue hydration but may reduce metabolic efficiency. Verifying a recent study [76, 78]. These trends support the adaptive drought tolerance strategies of *L. leucocephala* and highlight the importance of extending irrigation intervals to balance resilience, growth, and efficiency in semi-arid forestry systems.

Among the irrigation methods, Table 5 reveals that the protein and relative water content were significantly affected by different irrigation methods. However, the chlorophyll content and the water use efficiency were not significantly influenced by the methods of watering. The highest protein value (9.53%) was achieved through the deep irrigation method without wicks, while the minimum value of protein (7.25%) was recorded under the deep irrigation with wicks method. The relative water contents under the methods of surface irrigation (66.67%) and deep irrigation without wicks (66%) were significantly better than those under the deep irrigation with wicks method (60.67%). *Leucaena leucocephala* protein content and relative water content (RWC) were considerably altered by the irrigation strategy. While wick-based deep irrigation generated the lowest values (protein 7.25%, RWC 60.7%), the deep irrigation strategy without wicks provided the largest leaf protein (9.53%) and maintained high RWC (66%). These results are attributable to how oxygen and moisture travel around in the rhizosphere. Like what was found in subsurface tomato investigations, where oxygen-deprived places make things less productive, wick systems create macrozones that are always saturated, which lowers oxygen levels and slows root metabolism and protein synthesis [82]. Conversely, non-wick methods aid in the soil's respiration and moisture cycle, which boosts the synthesis of metabolic proteins and maintains the moisture content of the leaves. These results are consistent with Leucaena's drought physiology, which shows that adequate aeration and mild stress promote protein synthesis and water retention [76]. In the interim, the irrigation method had no significant effect on water consumption efficiency (WUE) or chlorophyll concentration. This is a symptom of physiological buffering since WUE frequently responds more to general water-biomass dynamics than to specific approaches, and chlorophyll usually stays steady under modest water stress [83]. Strong WUE and RWC were maintained by deficit watering at 50% AET, which is in line with larger Leucaena studies [41] demonstrating that WUE optimization is determined by irrigation quantity rather than delivery technique. Because they maintain both hydration and protein production, surface and deep non-wick irrigation are usually the greatest options for sapling resilience in water-limited settings.

Regarding the interaction, Table 5 also demonstrated that the protein and relative water content were significantly affected by the interaction between the periods and methods of irrigation. In addition, even though the chlorophyll content and the water use efficiency were not significantly influenced by the mentioned interaction, the Duncan's multiple range test revealed that there were statistical differences among the means of these two parameters. The highest level of protein (11.37%) was achieved through irrigation every 9 days with deep non-wick irrigation, whereas the lowest level of protein (5.43%) was observed under 3 days irrigation with deep wick irrigation method. The maximum chlorophyll content (57.25) was recorded under every 9 days surface irrigation, while the minimum value (47.50) was found under every 3 days deep wick irrigation method. Moreover, the best water use efficiency (3.41 g/l) was also achieved under every 9 days surface irrigation, while the minimum value (1.27 g/l) was found under every 3 days deep non-wick irrigation method. In contrast, the greatest relative water content (74 %) was recorded under irrigation every 3 days with surface and deep non-wick irrigation method, whereas the lowest value of relative water content (54 %) was identified under the irrigation every 9 days with deep wick irrigation method. The significant effects of irrigation length and technique on protein and relative water content (RWC) demonstrated the combined effects of soil water dynamics and delivery strategy on the physiological performance of *Leucaena leucocephala*. The maximum protein level (11.37%) over 9 days of deep non-wick irrigation, which promotes osmo-protectant protein production and enzymatic activity, reflects a compromise between proper aeration and moderate water stress

Similarly, under controlled drought stress, legumes accumulated more proteins, which helped them respond to the stress [77, 78]. In contrast, [82] observed that in subsurface irrigation systems, increased root-zone saturation and lower oxygen availability limit protein metabolism, resulting in the lowest protein value (5.43%) during 3-day irrigation with deep wick irrigation. Although the interaction did not statistically significantly alter the amount of chlorophyll, unique patterns did show up, with the maximum value (57.25) occurring under 9-day surface irrigation and the lowest value (47.50) occurring under 3-day deep wick irrigation. This indicates that while over-saturation or excessive watering may hasten chlorophyll breakdown, moderate water stress maintains chlorophyll stability and photosynthetic capacity. Comparable studies in legume plants demonstrated that whereas excessive irrigation resulted in pigment loss from oxidative stress and inadequate nitrogen uptake, moderate dryness retained chlorophyll. It has achieved the highest percentage of relative water content (74%) under frequent (3-day) surface or deep non-wick irrigation, the relative water content showed a significant trend, indicating enhanced hydration and turgor maintenance. These findings are consistent with those of Taiz et al. [79], who found that regular watering keeps leaf water status high by avoiding water deficit. The lowest RWC (54%) under 9-day deep wick irrigation, however, suggests that water uptake efficiency is decreased due to compounded stress from extended intervals and inadequate aeration. Although not statistically significant overall, water use efficiency (WUE) exhibited statistical variability across averages, with the lowest value (1.27 $g\ L^{-1}$) occurring under 3-day deep non-wick irrigation and the highest value (3.41 $g\ L^{-1}$) occurring under 9-day surface irrigation. According to studies that an intermediate water deficit increases WUE, this pattern shows that surface irrigation under moderate stress maximizes biomass per unit water by minimizing needless evaporation [80]. On the other hand, as observed in legumes grown under well-watered conditions, excessive watering at short intervals lowers WUE because it increases transpiration rates without corresponding biomass gain [81].

Table 5. Influence of irrigation periods, irrigation methods and their interactions on protein, chlorophyll content, relative water content and water use efficiency of *Leucaena leucocephala* saplings.

Irrigation Periods (Once every)	Irrigation Methods	Protein (%)	Chlorophyll Content	Relative Water Content (%)	Water Use Efficiency (g/l)
3 days		7.70±0.73c	49.00±1.40b	71.00±1.53a	1.75±0.16b
6 days		8.31±0.42b	52.67±0.67ab	63.33±0.33b	2.85±0.38a
9 days		9.39±0.54a	54.67±2.14a	59.00±1.29c	2.49±0.44ab
P-Value		<0.01	0.021	<0.01	0.100
	SI	8.61±0.46b	54.08±1.00a	66.67±1.90a	2.87±0.48a
	DI without W	9.53±0.61a	50.67±1.86a	66.00±2.04a	2.21±0.35a
	DI with W	7.25±0.53c	51.58±1.86a	60.67±1.17b	2.02±0.21a
	P-Value	<0.01	0.200	<0.01	0.214
	SI	10.44±0.11b	51.50±1.32ab	74.00±0.57a	1.94±0.29ab
3 days	DI without W	7.24±0.05f	48.00±3.29b	74.00±0.57a	1.27±0.19b
	DI with W	5.43±0.05g	47.50±2.40b	65.00±0.57b	2.05±0.08ab
	SI	7.70±0.05e	53.50±0.45ab	64.00±0.57bc	3.26±0.90ab
6 days	DI without W	9.98±0.05c	53.00±1.41ab	63.00±0.57cd	3.18±0.55ab
	DI with W	7.24±0.16f	51.50±1.32ab	63.00±0.57cd	2.11±0.50ab
	SI	7.70±0.16e	57.25±1.80a	62.00±0.57de	3.41±1.10a
9 days	DI without W	11.37±0.26a	51.00±4.56ab	61.00±0.57e	2.18±0.44ab
	DI with W	9.09±0.05d	55.75±4.37a	54.00±0.57f	1.89± 0.50ab
P-Value		<0.01	0.632	0.00001	0.480

Means within each column for each factor followed by the same letter are not significantly different from each other according to Duncan's Multiple Range Test at a 5% level. (S: Surface, I: Irrigation, D: Deep, W: Wicks).

Conclusion

This study demonstrated that irrigation frequency had a greater influence on the performance of *Leucaena leucocephala* saplings than irrigation method. Irrigating every 3 or 6 days significantly enhanced growth and biomass accumulation, with 6-day intervals offering comparable benefits to 3-day irrigation while conserving water. Surface irrigation supported stem and root development, whereas wick-based irrigation promoted leaf growth but reduced protein content and relative water content. Nutrient uptake varied by element: nitrogen was highest under infrequent deep irrigation, phosphorus under 6-day surface irrigation, and potassium under frequent wick irrigation. Physiological traits responded favorably to moderate irrigation intervals, which improved protein synthesis, chlorophyll stability, and water-use efficiency. In contrast, frequent irrigation primarily enhanced leaf hydration. Based on these findings, the study recommends a 6-day irrigation schedule using surface or deep non-wick methods for *L. leucocephala* saplings in semi-arid regions. This approach optimizes growth and nutrient efficiency while promoting water conservation during the critical establishment phase.

Acknowledgments

We sincerely acknowledge the support of Salahaddin University–Erbil, particularly the College of Agricultural Engineering Sciences and the Department of Forestry. We also extend our gratitude to Directorate of Education in Barda Rash District for providing an area inside their forest for conduction our experiment.

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تأثير فترات الري وطرق الري المختلفة في النمو والكتلة الحيوية وامتصاص العناصر الغذائية والصفات الفسيولوجية لشتلات اللوسينيا ***Leucaena leucocephala (Lam.) de Wit*** المزروعة في منطقة بردرش، إقليم كردستان، العراق

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الخلاصة

إدارة الري هي واحدة من أبرز الممارسات التنموية الغابية الهامة في تعزيز نمو واستقرار المشجر في المناطق الجافة وشبه الجافة. لذلك، قامت الدراسة الحالية بتقييم تأثيرات فترات الري المختلفة وطرق الري وتداخلاتهما في نمو، وتوزيع الكتلة الحيوية، وامتصاص العناصر الغذائية، والخصائص الفسيولوجية لشتلات شجرة اللوسينيا(***Leucaena leucocephala***) في قضاء بردارش، إقليم كوردستان، العراق. تم إجراء التجربة بتصميم القطاعات العشوائية الكاملة (***RCBD***) بعاملين. العامل الأول كان عبارة عن ثلاث فترات للري (كل 3، 6، و9 أيام) والعامل الثاني كان ثلاث طرق للري (الري السطحي، الري العميق بدون فتائل، والري العميق باستخدام الفتائل). أظهرت النتائج أن صفات النمو والكتلة الحيوية تأثرت بشكل كبير بفترات الري. أظهرت الشتلات التي تم ريها كل ثلاثة وستة أيام زياده في معدل كل من(طول الساق وقطره وعدد الأوراق وتراكم الكتلة الحيوية ومحتوى الماء النسبي) مقارنة بالشتلات التي تم ريها كل تسعة أيام، والتي أنخفضت فيها مؤشرات النمو بسبب الجفاف. أظهرت طرق الري أن نمو الساق وكتلة الجذور تحسنت تحت الري السطحي، في حين زادت نسبة كتلة الأوراق تحت الري العميق باستخدام الفتائل. واظهرت النتائج ايضا اختلاف القيم الممتصة للعناصر الغذائية بين المعاملات. وكان أعلى محتوى للنيتروجين تحت الري العميق الأقل تكرارًا (كل 9 أيام) بدون فتائل، بينما كان أفضل محتوى للفوسفور تحت الري السطحي المتوسط (كل 6 أيام)، والبوتاسيوم تحت الري بالفتائل الأكثر تكرارًا (كل 3 أيام). أوضحت الخصائص الفسيولوجية أن محتوى البروتين، ومحتوى الكلوروفيل، وكفاءة استخدام المياه تحسنت تحت تكرار الري المعتدل والأقل (6–9 أيام)، بينما ازداد المحتوى المائي النسبي تحت الري الأكثر تكراراً (كل 3 أيام). أوضحت تقنيات الري أن محتوى البروتين والمحتوى المائي النسبي انخفض تحت الري العميق باستخدام الفتائل. وأظهرت النتائج أن استخدام الري السطحي أو العميق غير الفتيلية كل ستة أيام يحقق أقصى توفير للمياه دون التأثير على نمو الشتلات وكفاءة العناصر الغذائية. وقد عززت هذه النتائج المعرفة حول إدارة الري لبرامج التشجير وإعادة التشجير في المناطق شبه الجافة.

الكلمات المفتاحية: اللوسينيا، فترات الري، طرق الري ، امتصاص المغذيات، كفاءة استخدام المياه.