



Influence of Irrigation Intervals and Mulching Treatments on Growth and Development of *Paulownia tomentosa* (Thunb.) Steud. Saplings in the Bazian District, Kurdistan Region, Iraq

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Received:17/08/2025

Revised: 06/11/2025

Accepted: 04/02/2026

Published: 08/03/2026

ABSTRACT

The successful growth of *Paulownia* plantations depends on application of appropriate silvicultural techniques. Namely, irrigation management and soil moisture methods like mulching treatments are important. Therefore, this study investigates the effects of varied irrigation intervals, mulching treatments, their interactions on growth, biomass allocation, nutrient uptake, and physiological responses of 36 *Paulownia tomentosa* saplings under semi-arid conditions in Bazian district, Kurdistan Region of Iraq. A factorial experiment was conducted using three irrigation intervals (three, six, and nine days) with three mulching treatments (no mulch, hay mulch, and black plastic film).

Results revealed that irrigation frequency had a dominant and statistically significant influence on morphological parameters. Frequent irrigation, especially every 3 days, improved stem height (127.66 cm), diameter (23.25 mm), and leaf number (21.77), with best results when combined with no or hay mulch. In contrast, irrigation every 9 days led to the weakest growth, regardless of mulching. Regarding biomass accumulation, frequent irrigation, every 3 days with hay, greatly boosted dry biomass (631.86 g) in all the plant parts. While mulching alone had little effect, with irrigation particularly hay mulch enhanced growth. Biomass ratios remained stable: treatments affected total biomass more than how distributed among plant parts.

Nutrient uptake was significant by irrigation and mulching. Hay mulch improved nitrogen uptake (3.03%), black plastic mulch enhanced potassium absorption (0.383%). Phosphorus uptake was affected by irrigation. The highest nitrogen (3.23%) occurred under 9-day irrigation with hay, and the highest potassium (0.51%) under 3-day irrigation with black plastic. Protein 14.98% and proline 8.92 $\mu\text{g/g}$ levels, both were under 9-day irrigation with hay mulch. No significant changes for chlorophyll. Water use efficiency reached to highest (1.53 g/L) under 9-day irrigation with black plastic.

Frequent irrigation promoting significantly growth and biomass, while mulching with hay improved nutrient use and physiological resilience when combined with irrigation in water-limited environments.

Keywords: *Paulownia tomentosa*, Irrigation Intervals, Mulching Treatments, Biomass Allocation, Nutrient Uptake, Physiological Traits.

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INTRODUCTION

Paulownia tomentosa (Thunb.) Steud., commonly known as the Empress Tree or Princess Tree, is a fast-growing deciduous species native to central and western China that has gained global attention for its remarkable growth characteristics and versatile uses [1]. In natural conditions *Paulownia tomentosa* can reach heights of 20–30 m and diameters up to 2 m, featuring large heart-shaped leaves (~20–40 cm across) and showy violet-blue spring flowers. Its rapid growth rate and light, workable wood make it valuable for timber, agroforestry, and biomass applications [2].

Paulownia tomentosa is economically and environmentally valuable, known for its lightweight, warp-resistant timber used in high-demand wood products and widely cultivated in China [3]. It offers multiple economic benefits, including high-quality timber, honey production, and medicinal uses, while also enhancing soil fertility and controlling erosion through its nitrogen-rich leaves. Its fast growth and low input requirements make it ideal for smallholder farmers. When well-managed in agroforestry systems, *Paulownia tomentosa* can significantly support sustainable

rural development [4]. The species supports intercropping with various crops such as wheat, corn, and vegetables [5], its leaves provide nutritious livestock fodder and enhance soil quality, making it beneficial for agroforestry systems [6]. Environmentally, it rapidly sequesters carbon, aiding in climate change mitigation [7] and it can regenerate from stump sprouts, reducing the need for frequent replanting [8]. It aids in soil remediation by absorbing heavy metals like zinc from polluted soils [9]. *Paulownia tomentosa* can endure wildfires due to its roots' ability to regrow rapidly developing stems. It exhibits tolerance to pollutants and is indifferent to soil type; ecologically, it serves as a pioneer species [10].

In the context of the Kurdistan Region of Iraq, where water scarcity and soil degradation present significant challenges to afforestation efforts, understanding the optimal silvicultural techniques for *Paulownia tomentosa* becomes particularly relevant. The species' tolerance to various soil and climate conditions, suggests potential adaptability to Kurdistan's semi-arid conditions. However, its successful establishment and growth in this region depend on the application of the appropriate silvicultural or management techniques, such as irrigation management and techniques for protecting soil moisture content such as mulching treatments [11].

Water management represents one of the most critical factors for successful *Paulownia tomentosa* cultivation in semi-arid regions (like Kurdistan). While *Paulownia* species are often described as having low water requirements compared to other fast-growing species, their rapid growth still necessitates careful irrigation management, particularly during establishment [12]. Water availability plays a central role in promoting stem elongation [13], particularly in fast-growing species like *Paulownia tomentosa* [14]. Research in Mediterranean climates similar to parts of Kurdistan has shown that *Paulownia*'s high biomass production comes with significant water demands that must be carefully managed in water-limited environments [11,15] reported that adequate water supply supports optimal physiological processes, such as cell expansion, nutrient uptake, and photosynthesis, which are critical for growth, health and productivity of sweet orange trees. However, reduced water availability can negatively impact the plant physiological processes, nutrient uptake, photosynthesis, and overall growth. Moreover, water is indispensable for sustaining plant health, optimizing growth, and ensuring agricultural productivity, especially in water-scarce regions. Hence, scientific management of available water resources as well as use of water saving techniques, such as mulching treatments becomes necessary for plant growth and yield [15].

Mulching directly influences moisture content, soil temperature, weed control and nutrient availability. Applying mulch to the topsoil reduces evaporation rates, so preserving moisture content for an extended duration [16,17]. There are two main categories of mulch which are organic and inorganic mulches. Organic mulches, such as straw and compost, absorb moisture and release it gradually, whereas inorganic mulches, like plastic films, serve as physical barriers [18]. Straw mulch decreased evaporation by 35% in arid regions [19], whereas plastic mulches, such as polyethylene, reduced irrigation requirements by 30–50% by inhibiting subsurface water loss [20]. Organic mulching improves organic matter, reduces soil degradation, and increases the soil's capacity to hold onto water. Mulching can prolong the time that plants receive water by retaining moisture in the root zone. In comparison to uncovered soil, mulching with composted yard waste increased soil nutrient levels, such as phosphorus (P), potassium (K), calcium (Ca), and organic matter. The decomposition of organic matter under plastic mulch releases soluble nutrients such nitrate (NO₃⁻), ammonium (NH₄⁺), calcium (Ca²⁺), magnesium (Mg²⁺), potassium (K⁺), and fulvic acid, which improves the soil's nutrient availability [17].

Therefore, the primary objective of this investigation was to ascertain the water requirement and mulching effect in the field in order to facilitate the growth and production of *Paulownia tomentosa* saplings. The specific objectives were to identify the effect of different irrigation periods and mulching treatments on the growth, biomass allocation, nutrient uptake and physiological traits of *Paulownia tomentosa* saplings and determine the best irrigation interval for the establishment stage of *Paulownia* Plantation.

Materials And Methods

Study Location

The study was conducted from the middle of June to the early November 2024 on *Paulownia tomentosa* seedlings in an exposed field in the Bazian district, within the Sulaymaniyah Governorate in the Kurdistan Region of Iraq. The site is located at coordinates 35.5589° N Latitude and 45.1864° E Longitude, at an elevation about 781 meters (2,687 feet) above sea level. A representative number of soil samples were gathered from the top 50 cm of the field soil prior to the experiment; as this layer represents the active root zone where most nutrient and water uptake [47], and they were transported to the soil laboratory at the Directorate of Agricultural Research in Sulaimani–Bakrajo for study of their physical and chemical characteristics, as indicated in Table 1. During the experiment, air temperature and relative humidity were daily recorded using thermo-hygrograph equipment, then the mean of minimum, maximum and average of both the air temperature and relative humidity for each month were found, as showed in Table 2.

Table 1: A few physical and chemical characteristics of the soil

Soil Properties	Value	Soil Properties	Value
EC (dS.m ⁻¹)	0.8	HCO ₃ ⁻ (meq/L)	2.4
pH	8.79	CO ₃ ⁻² (meq/L)	0.2
N (%)	0.56	O.M. (%)	0.59
Available P (ppm)	33	CaCO ₃ (%)	3
Soluble K ⁺ (meq/L)	0.246	Sand (%)	1
Soluble Na ⁺ (meq/L)	0.652	Silt (%)	53.64
Soluble Ca ⁺² (meq/L)	4	Clay (%)	45.36
Soluble Mg ⁺² (meq/L)	3	Texture	Silty Clay
Cl ⁻ (meq/L)	0.8		

Table 2: The mean of minimum, maximum and average of the air temperature and relative humidity for during the study (July-October 2024)

Months	Temperature °C			Relative Humidity %		
	Minimum	Maximum	Average	Minimum	Maximum	Average
July	24.67	48.00	36.33	13.17	35.67	24.42
August	22.48	45.68	34.08	14.42	40.13	27.27
September	19.50	40.77	30.13	16.53	48.07	32.30
October	11.58	32.26	21.92	11.52	40.35	25.94

The Species Under Study

The required number of newly sprouted *Paulownia tomentosa* seedlings (84 saplings from root cutting) were bought from a private company named Hawargay Hawkary for Paulownia trees in Erbil City on June 13, 2024, for this study. The average stem height, stem diameter, and leaf number of the seedlings were approximately 17.47 cm and 5.12 mm, and 9.75 respectively.

The Experimental Design

The experiment was conducted based on a factorial using a two-factor randomized complete block design (RCBD). The first factor considered was three irrigations intervals which were; once every 3 days (I3), once every 6 days (I6) and once every 9 days (I9). To find the full water field capacity, the soil in the pot was saturated, the tops were covered with aluminum foil, and the soil was daily weighed until no weight loss occurred. On this base, 20 L of water was then added to the soil to reach the full water field capacity for each irrigation interval [21].

The second factor was three mulching treatments which were non-mulching (MC), mulching with black plastic film (MP), and mulching with hay (MH). Each treatment combination was replicated four times, resulting in a total of 36 experimental units.

Seedling Measurements

Morphological Growth Parameters

At the commencement of the experiment (July), growth parameters, including stem height (cm), stem diameter (mm), and leaf count, were assessed for all seedlings. Stem height was quantified from the soil surface to the peak of the highest living apical shoot utilising a measuring tape, and documented in centimetres (cm). The stem diameter was measured 5 cm above the soil surface with a digital vernier calliper (Digimatic Calliper, Mitutoyo, Japan) and documented in millimetres (mm). The quantity of leaves for each seedling was determined manually. Additionally, the aforementioned characteristics were re-evaluated after the trial (November) to ascertain increases in stem height (cm), stem diameter (mm), and leaf count.

Biomass Parameters

Biomass Allocation

From each treatment three seedlings were randomly selected and destructed at the end of the experiment. The roots were cleaned carefully from the soil by washing. The seedlings were parted into their contents (stem, leaf and root) and dried by oven at 60 °C until a constant dry weight were established [22]. Parts of seedlings were then weighted by a sensitive digital balance to calculate stem dry weight, leaf dry weight, root dry weight and total seedling dry weight.

Biomass Ratio

Parameters of biomass ratio were calculated from the parameters of biomass allocation [23]. The biomass ratios involved stem mass ratio (SMR) (stem dry weight / total dry weight of the seedling), leaf mass ratio (LMR) (leaf dry weight / total dry weight of the seedling), root mass ratio (RMR) (root dry weight / total dry weight of the seedling), root to shoot ratio (R:S) (root dry weight / shoot dry weight).

Nutrient Uptake Parameters

The macro nutrient contents such as nitrogen (N), phosphorus (P) and potassium (K) measured from previously dried and powdered leaf samples.

Nitrogen content (%)

The micro-Kjeldahl digestion method was used to determine total nitrogen content [24].

Total phosphorus content (%)

The colorimetric method (V-1100 digital) was used to estimate total phosphorus content using a spectrophotometer at 410 nm [25].

Total potassium content (%)

The flame photometric (BWB- Technologies) method was used to find total potassium content [25].

Physiological Parameters of the Leaf

The physiological parameters of the leaf which included protein, proline, chlorophyll contents, and water use efficiency were measured.

Protein Content (%)

Protein content was calculated according to the equation described [26] and as follow:

$$\text{Protein \%} = \text{N(\%)} * 4.64$$

Where:

N %: Nitrogen percentage.

4.64: Constant ratio

Proline (µg/g)

Proline plays a critical role in plant adaptation to abiotic stress, particularly under drought and limited irrigation conditions. It functions as an Osmo protectant by stabilizing cellular structures and maintaining osmotic balance, allowing cells to retain water and survive dehydration. Because of its rapid accumulation under adverse conditions, proline is widely recognized as a reliable biochemical marker of stress tolerance in plants, including in *Paulownia tomentosa* under extended irrigation intervals [27].

Proline content in plant leaves can be estimated using the acid-ninhydrin method [28]. In this procedure, 0.5 g of fresh leaf tissue is homogenized in 10 mL of 3% sulfosalicylic acid and the extract is filtered. Two milliliters of the filtrate are then mixed with 2 mL of acid-ninhydrin reagent and 2 mL of glacial acetic acid in a test tube. The mixture is heated in a boiling water bath at 100°C for one hour and then cooled in an ice bath. Four milliliters of toluene are added, and the solution is mixed vigorously to extract the colored complex into the toluene layer. The absorbance of the toluene phase is measured at 520 nm using a spectrophotometer. Proline concentration is determined by comparing the absorbance to a standard curve prepared from known concentrations of L-proline and is expressed as µmol proline per gram of fresh weight.

Chlorophyll Content

The measurement of chlorophyll content was measured non-destructively using a SPAD-502Plus Chlorophyll Meter (Konica Minolta, Japan). The device estimates relative chlorophyll concentration by measuring the differential transmittance of red (approximately 650 nm) and near-infrared (approximately 940 nm) light through the leaf. For each seedling, three mature leaves from different canopy positions (top, middle, and bottom) were selected [16], the readings were taken and averaged to obtain a single value per seedling.

Water Use Efficiency (g/L)

Water Use Efficiency (WUE), which is the ratio of total biomass generated to total water utilized during the process, is a crucial metric in agronomy, plant physiology, and environmental studies. It gauges how well a plant uses water for development and growth. WUE is typically expressed in units such as grams of biomass per liter of water

consumed. It can be calculated by the following formula [29]:

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

Data Analysis:

All data of the studied parameters were analyzed according to the Analysis of Variance (ANOVA) using Agri Analyze online tool which provides comprehensive online analytics solutions [30]. The significant differences between treatment means were compared by Duncan Multiple Rang Test at $p \leq 0.05$ [31].

Results And Discussions

Influence of irrigation intervals, mulching treatments and their interactions on growth parameters of *Paulownia tomentosa* saplings

The results in Table 3 show that stem height was significantly affected by irrigation intervals ($p = 0.00018$) and their interaction with mulching treatments ($p = 0.00114$), while mulching alone had no effect ($p = 0.85729$). Saplings irrigated every 3 days achieved the highest stem height increment (127.33 cm), whereas those irrigated every 9 days recorded the lowest (88.55 cm). The interaction further revealed that watering every 3 days combined with no mulch or hay mulch produced the tallest saplings (145.0 cm and 143.3 cm, respectively), while the lowest increment (77.33 cm) occurred under 9-day irrigation without mulch. These findings confirm the central role of water availability in stimulating stem elongation [13,14], as adequate water supply promotes cell division and expansion, which are vital for growth [15]. Previous work similarly reported that *Paulownia* saplings irrigated every 3 days with 20–25 L of water achieved significantly greater stem height than those under less frequent regimes [32], and that high irrigation frequency during the establishment year enhances vegetative growth [33].

Stem diameter was also significantly influenced by irrigation intervals ($p = 0.00061$) and their interaction with mulching ($p = 0.02253$), though mulching alone had no effect ($p = 0.48323$). The greatest diameter increments were obtained with 3-day irrigation, either without mulch (26.17 mm) or with hay mulch (25.64 mm), while the smallest diameter (13.80 mm) was recorded under 9-day irrigation without mulch. These results are consistent with earlier studies indicating that stem thickening is closely linked to consistent water supply, which maintains cambial activity and xylem expansion in fast-growing trees [12,29], and that frequent irrigation significantly enhances *Paulownia* stem diameter [32].

Leaf production followed a similar pattern, with significance only for irrigation intervals ($p = 0.02323$). The highest leaf numbers were observed under 3-day (21.77) and 6-day irrigation (20.88), while 9-day irrigation resulted in the lowest (17.44). Duncan's test indicated that the greatest leaf number (23.66) occurred under 3-day irrigation without mulch, compared to the lowest (16.33) under 6-day irrigation with hay mulch. These findings emphasize that leaf initiation and expansion are highly sensitive to water availability, which regulates turgor and nutrient uptake [34]. Although mulching did not significantly affect leaf number, previous work also found that irrigation intervals exerted a stronger influence on morphological traits of *Paulownia* seedlings than mulching treatments [16].

Overall, the study highlights that irrigation frequency, particularly every 3 days, is the dominant factor in improving morphological performance of *Paulownia tomentosa* seedlings under semi-arid conditions. While mulching alone had little effect, its combination with frequent irrigation—especially hay mulch—supported higher growth in some parameters, underscoring the primacy of water availability in regulating shoot growth during establishment.

Table 3: Influence of irrigation intervals, mulching treatments and their interactions on growth parameters of *Paulownia tomentosa* saplings

Irrigation Intervals	Mulching Treatments	Stem Height Increment (cm)	Stem Diameter Increment (mm)	Leaf Number Increment
Once every 3 days		127.66 ^a ± 9.20	23.25 ^a ± 1.55	21.77 ^a ± 0.72
Once every 6 days		102 ^b ± 6.98	18.84 ^b ± 1.17	20.88 ^a ± 1.59
Once every 9 days		88.55 ^b ± 5.27	16.11 ^b ± 0.99	17.44 ^b ± 0.68
P-Value		0.00018	0.00061	0.02323
	Without mulching	108.33 ^a ± 10.19	19.88 ^a ± 1.85	20.44 ^a ± 1.10
	Black plastic film	104.55 ^a ± 6.63	18.36 ^a ± 0.88	20.66 ^a ± 1.13
	Hay	105.33 ^a ± 10.53	19.95 ^a ± 1.90	19 ^a ± 1.46
	P-Value	0.85729	0.48323	0.48784
Once every 3 days	Without mulching	145 ^a ± 6.11	26.16 ^a ± 1.53	23.66 ^a ± 0.88
	Black plastic film	94.66 ^{bc} ± 12.54	17.95 ^b ± 0.84	20.33 ^{abc} ± 0.88

	Hay	143.33 ^a ± 2.02	25.64 ^a ± 2.22	21.33 ^{abc} ± 1.33
Once every 6 days	Without mulching	102.66 ^{bc} ± 3.92	19.48 ^b ± 2.05	17.33 ^{bc} ± 0.88
	Black plastic film	116.33 ^b ± 14.74	19.69 ^b ± 0.28	18.66 ^{abc} ± 1.85
	Hay	87 ^c ± 11.71	17.35 ^b ± 3.23	16.33 ^c ± 0.33
Once every 9 days	Without mulching	77.33 ^c ± 5.17	13.80 ^b ± 0.70	20.33 ^{abc} ± 1.76
	Black plastic film	102.66 ^{bc} ± 5.81	17.65 ^b ± 1.85	23 ^{ab} ± 2.51
	Hay	85.66 ^c ± 10.33	16.87 ^b ± 1.94	19.33 ^{abc} ± 4.17
P-Value		0.00114	0.02253	0.52533

Means within each column for each factor that share the same letter are not substantially different from one another, as determined using Duncan's Multiple Range Test at a 5% significance level.

Influence of irrigation intervals, mulching treatments and their interactions on biomass allocation of *Paulownia tomentosa* saplings

The results in Table 4 revealed that irrigation frequency had a statistically significant effect on all dry biomass components, with p-values of 0.00002 for stem dry weight, 0.00223 for leaf dry weight, 0.01191 for root dry weight, and 0.00085 for total dry weight, indicating that frequent watering promotes dry matter accumulation across all plant organs. The interaction between irrigation and mulching was also significant for several parameters, such as stem ($p = 0.00112$), leaf ($p = 0.00379$), root ($p = 0.02946$), and total dry weight ($p = 0.00458$), while mulching alone had no significant effects in most cases except leaf dry weight ($p = 0.0248$). Furthermore, among irrigation intervals, once every 3 days was the most effective interval which was 131.41g for stem, 85.5g for leaves, 289.95g for roots and 506.86g for total. While once every 9 days was the least effective interval which is 65.01g for stem, 165.17g for root, 293.1g for total and once every 6 days with 56.7g for leaves. For mulching treatments, without mulching was the most effective treatment to produce the greatest leaf dry weight which was 80.57g, while black plastic film mulching was the least effective treatment to produce the lowest leaf dry weight which was 59.81g. As mentioned above, even though mulching treatments did not have significant effect on the other dry biomass parameters, the highest value of them were recorded under hay mulch treatment.

The Duncan's Multiple Range Test (DNMRT) confirmed that the best performing treatments in terms of dry weight were consistently those under once-every-3-days irrigation, particularly when combined with hay mulch or no mulching. For instance, the highest recorded dry weights were 162.2 g for stem, 109.03 g for leaves, 383.97 g for roots, and 631.87 g total, demonstrating that regular moisture availability is crucial for biomass development.

These findings are consistent with earlier study by Farooq et al. [34], who showed that optimal irrigation improves photosynthesis, carbon fixation, and dry matter partitioning. Although mulching alone did not significantly increase dry biomass, its role in enhancing irrigation efficiency especially with organic mulch like hay was evident through its interaction effects. In conclusion, the results emphasize that frequent irrigation is also the primary driver of dry biomass production in *Paulownia tomentosa*, while mulching can serve as a supporting practice to improve soil moisture and potentially contribute to more consistent growth outcomes under field conditions. In another research by Choudhary et al. [15] who determined that water is crucial for plant growth and productivity, in his scientific report includes: Nutrient Transport: Water acts as a medium for transporting nutrients from the soil to plant roots and throughout the plant tissues. Photosynthesis: Water is essential for photosynthesis, enabling plants to produce energy and food. It facilitates CO₂ assimilation and supports stomatal conductance.

Table 4: Influence of irrigation intervals, mulching treatments and their interactions on biomass allocation of *Paulownia tomentosa* saplings

Irrigation Intervals	Mulching Treatments	Stem Dry Weight Increment (g)	Leaf Dry Weight Increment (g)	Root Dry Weight Increment (g)	Total Dry Weight Increment (g)
Once every 3 days		131.41 ^a ±15.53	85.5 ^a ± 9.28	289.95 ^a ±42.66	506.86 ^a ±61.91
Once every 6 d.		82.35 ^b ± 6.87	56.7 ^b ± 6.23	173.9 ^b ± 24.60	312.95 ^b ±32.22
Once every 9 d.		65.01 ^b ± 6.89	62.91 ^b ± 6.97	165.17 ^b ±30.04	293.1 ^b ± 40.43
P-Value		0.00002	0.00223	0.01191	0.00085
	Without mulching	94 ^a ± 18.69	80.57 ^a ± 8.49	199.01 ^a ±41.22	373.58 ^a ±65.91
	Black plastic film	85.28 ^a ± 6.05	59.81 ^b ± 6.67	206.65 ^a ±23.25	351.75 ^a ±31.94
	Hay	99.48 ^a ± 15.28	64.72 ^b ± 9.22	223.36 ^a ±47.57	387.57 ^a ±67.43

	P-Value	0.40487	0.0248	0.82941	0.76998
Once every 3 days	Without mulching	162.2 ^a ± 17.88	109.03 ^a ±6.29	319.6 ^{ab} ±61.90	590.83 ^a ±74.60
	Black plastic film	77.83 ^b ± 15.15	53.76 ^{cde} ±4.91	166.3 ^{bc} ±34.01	297.9 ^b ± 52.24
	Hay	154.2 ^a ±13.27	93.7 ^{ab} ± 12.51	383.96 ^a ±65.98	631.86 ^a ±67.34
Once every 6 days	Without mulching	65.56 ^b ± 14.61	76.13 ^{bcd} ±6.85	159.93 ^{bc} ±58.009	301.63 ^b ±78.00
	Black plastic film	94.83 ^b ± 8.10	48.3 ^{de} ± 9.80	216.36 ^{bc} ±36.93	359.5 ^b ± 51.86
	Hay	86.66 ^b ± 7.71	45.66 ^c ±6.21	145.4 ^c ± 33.62	277.73 ^b ±43.79
Once every 9 days	Without mulching	54.23 ^b ± 11.89	77.36 ^{bc} ±13.24	117.5 ^c ± 42.86	228.3 ^b ± 61.16
	Black plastic film	83.2 ^b ± 8.27	56.56 ^{cde} ±8.79	237.3 ^{abc} ± 51.35	397.86 ^b ±65.44
	Hay	57.6 ^b ± 10.48	54.8 ^{cde} ±13.20	140.73 ^c ±48.19	253.13 ^b ±56.63
	P-Value	0.00112	0.00379	0.02946	0.00458

Means within each column for each factor that share the same letter are not substantially different from one another, as determined using Duncan's Multiple Range Test at a 5% significance level.

Influence of Irrigation Intervals and Mulching on Biomass Partitioning Indices: SMR, LMR, RMR, and R:S in *Paulownia tomentosa*

Biomass partitioning indices—Stem Mass Ratio (SMR), Leaf Mass Ratio (LMR), Root Mass Ratio (RMR), and Root-to-Shoot Ratio (R:S) offer insight into how plants allocate assimilated resources among organs under different environmental conditions [35].

The results in Table 5 showed that SMR was the only index significantly influenced by the interaction between irrigation interval and mulching treatment ($p = 0.04491$), while it was not significantly affected by the irrigation interval and mulching treatments individually. Additionally, the other indices (LMR, RMR, and R:S) remained statistically unaffected by the irrigation interval, mulching treatments, and their interaction ($p > 0.05$). The highest SMR (0.32) occurred under moderate irrigation (once every 6 days) with hay mulch suggesting that a mild water stress combined with organic cover(hay) may stimulate greater investment in above-ground structures [36], while the lowest SMR (0.21) was in once every 9 days with black plastic film. These findings are consistent with earlier observations that biomass partitioning tends to remain stable unless stress thresholds are exceeded, and changes are often more subtle than total biomass shifts [34].

Overall, the stability of partitioning indices across treatments in *Paulownia* suggests a strong and balanced growth strategy, where environmental management primarily affects the quantity of biomass more than its distribution among plant parts [37].

Table 5: Influence of irrigation intervals, mulching treatments and their interactions on biomass partitioning indices of *Paulownia tomentosa* saplings

Irrigation Intervals	Mulching Treatments	Stem Mass Ratio	Leaf Mass Ratio	Root Mass Ratio	Root to Shoot Ratio
Once every 3 days		0.26 ^{ab} ±0.01	0.17 ^a ±0.01	0.56 ^a ±0.01	1.31 ^a ±0.11
Once every 6 days		0.27 ^a ± 0.01	0.19 ^a ±0.02	0.535 ^a ±0.02	1.21 ^a ±0.12
Once every 9 days		0.23 ^b ±0.008	0.23 ^a ±0.03	0.532 ^a ±0.03	1.25 ^a ±0.17
	P-Value	0.07441	0.2986	0.77753	0.87901
	Without mulching	0.24 ^a ± 0.01	0.24 ^a ±0.02	0.50 ^a ±0.02	1.07 ^a ±0.11
	Black plastic film	0.24 ^a ± 0.01	0.17 ^a ±0.01	0.57 ^a ±0.01	1.40 ^a ±0.08
	Hay	0.26 ^a ± 0.01	0.19 ^a ±0.03	0.54 ^a ±0.03	1.30 ^a ±0.17
	P-Value	0.42505	0.17016	0.31489	0.29374
Once every 3 days	Without mulching	0.27 ^{ab} ±0.009	0.19 ^a ±0.02	0.53 ^a ±0.03	1.16 ^a ±0.17
	Black plastic film	0.26 ^{ab} ± 0.01	0.18 ^a ±0.02	0.55 ^a ±0.02	1.24 ^a ±0.10
	Hay	0.24 ^b ± 0.02	0.15 ^a ±0.02	0.599 ^a ±0.03	1.54 ^a ±0.25
Once every 6 days	Without mulching	0.22 ^b ± 0.01	0.27 ^a ±0.05	0.50 ^a ± 0.05	1.05 ^a ±0.25
	Black plastic film	0.26 ^{ab} ± 0.02	0.13 ^a ±0.01	0.597 ^a ±0.01	1.49 ^a ±0.09
	Hay	0.32 ^a ± 0.03	0.16 ^a ±0.02	0.50 ^a ±0.05	1.09 ^a ±0.22
Once every 9 days	Without mulching	0.24 ^b ± 0.01	0.26 ^a ±0.03	0.48 ^a ±0.04	0.99 ^a ±0.20
	Black plastic film	0.21 ^b ± 0.01	0.19 ^a ±0.02	0.58 ^a ±0.04	1.48 ^a ±0.23
	Hay	0.23 ^b ± 0.01	0.24 ^a ±0.09	0.51 ^a ±0.10	1.27 ^a ±0.44
	P-Value	0.04491	0.57555	0.79151	0.70688

Means within each column for each factor that share the same letter are not substantially different from one another, as determined using Duncan's Multiple Range Test at a 5% significance level.

Influence of irrigation intervals, mulching treatments and their interactions on nutrient uptake of *Paulownia tomentosa* saplings

The findings in Table 6 displayed that uptake of nitrogen (N), phosphorus (P) and potassium (K) were significantly influenced by irrigation intervals, mulching treatments (except phosphorus), and their interactions. The uptake patterns of these three elements varied according to the applied treatments. The p-values in the Table 6 indicate statistically significant effects of both irrigation intervals and mulching treatments on nitrogen and potassium uptake, while phosphorus uptake was only significantly affected by irrigation. Specifically, irrigation intervals had a highly significant effect on nitrogen ($p = 0.00002$), phosphorus ($p < 0.01$), and potassium ($p < 0.01$), Mulching treatments also significantly affected nitrogen ($p < 0.01$) and potassium ($p < 0.01$) uptake, with hay mulch leading to the highest nitrogen content. However, there was no significant difference among mulching treatments for phosphorus ($p = 1.0$), suggesting that phosphorus uptake was not influenced by the type of mulch used.

Regarding the irrigation intervals, once every 9 days was the best interval for nitrogen (2.93%), while once every 3 days was the best for Phosphorus (0.17%) and Potassium (0.41%). The lowest values were with irrigation every 6 days for nitrogen (2.74%) and phosphorus (0.13%), while potassium showed similarly low levels (0.33%) under both 6-day and 9-day irrigation intervals. This suggests that while moderate water stress may enhance nitrogen assimilation through increased root activity, frequent irrigation is essential for optimal phosphorus and potassium uptake due to their lower soil mobility and role in water regulation. Similar findings have been reported where improving soil water retention enhanced N, P, and K availability to crops [48], and higher fertility combined with adequate moisture improved nutrient content in plant tissues [49]. These results highlight the importance of balanced irrigation to maintain nutrient use efficiency and support vigorous growth in semi-arid forestry systems.

Regarding the mulching treatments, hay mulch showed the highest value for nitrogen (3.03%), no mulch for phosphorus (0.154%) and for potassium (0.383%) with black plastic film. For nitrogen the lowest value (2.67%) with black plastic film, for phosphorus (0.14%) with hay mulch and for potassium (0.31%) with no mulch. In addition, the interaction between irrigation intervals and mulching treatments playing a significant role in governing nutrient (N, P, K) absorption in *Paulownia tomentosa* seedlings. For nitrogen, the interaction was highly significant ($p < 0.01$), with the "9-day irrigation \times hay" combination yielding peak nitrogen (3.23%), statistically comparable to "3-day irrigation \times hay" (3.13%) but the lowest point is (2.45%) with black plastic film once every 3 days. Phosphorus showed a strong irrigation-mulching interaction ($p < 0.01$), where "3-day irrigation \times black plastic" (0.19%) and "3-day irrigation \times hay" (0.19%) outperformed other combinations while the lowest point is "6-day irrigation \times black plastic and hay" (0.11%). Potassium interactions ($p < 0.01$) peaked under "3-day irrigation \times black plastic" (0.51%), unmatched by other treatments but the lowest point is "9-day irrigation \times hay" (0.19%).

The superiority of hay mulch in nitrogen enhancement supports other researchers who attributed organic mulch efficacy to moisture retention and microbial nutrient mineralization. Conversely, *black plastic* excelled in phosphorus/potassium under frequent irrigation, echoing [38] on synthetic mulches accelerating root-zone warming.

The enhanced nitrogen uptake under hay mulch aligns with the findings [39], who demonstrated that organic mulches improve soil moisture retention and microbial activity, thus promoting nitrogen mineralization and availability. Similar outcomes highlighted the role of straw and organic mulches in enhancing soil fertility and nutrient cycling [40,41]. found that straw mulch reduced weed biomass by 70–90% in container-grown plants, comparable to herbicide effects, the study found that mulching enhanced nitrogen use efficiency, with apparent N recoveries increasing from 33.7% to 40% for planted crops and from 22.7% to 29.2% for regenerated crops when using paddy straw mulch at 160 kgN/ha [42].

In contrast, the highest phosphorus uptake was recorded in the no mulch treatment, suggesting that mulch application did not improve and might even limit phosphorus availability in this context. This may be due to reduced soil aeration or phosphorus fixation in mulched soils, especially when microbial activity is not sufficiently balanced by phosphorus solubilization processes. Similar findings were observed noted that mulch had a minimal or inconsistent effect on phosphorus uptake in several crop systems [43]. Potassium uptake was maximized under black plastic mulch, which is consistent with findings from [38], who reported that synthetic mulches increase soil temperature and reduce leaching, both of which enhance potassium solubility and root absorption. The warming effect of plastic mulch can also stimulate root activity and improve the uptake of mobile ions like potassium, especially under regular irrigation. Meanwhile, the lowest potassium level (0.31%) occurred in no mulch, where increased evaporation and potential leaching may have reduced potassium retention in the root zone [44].

Table 6: Influence of irrigation intervals, mulching treatments and their interactions on nutrient uptake of *Paulownia tomentosa* saplings

Irrigation Intervals	Mulching Treatments	Nitrogen (%)	Phosphorus (%)	Potassium (%)
Once every 3 days		2.77 ^b ±0.10	0.17 ^a ±0.009	0.41 ^a ±0.02
Once every 6 days		2.74 ^b ±0.059	0.13 ^c ±0.006	0.33 ^b ±0.02
Once every 9 days		2.93 ^a ±0.08	0.14 ^b ±0.006	0.33 ^b ±0.01
P-Value		0.00002	<0.01	<0.01
	Without mulching	2.74 ^b ±0.05	0.154 ^a ±0.004	0.31 ^b ±0.01
	Black plastic film	2.67 ^b ±0.07	0.15 ^{ab} ±0.01	0.383 ^a ±0.03
	Hay	3.03 ^a ±0.07	0.14 ^b ±0.01	0.38 ^a ±0.01
	P-Value	<0.01	1.0	<0.01
Once every 3 days	Without mulching	2.74 ^c ±0.03	0.14 ^d ±0.005	0.34 ^e ±0.02
	Black plastic film	2.45 ^e ±0.05	0.19 ^a ±0.005	0.51 ^a ±0.02
	Hay	3.13 ^a ±0.04	0.19 ^a ±0.005	0.39 ^b ±0.02
Once every 6 days	Without mulching	2.54 ^{de} ±0.03	0.15 ^c ±0.005	0.32 ^f ±0.02
	Black plastic film	2.94 ^b ±0.02	0.11 ^f ±0.005	0.29 ^e ±0.02
	Hay	2.74 ^c ±0.02	0.11 ^f ±0.005	0.39 ^b ±0.02
Once every 9 days	Without mulching	2.94 ^b ±0.01	0.16 ^b ±0.005	0.28 ^b ±0.02
	Black plastic film	2.64 ^{cd} ±0.04	0.13 ^{de} ±0.005	0.35 ^d ±0.02
	Hay	3.23 ^a ±0.04	0.12 ^{ef} ±0.005	0.36 ^c ±0.02
P-Value		<0.01	<0.01	<0.01

Means within each column for each factor that share the same letter are not substantially different from one another, as determined using Duncan's Multiple Range Test at a 5% significance level.

Influence of irrigation intervals, mulching treatments and their interactions on Protein, Proline and Chlorophyll of *Paulownia tomentosa* saplings

The results presented in Table 7 demonstrated that protein and proline were significantly affected by irrigation intervals, mulching treatments and their combinations. However, chlorophyll content was not significantly influenced by any study factors. On the other hand, water use efficiency was only significantly affected by irrigation intervals, and interaction between irrigation intervals and mulching treatments.

Regarding the irrigation intervals, once every 9 days was the highest interval for protein (13.62%) and proline (6.13 µg/g) but for chlorophyll (52.66) once every 3 days. The lowest values were with irrigation every 6 days for protein (12.71%) and proline (3.65 µg/g) while chlorophyll showed similarly low levels (49.7) under once every 9-day irrigation intervals.

Regarding the mulching treatments, hay mulch showed the highest value for protein (14.07%), for proline (6.22 µg/g) and for chlorophyll (52.15). For protein the lowest value (12.42%) with black plastic film, for proline (3.3 µg/g) and chlorophyll (49.68) both with no mulch treatment.

Regarding the interaction effects, for the greatest value of protein (14.98%) recorded under the combination of 9-day irrigation and hay mulch, while the lowest value was (11.36%) under the 3-day irrigation × black plastic mulch. About proline content (stress biomarker) the highest content (8.92 µg/g) was also observed under the "9-day irrigation combined with hay mulch" while the lowest value was (2.07 µg/g) obtained under the combination of "6-day irrigation and hay mulch", indicating that this combination most effectively mitigated water stress.

Despite statistical neutrality for chlorophyll content, DNMRT comparisons showed numerical trends: the 3-day irrigation × hay mulch combination yielded peak chlorophyll (54.2), while 9-day intervals without mulch performed the weakest (47.4).

These contrasts sharply with protein and proline results (where 9-day + hay dominated), suggesting chlorophyll synthesis was less responsive to water stress than osmotic biomarkers. The stability aligns with [38] indicating *Paulownia* preserves photosynthetic machinery under irrigation variability.[38] reported that *Paulownia* and similar fast-growing hardwoods maintain chloroplast integrity and pigment concentrations under moderate drought. Similarly, some tree species maintain stable chlorophyll levels under water stress by enhancing antioxidant activity and internal osmotic balance, thereby protecting the photosynthetic apparatus [45].

These findings imply that chlorophyll content alone may not be a sensitive stress indicator in *Paulownia*, particularly under intermittent or moderate drought conditions, whereas proline and protein serve as more dynamic markers of physiological stress.

Regarding the data showed for Water use efficiency (WUE) in g/l, the highest value among the irrigation intervals was under irrigation once every 9 days (1.12 g/l), while the lowest was considered with irrigation every 3 days (0.68 g/l), and this difference was statistically significant ($p = 0.02052$).

About mulching treatments, the highest value was under black plastic film (0.95 g/l), and the lowest is under no mulching (0.82 g/l), however the differences were not statistically significant ($p = 0.61332$). As per for the interaction, once every 9 days with black plastic film formed the highest (1.53 g/l), while the lowest efficiency was detected in once every 3 days with black plastic film (0.40 g/l), with a near-significant interaction effect ($p = 0.05278$).

These results recommend that less frequent irrigation (every 9 days) increases WUE, likely due to reduced water loss and improved water absorption efficiency under mild water stress conditions. The superior performance of black plastic film mulch can be attributed to its ability to conserve soil moisture and reduce evaporation, which aligns with previous studies [46] which found that plastic mulching significantly improved WUE in semi-arid environments. Similarly, Farooq et al. [34] emphasized that moderate water stress combined with soil moisture conservation practices can optimize WUE by enhancing root development and water uptake efficiency. Therefore, the interaction of efficient irrigation scheduling and appropriate mulching, particularly black plastic film, appears to be a promising strategy for improving water productivity in arid and semi-arid zones.

Table 7: Influence of irrigation intervals, mulching treatments and their interactions on Protein, Proline, Chlorophyll and Water Use Efficiency of *Paulownia tomentosa* saplings

Irrigation Intervals	Mulching Treatments	Protein (%)	Proline ($\mu\text{g}/\text{g}$)	Chlorophyll Content	Water Use Efficiency(g/l)
Once every 3 days		12.86 ^b ±0.46	5.28 ^b ±0.63	52.66 ^a ±1.01	0.68 ^b ±0.08
Once every 6 days		12.71 ^b ±0.27	3.65 ^c ±0.68	51.04 ^{ab} ±0.78	0.82 ^b ±0.08
Once every 9 days		13.62 ^a ±0.40	6.13 ^a ±0.93	49.7 ^b ±1.10	1.12 ^a ±0.15
	P-Value	0.00002	<0.01	0.09151	0.02052
	Without mulching	12.71 ^b ±0.27	3.3 ^c ±0.37	49.68 ^a ±1.19	0.82 ^a ±0.09
	Black plastic film	12.42 ^b ±0.34	5.54 ^b ±0.55	51.56 ^a ±0.76	0.95 ^a ±0.18
	Hay	14.07 ^a ±0.35	6.22 ^a ±1.05	52.15 ^a ±1.0006	0.85 ^a ±0.08
	P-Value	<0.01	<0.01	0.15542	0.61332
Once every 3 days	Without mulching	12.71 ^c ±0.15	4.8 ^e ±0.05	52.9 ^{ab} ±2.58	0.79 ^b ±0.10
	Black plastic film	11.36 ^e ±0.26	3.36 ^f ±0.03	50.9 ^{abc} ±1.50	0.40 ^b ±0.07
	Hay	14.52 ^a ±0.18	7.69 ^b ±0.06	54.2 ^a ±0.85	0.85 ^b ±0.09
Once every 6 days	Without mulching	11.78 ^{de} ±0.15	2.53 ^g ±0.04	48.76 ^{bc} ±1.17	0.79 ^b ±0.20
	Black plastic film	13.64 ^b ±0.10	6.37 ^d ±0.05	51.33 ^{abc} ±1.08	0.94 ^b ±0.13
	Hay	12.71 ^c ±0.10	2.07 ^h ±0.05	53.03 ^{ab} ±0.52	0.73 ^b ±0.11
Once every 9 days	Without mulching	13.64 ^b ±0.05	2.57 ^g ±0.04	47.4 ^c ±0.90	0.87 ^b ±0.23
	Black plastic film	12.25 ^{cd} ±0.21	6.91 ^c ±0.05	52.46 ^{abc} ±1.73	1.53 ^a ±0.25
	Hay	14.98 ^a ±0.18	8.92 ^a ±0.04	49.23 ^{abc} ±2.06	0.97 ^b ±0.21
	P-Value	<0.01	<0.01	0.16135	0.05278

Means within each column for each factor that share the same letter are not substantially different from one another, as determined using Duncan's Multiple Range Test at a 5% significance level.

Conclusion

The results of this study clearly demonstrate that irrigation interval is the most influential factor affecting the early growth, biomass production, nutrient uptake, and physiological responses of *Paulownia tomentosa* saplings. Irrigation every 3 days significantly enhanced stem elongation, diameter expansion, leaf production, and total dry biomass, confirming that frequent water availability is critical for the establishment of this fast-growing species, especially under semi-arid conditions.

Mulching alone did not show consistent statistical significance across most traits; however, its interactive role with irrigation particularly in combination with hay mulch enhanced both vegetative growth and nitrogen uptake. This

indicates that organic mulching may act as a complementary strategy to improve soil moisture retention and microbial activity, indirectly supporting growth under optimal irrigation.

Biomass partitioning remained stable, indicating treatments influenced total biomass more than its distribution. Nutrient uptake varied by element: nitrogen and potassium responded to both irrigation and mulching, while phosphorus was affected only by irrigation. Elevated proline and protein levels under 9-day irrigation with hay mulch signaled greater stress, whereas chlorophyll content stayed relatively unchanged.

Briefly, integrating scientifically timed irrigation with organic mulching practices, particularly during the early establishment phase, can significantly enhance the growth and efficiency of *Paulownia tomentosa* plantations in water-scarce regions. This research provided critical insight for sustainable water and soil management practices in afforestation and agroforestry systems.

Acknowledgments

We sincerely acknowledge the support of Salahaddin University–Erbil, particularly the College of Agricultural Engineering Sciences and the Department of Forestry. Our special thanks go to Assist. Prof. Dr. Sherzad Omar Hamad for his valuable guidance and continuous cooperation throughout this study. We also extend our gratitude to ARD Company for supplying the field in Bazian District in Sulaimani, and to the Directorate of Agricultural Research in Sulaimani–Bakrajo for their collaboration in facilitating the experimental tests.

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تأثير فترات الري ومعالجات التغطية على نمو وتطور شتلات الباولونيا تومينتوسا Thunb. Steud. في منطقة بازيان، إقليم كردستان، العراق

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الخلاصة

يعتمد النمو الناجح لمزارع الباولونيا على تطبيق تقنيات الزراعة الحرجية المناسبة. وتحديدًا، تُعد إدارة الري وطرق رطوبة التربة مثل معالجات التغطية بالغلاف مهمة. لذلك، تبحث هذه الدراسة في آثار فترات الري المتنوعة ومعالجات التغطية بالغلاف وتفاعلاتها على النمو وتخصيب الكتلة الحيوية وامتصاص العناصر الغذائية والاستجابات الفسيولوجية لـ 36 شتلة الباولونيا تومينتوسا في ظل الظروف شبه القاحلة في قضاء بازيان بإقليم كردستان العراق. أُجريت تجربة عاملية باستخدام ثلاث فترات ري (كل ثلاثة وستة وتسعة أيام) مع ثلاث معالجات تغطية بالغلاف (بدون تغطية بالغلاف، تغطية بالغلاف القشّي، وغشاء بلاستيكي أسود). شفت النتائج أن تكرار الري كان له تأثير مهم وذو دلالة إحصائية على المعايير المورفولوجية. أدى الري المتكرر، وخاصة كل 3 أيام، إلى تحسين ارتفاع الساق (127.66 سم)، وقطرها (23.25 مم)، وعدد الأوراق (21.77)، مع أفضل النتائج عند دمجها مع عدم تغطية الغلاف القشّي أو تغطيته بالغلاف القشّي. في المقابل، أدى الري كل 9 أيام إلى أضعف نمو، بغض النظر عن التغطية. وفيما يتعلق بتراكم الكتلة الحيوية، فإن الري المتكرر، كل 3 أيام بالتنب، عزز بشكل كبير الكتلة الحيوية الجافة (631.86 جم) في جميع أجزاء النبات. في حين أن التغطية وحدها كان لها تأثير ضئيل، إلا أن الري، وخاصة نشارة التبن، عزز النمو. وظلت نسب الكتلة الحيوية مستقرة: حيث أثرت المعالجات على الكتلة الحيوية الكلية أكثر من كيفية توزيعها بين أجزاء النبات. كان امتصاص العناصر الغذائية مهمًا من خلال الري والتغطية. حسن نشارة التبن امتصاص النيتروجين (3.03%)، وعزز نشارة البلاستيك الأسود امتصاص البوتاسيوم (0.383%). تأثر امتصاص الفوسفور بالري. حدث أعلى مستوى للنيتروجين (3.23%) تحت الري لمدة 9 أيام بالتنب، وأعلى مستوى للبوتاسيوم (0.51%) تحت الري لمدة 3 أيام بالبلاستيك الأسود. بلغت مستويات البروتين 14.98% والبرولين 8.92 ميكروغرام / غرام، وكلاهما كان تحت الري لمدة 9 أيام بنشارة التبن. لم تحدث أي تغييرات ملحوظة في الكلوروفيل. بلغت كفاءة استخدام المياه أعلى مستوياتها (1.53 غ/لتر) عند الري لمدة 9 أيام بالبلاستيك الأسود. عزز الري المتكرر النمو والكتلة الحيوية بشكل ملحوظ، بينما حسن التغطية بالقش من استخدام المغذيات والمرونة الفسيولوجية عند دمجها مع الري في البيئات محدودة المياه.

الكلمات المفتاحية: بولونيا تومينتوسا، فترات الري، معالجات التغطية، تخصيب الكتلة الحيوية، امتصاص العناصر الغذائية، السمات الفسيولوجية.