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Improving Yield and Water Use Efficiency of Drought-Tolerant Saplings Using Subsurface Irrigation in a Semi-Arid Environment

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Abstract: Efficient and sustainable management of land and water resources is crucial for maintaining environmental stability and increasing productivity, particularly in semi-arid regions where water scarcity is a significant challenge. In these areas, adopting water-saving irrigation technologies is essential to optimize resource use. This study evaluated the effects of surface and subsurface irrigation methods on the yield and water use efficiency (WUE) of four drought-tolerant tree species: *Ailanthus altissima* (Heaven Tree), *Melia azedarach* (Chinaberry), *Morus alba* (White Mulberry), and *Robinia pseudoacacia* (Black Locust) under semi-arid conditions in Isfahan, central Iran. The study employed a randomized complete block design with three repetitions. Sapling water requirements were estimated based on canopy cover, and soil moisture was monitored using Time-Domain Reflectometry (TDR). After two years, yield and WUE were measured for each species under both irrigation systems. Results showed that daily water requirements differed by species, with *M. alba*, *M. azedarach*, *A. altissima*, and *R. pseudoacacia* requiring 1.85, 1.77, 1.65, and 1.50 liters per day, respectively. Subsurface irrigation significantly increased yield and WUE for all species. For instance, *M. alba* yield increased from 23.33 to 32.33 kg per sapling, while *R. pseudoacacia* yield increased from 20.1 to 28.33 kg. Moreover, WUE under subsurface irrigation reached 2.07 kg ha^{-1}, compared to 1.31 kg ha^{-1} under surface irrigation. These findings highlight the effectiveness of subsurface irrigation as a practical and eco-friendly strategy for improving tree productivity and water use efficiency in water-limited environments.

Key words: water requirement, water-saving irrigation, sustainable water management, water productivity.

Semi-arid regions are characterized by high air temperatures, low and irregular precipitation, strong

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winds, and high evaporative demand, which together impose severe limitations on water availability for agricultural production and ecosystem development. These constraints have intensified in recent decades due to climate change, which has increased the frequency of drought events, altered rainfall patterns, and exacerbated water scarcity in dry and semi-arid environments worldwide (IPCC, 2023; Ahmed *et al*., 2023). As a result, sustainable water management has become a critical challenge, particularly in regions where water resources are already limited and unevenly distributed.

In semi-arid landscapes, water supply largely depends on surface water transferred from distant river systems and limited groundwater recharge driven by sporadic rainfall events. Under such conditions, inefficient irrigation practices lead to significant water losses through evaporation, runoff, and deep percolation, reducing water availability for plants and threatening the sustainability of agricultural and afforestation projects (Kisekka *et al*., 2020; Zhang *et al*., 2022). Therefore, improving irrigation efficiency at the field scale is considered one of the most effective strategies for mitigating water scarcity and enhancing productivity in arid and semi-arid regions.

Water use efficiency (WUE), commonly defined as the ratio of biomass or yield produced per unit of water consumed, is a key indicator for evaluating the performance of irrigation systems under water-limited conditions (Farooq *et al*., 2020). Recent studies have shown that advanced irrigation technologies, particularly subsurface irrigation systems such as subsurface drip irrigation (SSDI), can significantly enhance WUE by delivering water directly to the root zone and minimizing non-beneficial water losses associated with surface evaporation and soil surface wetting (Li *et al*., 2020; Patel *et al*., 2021). Although SSDI systems require higher initial installation costs, they have demonstrated superior performance in maintaining optimal soil moisture conditions and sustaining plant growth under drought stress (Wang *et al*., 2021; Zhang and Liu, 2022).

Despite the documented benefits of subsurface irrigation, its effectiveness compared to conventional surface irrigation systems is highly dependent on plant species, soil properties, and climatic conditions. Most existing studies have focused on annual crops and orchard systems, while limited attention has been given to drought-tolerant tree species used in natural, rehabilitated, or urban green spaces. This knowledge gap is particularly evident in semi-arid regions such as Iran, where afforestation and land rehabilitation programs play an important role in combating desertification and climate change impacts.

Accurate estimation of plant water requirements is a prerequisite for optimizing irrigation management in such environments. However, direct measurement methods such as lysimetry are often costly, time-consuming, and impractical for field-scale applications. Consequently, indirect approaches based on canopy cover, plant characteristics, and local climatic variables have gained increasing attention as reliable and cost-effective alternatives for estimating water requirements, especially for woody species irrigated on a per-tree basis (Zhang and Liu, 2022). These methods are particularly relevant for subsurface irrigation systems, where irrigation scheduling is determined for individual plants rather than cultivated area.

Given the increasing pressure on water resources under climate change and the growing need for efficient irrigation technologies in semi-arid regions, a systematic evaluation of irrigation strategies for drought-tolerant tree species is urgently required; however, such an evaluation is constrained by the limited number of comparative studies examining the effects of surface and subsurface irrigation on plant growth and water-use efficiency under semi-arid field conditions.

Therefore, the main objective of the present study was to evaluate the effects of surface and subsurface irrigation systems on yield and water use efficiency of selected drought-resistant saplings in a semi-arid environment. The study aims to (i) compare water consumption and WUE between irrigation methods, (ii) assess the suitability of subsurface irrigation for drought-tolerant tree species, and (iii) provide practical recommendations for improving irrigation management and sustainable water use in semi-arid regions such as Iran.

Materials and Methods

Experimental farm

The experimental field was located within the Isfahan University of Technology campus, situated in the northwest of Isfahan city, central Iran (32°43′N, 51°33′E. The site lies at an elevation of approximately 1,600 m amsl and is classified as having a cold semi-arid according to the Emberger climate classification. The area endures hot and arid summers, accompanied by mild winters that are relatively humid. Historical climate data shows an annual average temperature of 17.0°C, with yearly precipitation averaging 116.9 mm and relative humidity around 38%. In the summer, temperatures can soar above 48°C, while winter temperatures may plunge to -30°C. The region frequently experiences strong winds, primarily from the west, southwest, and northwest, with daytime wind speeds typically between 6.6 and 11.9 km h^{-1}, and nighttime speeds ranging from 4.6 to 8.9 km h^{-1}.

Experimental design and treatments

The experiment was conducted using a completely randomized design with three replications. The study involved two main factors: irrigation methods and sapling species. For subsurface irrigation, porous earthenware reservoirs were fabricated specifically for this study. Each reservoir measured 50 cm in height with an outer diameter of 11 cm, yielding a total volume of 4750 cm^3. The reservoirs were shaped using plaster molds and subsequently fired in a pottery kiln at 900°C. Detailed dimensions of the reservoirs are presented in **Table 1.**[3]. The reservoirs were each placed in pits with a radius and depth of 50 cm, at 2-meter by 2-meter intervals. Saplings were then planted, and one earthenware reservoir was installed adjacent to the root zone of each sapling (Fig. 1). To minimize evaporation losses, each reservoir was covered with a lid.

Table 1. Dimensions of the earthenware reservoirs used in this study

Parameter	Reservoir dimension
Thickness (cm)	1
Height (cm)	50
Inner diameter (cm)	10
Outer diameter (cm)	11
Area (cm^2)	1916.97
Volume (cm^3)	4750

The above mentioned, 2-years saplings including four species of Heaven Tree (*Ailanthus altissima*), Chinaberry (*Melia azedarach*), White mulberry (*Morus alba*) and Black locust (*Robinia pseudoacacia*) were planted in March 2016.



Fig.1. An overall view of the implementation of the plan in the arena.

The required water was supplied for the saplings, through leakage by earthenware (Fig. 1).

Determination of water requirement

In this study, daily water requirements of the saplings during the growing season were estimated using the FAO Penman-Monteith method, based on a 10-year dataset (2009-2019) from the Isfahan Meteorological Station, located in the rural area of Isfahan (51°42′E and 32°31′N). Water requirement estimations were further refined using plant coefficients (Kp), which vary depending on the specific water needs of different plant species. These coefficients span from 0.1 to 0.9 and are categorized into four distinct levels based on Khosroshahi (2013): very low (less than 0.1), low (0.1-0.3), moderate (0.4-0.6), and high (0.7-0.9). Accordingly, the tree species studied in this experiment were classified as having moderate water requirements, with a plant coefficient (K_p) ranging from 0.4 to 0.6. In order to measure the dry matter content, fresh tree organs were dried in an oven at 700C for 48 hours after harvesting in September 2018 and then weighed with a digital scale.

In subsurface irrigation systems, evaporation from the soil surface is significantly minimized, as the soil remains dry at the surface. Consequently, the plant's water consumption primarily reflects transpiration from the leaf canopy. For the design of the subsurface irrigation system, plant water demand was calculated using the following equation (Hershfield, 1964):

$$T_d=0.1 \times U_d \times \sqrt{(P_d)} \quad ...(1)$$

where, is the daily water requirement (mm/ day), is the daily evapotranspiration (mm/ day), and is the canopy cover percentage (The ratio of canopy area to tree spacing area). and, is calculated using equation 2:

$$U_d=ET_c \times \text{Irrigation Interval} \quad ...(2)$$

where,

$$ET_c=ET_0 \times K_p \quad ...(3)$$

Here, ET_c represents the plant evapo-transpiration (mm day^{-1}), is the reference potential evapotranspiration (mm day^{-1}) and is the plant coefficient.

Irrigation water analysis

The quality of the irrigation water was assessed through standard laboratory procedures conducted at the Water and Soil Laboratory of Isfahan University of Technology. Electrical conductivity (EC) and pH values were measured using an EC-meter and a pH-meter, respectively. Chloride (Cl^-) and sodium (Na^+) concentrations, expressed in milliequivalents per liter (meq L^{-1}), were determined using the argentometric titration method and a flame photometer, respectively, as described by Richards (1954). Carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) levels were also determined via titration techniques.

Calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations were quantified using complexometric titration with EDTA. The titrations employed specific metallochromic indicators: Calcon or Murexide for calcium, and Eriochrome Black T for total hardness (Ca^{2+} + Mg^{2+}). The magnesium content was subsequently calculated by subtracting the calcium value from the total hardness.

The Sodium Adsorption Ratio (SAR), a key indicator of water suitability for irrigation, was calculated using the following formula:

$$SAR = Na \Big/ \sqrt{\frac{(Ca) + (Mg)}{2}} \quad ...(1)$$

where [Na^+], [Ca^{2+}], and [Mg^{2+}] represent the concentrations of sodium, calcium, and magnesium ions in milliequivalents per liter (meq L^{-1}). The chemical properties of the irrigation water showed an EC of 0.29 dS m^{-1}, a pH of 8.04, and an SAR of 1.44. Ion concentrations (meq L) were 2.4 for Mg+Ca, 1.57 for Na, 13 for Cl, 6 for HCO_3 and 2 for CO_3.

Soil analysis: Soil samples were collected from the 0-50 cm depth layer to determine key physical and chemical properties. The electrical conductivity (EC) and pH of the soil were measured using saturated paste extract following the method of Slavich and Petterson (1993). Soil texture was determined via the hydrometer method, and textural classification was assigned according to the USDA soil texture triangle (Bouyoucos, 1962). Bulk density was assessed using the core sampling method, with a standard cylindrical core weighing 190.98 g. Soil porosity (f) was then calculated based on

the measured bulk density and an assumed particle density of 2.65 Mg m^{-3}.

Field capacity (FC) and permanent wilting point (PWP) were determined using a pressure plate apparatus at matric potentials of -33 kPa and -1500 kPa, respectively, in accordance with Klute (1986). Physical and chemical analysis of the soil at a depth of 0-50 cm revealed a sandy loam texture composed of 48.7% sand, 29.5% silt, and 21.8% clay. The soil exhibited a bulk density of () and a total porosity of 51% (v/v). Soil moisture limits were recorded at 13.48% for field capacity (FC) and 8.38% for permanent wilting point (PWP), both expressed on a mass basis (). Chemically, the soil layer was alkaline with a pH of 8.81 and an electrical conductivity (EC) of

Determination of soil wetting pattern: To evaluate the soil water distribution pattern, volumetric soil water content was measured at specified spatial and temporal intervals following irrigation. Soil samples were collected at 5, 25, and 50 cm horizontal distances from the irrigation reservoirs, and at vertical depths of 0-10, 10-25, 25-40, and 40-75 cm from the soil surface. Sampling was performed at three-time intervals: one, three, and six days after irrigation. The Time Domain Reflectometry (TDR) method was employed using a TRIME-FM model probe with a measurement accuracy of ±0.1%.

Water use efficiency: Water Use Efficiency (WUE) for each irrigation treatment (surface and subsurface) was calculated according to the method of Henry *et al*. (2006), using the following equation:

$$WUE=Y/W_t \quad ...(2)$$

where,

- WUE is the water use efficiency (kg $\cdot L^{-1}$),
- Y is the total yield of the plant (kg), and
- W_t is the total water used (including both irrigation water and rainfall).

To determine dry matter yield, plant samples were oven-dried at 70°C until reaching a constant weight, and then weighed using a precision laboratory digital scale.

Statistical analysis: Normality of the data was tested using the Kolmogorov-Smirnov test, and homogeneity of variances was verified by Levene's test. The significance of treatment effects was evaluated using an independent samples t-test with repeated measures across two consecutive years. When significant differences were detected, the Least Significant Difference (LSD) test was applied at confidence levels of $P < 0.05$ and $P < 0.01$. All statistical analyses were performed using SAS software version 9.4, and results are presented as mean values ± standard error (SE) based on three replicates per treatment.

Results and Discussion

Water requirements and irrigation inputs:

Water use efficiency (WUE), expressed in kg $\cdot L^{-1}$, was determined by dividing the total dry yield of each sapling species by the total water consumed, which included both irrigation and rainfall. The daily water requirement of each sapling was calculated based on the canopy cover area and is summarized in Table 2.

Table 2. Daily water requirement of studied saplings

Species	Water requirement (l/day)
M. alba	1.85
M. azedarach	1.77
A. altissima	1.65
R. pseudoacacia	1.5

Considering the rainfall data, subsurface irrigation treatments were supplemented with earthenware reservoirs (capacity: 4.75 L), refilled every 5 days. Saplings under surface irrigation received equivalent water quantities. Over the two-year period, the total water demand per sapling was 936.6 L (468.3 L yr^{-1}), with 566.6 L supplied by rainfall and 370 L through irrigation.

Effects of irrigation method on yield: The effect of irrigation method on the yield of the four sapling species is presented in Table 3. Subsurface irrigation significantly improved yield across all species compared to surface irrigation.

As table 3 shows, the average yield of each *Morus alba* sapling significantly increased from 23.33 kg in surface irrigation to 32.33 kg in subsurface irrigation, in the same manner *Melia azedarach* increased from 22 kg to 30 kg, *Ailanthus altissima* from 20 kg to 29.33 kg and *Robinia pseudoacacia* from 20.1 kg to 28.33 kg.

Table 3. Average sapling yield (kg) under surface and subsurface irrigation

Species	Irrigation method	Yield (Mean±SE)	Df	T	Sig.
Morus alba	Subsurface	32.33 ± 1.77a	1	122.83	0.02*
	Surface	23.33 ± 2.4b			
Melia azedarach	Subsurface	30 ± 4.5a	1	102	0.01*
	Surface	22 ± 3.3b			
Ailanthus altissima	Subsurface	29.53 ± 1.5a	1	25.92	0.07*
	Surface	20.5 ± 3.4b			
Robinia pseudoacacia	Subsurface	28.33 ± 2.1a	1	81	0.09*
	Surface	20.1 ± 2b			

Independent T-Test; SE= Standard Error; df= degree freedom, sig= signification
Note: The same lowercase letters within a row indicate no significant difference (LSD, P<0.05), and dissimilar lowercase letters within a column indicate significant difference (LSD, P<0.05),
ns and * mean insignificant and significant effects at 5% probability level, respectively.

Water Use Efficiency (WUE): WUE values further confirmed the superiority of subsurface irrigation (Table 4). The highest WUE was recorded for *Morus alba* under subsurface irrigation (0.034 kg ha^{-1}), while the lowest was observed under surface irrigation for *Ailanthus altissima* and *R. pseudoacacia* (0.021 kg ha^{-1}).

Based on the findings, it can be firmly stated that the subsurface irrigation system offers significant benefits in terms of efficiency and water use performance when compared to surface irrigation methods. Furthermore, the findings of this study align with those of Genaidy *et al*. (2016), who conducted a similar investigation involving subsurface irrigation for orange trees in Valencia, resulting in an increase in fruit quantity, weight, and overall tree productivity. They also noted improvements in both the physical and chemical attributes of the fruit. Recently, there has been a growing interest in implementing subsurface irrigation techniques with woody perennials. By utilizing subsurface drip irrigation, water and nutrients are applied more effectively, leading to notable enhancements in crop yield and quality, as it allows for even water distribution directly to the root zone. In this context, recent research has shown that subsurface drip irrigation significantly reduces irrigation water use by minimizing surface evaporation and markedly suppresses weed biomass compared to surface drip irrigation, thereby enhancing overall water use efficiency and reducing competition from weeds (Büser *et al*., 2025). Conversely, while Jha *et al.* (2016) indicated that the irrigation methods did not significantly affect dry matter yield, Ishfaq (2002) highlighted that drip irrigation can greatly enhance water use efficiency (WUE) relative to furrow systems by reducing water evaporation losses and maximizing the utilization of seasonal rainfall in the soil profile. Also, Recent research has shown that subsurface drip irrigation can significantly improve irrigation water use efficiency compared to traditional furrow irrigation. In a threeyear field experiment on tomatoes, subsurface drip irrigation

Table 4. Water Use Efficiency (kg of sapling L^{-1}) under surface and subsurface irrigation

Specie	Irrigation method	WUE (kg of sapling L^{-1})	WUE (kg L^{-1})
Morus alba	Subsurface	0.034	2.07a
	Surface	0.024	1.44b
Melia azedarach	Subsurface	0.032	1.92a
	Surface	0.023	1.40b
Ailanthus altissima	Subsurface	0.031	1.89a
	Surface	0.021	1.31b
Robinia pseudoacacia	Subsurface	0.030	1.83a
	Surface	0.021	1.31b

^{ns} and * mean insignificant and significant effects at 5% probability level, respectively.
Note: The same lowercase letters within a column indicate no significant difference (LSD, P>0.05), and dissimilar lowercase letters within a column indicate significant difference (LSD, P<0.05),

increased irrigation water use efficiency and crop performance while using less water than furrow irrigation, highlighting its potential for sustainable water management in agriculture (ElSadek *et al*., 2023). In contrast with the above-mentioned researches, Martínez-Gimeno *et al*. (2018) evaluated the water use efficiency of Clementine trees using surface and subsurface irrigation and concluded that on average, water saving in subsurface irrigation treatment compared to the surface treatment without significant difference in either yield or fruit composition were 23.0%. Recent studies have shown that subsurface drip irrigation promotes deeper root development and improved root growth by maintaining a moist soil environment in the root zone, thereby enhancing plant water uptake and overall growth performance compared to surface irrigation (Zhang *et al*., 2025). In a study by Martínez and Reca (2014), it was reported that the alternative subsurface irrigation method seems to work better than the surface drip irrigation, because the yield and efficiency of irrigation water consumption was higher for the first method. Although, in agricultural systems water is applied to produce crops and optimize its yield and quality, but in landscape systems, health, appearance and growth are most important. Landscapes can typically manage at lower irrigation levels that needed for crop production.

Water distribution in soil: As previously noted, soil water content distribution across different irrigation treatments was measured through field sampling and subsequently interpolated using Surfer 10.0 software and the Kriging geostatistical method. The results are illustrated in Figure 2. As shown in Figure 3, under subsurface irrigation, the highest water content was concentrated near the earthenware reservoir—coinciding with the zone of greatest root development—thereby ensuring optimal water availability for plant uptake. A decreasing trend in soil moisture was observed with increasing distance from the reservoir. This pattern reflects a key objective of pressurized irrigation systems, particularly subsurface methods: minimizing deep percolation and water losses beyond the root zone.

In the current investigation, the subsurface irrigation system demonstrated the maximum lateral and vertical spread of soil moisture at a depth of 20-40 cm, whereas in a surface irrigation system, due to evaporation and gravity, moisture is quickly removed from the root environment, and subsequently the plant's access to moisture is limited (Fig. 3), which aligns with the results reported by Jafari *et al*. (2022). Li *et al*. (2004) stated that various factors, such as soil texture and layering, emitter discharge rate, timing of irrigation cutoff, and hydraulic conductivity, influence the shape of the wetted front in subsurface irrigation. They found that higher discharge rates generally improve the horizontal distribution of water, whereas reduced discharge rates encourage

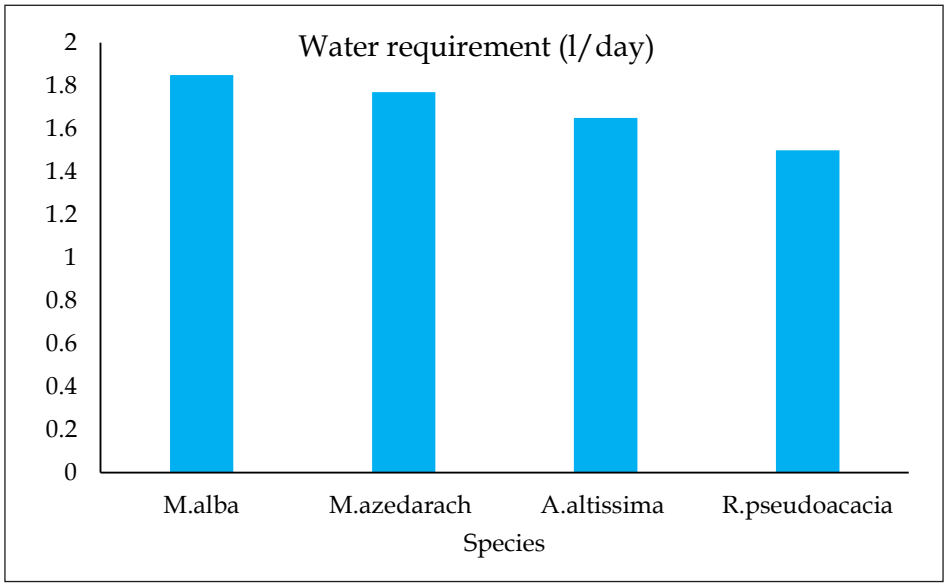
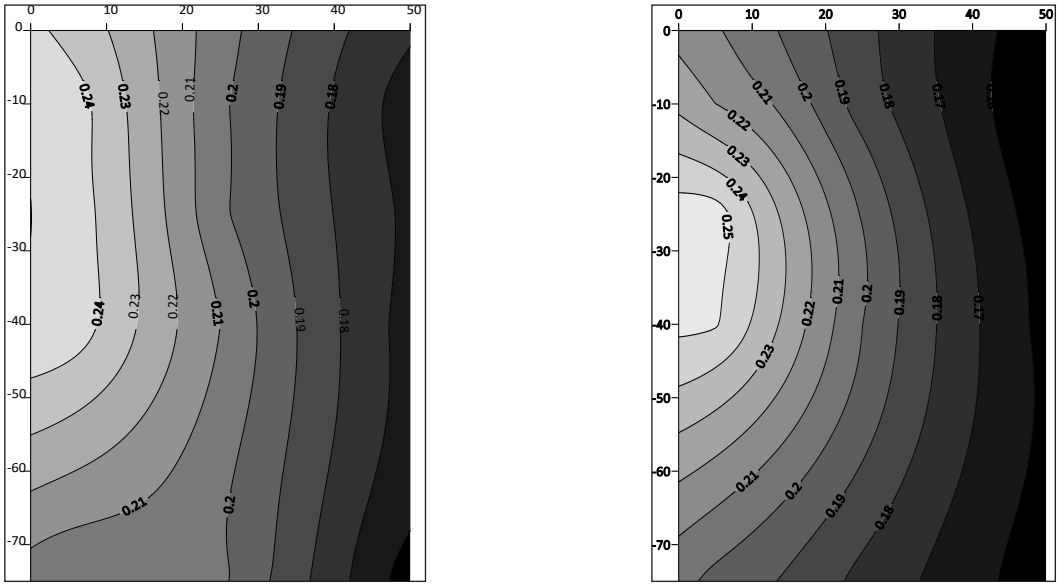


Fig. 2. Daily water requirement of studied saplings.



(a) Surface irrigation *(b) Subsurface irrigation*

Fig 3. Distribution of water content: a- surface irrigation, b- subsurface irrigation

deeper vertical infiltration. The patterns of soil wetting and the spatial variability of soil water under drip irrigation are influenced by several factors, including soil hydraulic properties, emitter discharge rate, emitter spacing, irrigation frequency, and root distribution. Recent research has shown that the emitter flow rate significantly affects the size and shape of the wetted soil volume. For example, Jia *et al*. (2024) investigated the influence of drip emitter flow rate on soil water movement under subsurface drip irrigation. They found that as emitter flow rate increases, the lateral and downward migration distances of the wetting front increase, but the pattern of water movement differs with soil texture — indicating that higher flow rates tend to promote horizontal spread relative to vertical movement compared to lower flow rates under otherwise equal conditions. This demonstrates that discharge rate significantly affects the shape and distribution of the wetted zone. Moreover, Sun *et al*. (2014) highlighted that soil water content is temporally dynamic and spatially heterogeneous, with its variability strongly influenced by scale and localized environmental factors.

Conclusions

The present study demonstrates that subsurface irrigation significantly enhances the growth, yield, and water use efficiency (WUE) of the four studied sapling species (*Morus alba, Melia azedarach, Ailanthus altissima, and Robinia pseudoacacia*) compared to surface irrigation. Over the two-year period, subsurface irrigation consistently increased sapling yield by 25-45% across species, while WUE was also notably higher under this method, with Morus alba achieving the maximum efficiency of 0.034 kg/ha. Soil moisture distribution analysis further confirmed that subsurface irrigation maintains optimal water availability within the root zone, minimizing water losses due to evaporation or deep percolation.

These findings corroborate previous studies emphasizing the advantages of subsurface irrigation in both agricultural and landscape systems, including improved water conservation, more uniform root-zone moisture, and enhanced plant productivity. By delivering water directly to the root zone, subsurface irrigation not only supports higher growth rates and yield but also allows more efficient use of available water resources, making it a particularly effective strategy for regions facing water scarcity. Overall, subsurface irrigation emerges as a superior method for maximizing sapling performance while promoting sustainable water management in urban and semi-arid landscapes.

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Data Availability Statement

Some or all the data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

Compliance with Ethical Standards

The authors declare that they have no conflict of interest.

Authors Contributions

Z. Jafari led the idea, analysis of the results, the discussion and writing. S.H. Matinkhah and K. Ebrahimi contributed to analysis and editing of the manuscript. All authors reviewed the manuscript.

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