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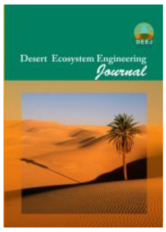

Investigation of Medicago sativa Cultivation under Various Irrigation Methods for Arid Regions

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Abstract

The establishment and development of vegetation in arid rangelands are severely hindered by prolonged drought and limited water availability, making the efficient use of water resources crucial. This two-year study (2016–2018) in Isfahan, Iran, evaluated the effects of three irrigation methods—clay pipe, surface tape, and furrow irrigation—on the growth performance of *Medicago sativa* (alfalfa). A randomized complete block design with three replications was used, where all treatments received an equal volume of irrigation water. The results showed that the irrigation method significantly affected numerous growth parameters ($P < 0.05$), including: Basal diameter and stem number, Canopy cover and plant vigor, Fresh forage and weed weights, Chlorophyll content, survival rate, and flowering, seeding yield and water use efficiency Clay pipe irrigation led to superior outcomes in key metrics such as plant height, basal diameter, stem number, vigor, stomatal conductance, germination rate, yield, and water use efficiency. In contrast, tape irrigation resulted in higher values for canopy cover, forage and weed biomass, survival, flowering, and seed production. Based on these findings, both clay pipe and tape irrigation methods are recommended as effective solutions for arid regions. Furrow irrigation, however, proved less suitable due to its limited impact on plant performance. Notably, the clay pipe system demonstrated the highest water use efficiency, making it a particularly promising method for water-scarce environments.

Keywords: Furrow irrigation, Tape irrigation, Clay pipes, *Medicago sativa*, Arid regions.

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1. Introduction

Drought is a major factor limiting crop productivity globally, making the development of drought-resistant crops and the use of water-efficient irrigation systems crucial for maintaining crop yields (Jones & Corlett, 1992; Levidow et al., 2014). Proper management of irrigation systems is essential for maximizing water use efficiency, and subsurface drip irrigation has emerged as a promising method to improve this efficiency. Unlike surface systems, these systems apply water directly to the root zone, reducing evaporation and surface runoff (Ayars et al., 1999). Furrow irrigation, a more traditional method, faces several challenges. It is difficult to automate, often leading to unequal water distribution and significant losses from deep drainage or runoff (Walker, 1989). Its disadvantages also include potential salinity hazards between furrows, tailwater losses, limited mobility for machinery, and an increased risk of soil erosion. Additionally, furrow systems typically require more labor and are harder to automate than other methods (Walker, 2003). In contrast, drip irrigation (both surface tape and subsurface) offers a precise and uniform application of water at a high frequency (Hanson & May, 2007). Research has shown the superior efficiency of drip irrigation over other methods. For example, Sammis (1980) found higher water use efficiency for subsurface irrigation compared to sprinkler and furrow systems for potatoes. Similarly, Clark (1979) reported that drip irrigation for corn production in Texas had a higher water use efficiency (14 kg ha^{-1} mm^{-1}) than both sprinkler and furrow irrigation (11.9 and 11.5 kg ha^{-1} mm^{-1}, respectively). Other studies have also demonstrated the benefits of drip irrigation. Restuccia and Abbate (1978) found that drip-irrigated tomatoes yielded more than furrow-irrigated tomatoes, even with similar water volumes. The key advantage of subsurface systems is that minimal water reaches the soil surface, greatly reducing evaporation and providing more water directly to the plant roots. This results in approximately 50-60% of the applied water being used by the plant, whereas flood irrigation can lose up to 50% of its water to evaporation and deep infiltration (Erdem et al., 2006). *Medicago sativa* (alfalfa) is a globally significant perennial forage legume valued for its high nutritional quality, nitrogen fixation, and soil improvement properties. Despite its adaptability and high yield potential, alfalfa is a water-intensive crop, which has led to scrutiny in arid regions (Orloff et al., 2005). Given that water scarcity is the primary limiting factor for plant production in arid and semi-arid areas, the use of highly efficient, low-pressure irrigation systems like subsurface irrigation has become essential. These systems deliver water precisely and efficiently, making them an ideal solution for cultivating water-demanding crops like alfalfa in dry environments. This study was thus conducted to compare three irrigation methods—tape, furrow, and subsurface irrigation—on *Medicago sativa* to identify the most suitable method for cultivating this species in the given conditions.

2. Materials and methods

2.1. Experimental site

The experiment was conducted at the research farm of Isfahan University of Technology, located in northwestern Isfahan City, Iran (32°43'N, 51°33'E; 1600 m a.s.l.). The region has a cold arid climate, characterized by hot, dry summers and mild, wet winters. Based on Emberger's climate classification, the area is categorized as cold and arid. The site experiences an average annual temperature of 17.03 °C, with an average annual rainfall of 116.9 mm and a relative humidity of 38%. The region is also prone to strong winds, with over 470 wind erosion events recorded annually.

2.2.1. Experimental design

2.2.1. 1. Construction of clay pipes

Porous clay pipes were constructed from clay, each with a length of 60 cm and an outer diameter of 5 cm. The pipes were shaped using plaster molds and then fired in a pottery kiln at 900°C.

Figure (1): Made clay pipes

Table (1): Dimensions of the clay pipes used in this study

Parameter	Dimension
Thickness (cm)	2
Volume of pottery (cm^3)	1.18
Area of pottery (cm^2)	312.5
Height of pottery (cm)	60
Inner diameter of the pottery (cm)	3
Outer diameter of the pottery (cm)	5

2.2.1.2. Water requirement of *Medicago sativa*

The water requirement of *Medicago sativa* was calculated using Netwat Software, with an estimated pure irrigation requirement of 9310 m^3/ha.

2.2.1.3. Experimental design and applying the treatments

The experiment was set up as a randomized complete block design with three replications. The treatments included three irrigation methods: subsurface clay pipes, surface tape, and furrow irrigation (Figure 2). To ensure all treatments received the same amount of water, a controlled approach was used for each method. Subsurface Clay Pipe: Channels were dug to a depth of 15 cm. The clay pipes, each 5 cm in length and 30 cm wide, were then installed at 15 cm intervals and covered with soil. Surface Tape: The tapes were placed directly on the soil surface. In both of these treatments, 100 seeds of Medicago sativa were planted 10 cm apart on each side of the pipes and tapes. Water was supplied from a 20-liter tank, and a volumetric meter was connected to the main tube to precisely measure the water used. For the clay pipe system, the depletion rate was 0.25, and irrigation was performed every four days. For the furrow irrigation treatment, furrows were created, and 100 Medicago sativa seeds were planted with a 10 cm spacing. These plots were also irrigated using a 20-liter tank. Critically, all treatments received an equal volume of water throughout the entire experiment, ensuring a fair comparison of the irrigation methods.

(a)

(b)

(c)

Figure (2): Different irrigation methods: a. clay pipe irrigation, b. tape irrigation, c. furrow irrigation

2.2.1.4. Irrigation water analysis

The quality of the irrigation water was characterized by measuring its key chemical properties. EC and pH: Electrical conductivity (EC) and pH were measured using an EC-meter and a pH-meter, respectively. Chloride and Sodium: Chloride and sodium concentrations were determined using Argentometric titration and a flame photometer, respectively (Richards, 1954). Carbonate and Bicarbonate: Carbonate and bicarbonate concentrations were measured via titration. Calcium and Magnesium: Calcium was determined using complexometric titration with EDTA, with Calcon or Murexide as the metallochromic indicator. Total hardness (Ca^{2+} + Mg^{2+}) was measured using Eriochrome Black T, and the magnesium concentration was then calculated by difference (Raij, 1966). The Sodium Adsorption Ratio (SAR) was calculated using Equation 1 (Richards, 1954), which is the ratio of sodium (Na) to calcium (Ca) and magnesium (Mg). The complete chemical properties of the irrigation water are presented in Table 2.

$$\mathrm{SAR} = \mathrm{Na} / \sqrt{\frac{(\mathrm{Ca}) + (\mathrm{Mg})}{2}} \tag{1}$$

Table (2): Chemical characteristics of irrigation water

EC (ds/m)	pH (-)	CO_3 (mmol/L)	HCO_3 (mmol/L)	Cl (mmol/L)	Na (mmol/L)	Mg+ Ca (mmol/L)	SAR (mmol/L)
0.29	8.05	2	6	13	1.57	2.4	1.44

2.2.1.5.

To characterize the experimental site, soil samples were collected from the 0–50 cm depth. The following physical and chemical properties were measured: Chemical Properties: EC and pH: Measured in a saturated soil extract (Slavich & Petterson, 1993). Physical Properties: Soil Texture: Determined using the hydrometer method and classified according to the USDA soil texture triangle (Bouyoucos, 1962). Bulk Density: Measured using the core method with cylinders of 190.98g. Porosity: Calculated based on the bulk density and a constant particle density of 2.65 mg/m³. Field Capacity (FC) and Permanent Wilting Point (PWP): Determined with a pressure plate at matric potentials of –33 and –1500 kPa, respectively (Klute, 1986). The complete physical and chemical properties of the soil are presented in Table 3.

Table (3): Physical and chemical characteristics of the soil

Depth (cm)	pH (-)	EC (ds/m)	Sand (%)	Clay (%)	Silt (%)	FC (kg/100kg)	PWP (kg/100kg)	Bulk density (mg/m^3)	Porosity ($m^3/100\ m^3$)
0-50	8.81	2	48.71	21.83	29.46	23.5	14.6	1.36	51%

2.2.1.6. Measured Parameters

Plant growth and performance parameters were recorded over two growing seasons (2016–2017). The following variables were measured: Plant Growth and Physiological Parameters, Plant Height: The distance from the plant's base to the top of the highest leaflet, measured with a ruler (Hucsh et al., 2003). Basal Diameter: The stem diameter at the ground surface, measured using a caliper (Tallant & Pelkki, 2004). Canopy Cover: The area was calculated by measuring the large and small diameters and assuming a circular or oval shape (Namiranian, 2007; Ke & Quackenbush, 2009). Stomatal Conductance: Measured with a Hand-Held Porometer (Pask et al., 2012). Chlorophyll Content: Measured using a SPAD Chlorophyll Content Meter (Hansatech, Kings Lynn, UK). Stem Number: The number of stems per plant was counted. Plant Vigor: Scored on a scale from 0 to 5: 5: Very Vigor, 4: Vigor, 3: Medium Vigor, 2: Semi-Dry, 1: Dry, 0: Very Dry. Fresh Forage and Weed Weight: Measured after cutting and weighing the fresh material from each treatment. Germination Rate: Determined by counting the number of germinated plants in each replication. Flowering and Seeding: The presence of flowering and seeding was investigated. Dry Matter: The wet parts of the crop were dried for 48 hours at 70°C in an oven and then weighed to determine the dry matter content. Survival Percentage (SP): The percentage of surviving plants was measured several months after planting (Azizi et al., 2015).

$$SP=\frac{s}{n}\times 100 \quad (2)$$

where SP is the percentage sapling survival (%); *s* is the number of remaining saplings at the end of the experiment (after nine months); and *n* is the number of saplings at the start of the experiment in each treatment.

The water use efficiency (WUE) under each treatment was calculated using the following formula (Jones, 1993):

$$\mathrm{WUE}=\frac{\mathrm{Y}}{\mathrm{W_t}} \quad (3)$$

Where, WUE is the water use efficiency (gr/lit), Y is a total yield of the crop (gr/m^2) and W_t is the total water consumed (lit). The wet parts of the crop were dried for 48 hours after harvest at 70℃ in an oven and then weighted with a digital scale to measure the amount of dry matter.

2.2.1.7. Statistical analysis

All data were initially tested for normality using the Kolmogorov–Smirnov test and for homogeneity of variance using Levene's test. A one-way ANOVA was performed to determine significant differences between treatments. When a significant F-statistic was found, post-hoc comparisons were conducted using the LSD test at significance levels of $P < 0.05$ and $P < 0.01$. All statistical analyses were carried out using SAS 9.2 software. Results are presented as the mean ± standard error (SE).

3. Results and Discussion

The results of our two-year field experiment revealed that the irrigation method had a significant influence on a wide range of growth and yield-related traits of *Medicago sativa* (Tables 4 and 5). Overall, the clay pipe and surface tape irrigation treatments consistently outperformed furrow irrigation in nearly all measured parameters.

Table (4): Analysis of variance of plant parameters of *Medicago sativa*

Variation resources	Treatment	Block	Error	CV
Height	62.23^{ns}	23.98^{ns}	10.88	8.38
Basal diameter	68.56*	5.92^{ns}	7.34	17.6
Canopy cover	957.8*	171.5^{ns}	61.05	26.24
Number of stems	4.5*	1.57^{ns}	0.44	11.56
Vigor	1.77*	0.83^{ns}	0.15	10.79
Forage fresh weight	1534252**	90277^{ns}	19298	10.62
Weed fresh weight	8108**	158.3^{ns}	354.2	15.9
Chlorophyll content	0.41*	0.14^{ns}	0.035	14.67
Stomatal conductance	13.36^{ns}	30.29^{ns}	11.94	16
Germination rate	38.11^{ns}	59.11^{ns}	20.27	6.1
Plant survival	117*	110.3*	12.33	5.51
Flowing	257.4**	14.78^{ns}	6.61	16.18
Seeding	131.4*	47.44^{ns}	13.61	13.89
Yield	16342**	8027^{ns}	1729	9.62
WUE	2.5*	0.57^{ns}	0.27^{ns}	6.57^{ns}

ns, * and ** insignificant and significant at 5% and 1% levels, respectively.

Table (5): Comparison of mean of *Medicago sativa* in different treatments

Variable	**Treatments**			LSD (0.05)
	Clay pipes irrigation	Tape irrigation	Furrow irrigation	
Height (cm)	42.62±2.83^{a}	41.25±0.28^{ab}	34.14±2.67^{b}	7.47
Basal diameter (cm)	18.3±2.49^{a}	18.21±0.60^{a}	9.98±0.58^{b}	6.18
Canopy cover (cm^2)	47.27±8.81^{a}	31±4^{a}	11.55±2.04$^{\mathbf{b}}$	17.71
Number of stems	6.51±0.73^{a}	6.36±0.51^{a}	4.32±0.11^{a}	1.5
Vigor	4.3±0.49^{a}	3.77±0.10^{a}	2.78±0.35^{b}	0.88
Forage fresh weight (gr)	2103±13^{a}	1101±84.28^{b}	718.3±136.7^{c}	314.9
Weed fresh weight (gr)	70±5.7^{7b}	173.3±15.9^{a}	111.7±1.66^{b}	42.66
Chlorophyll content	0.95±0.12^{a}	1.68±1.9^{a}	1.21±0.12^{b}	0.43
Stomatal conductance ($mmol/m^2s$)	23.87±3.38^{a}	19.78±1.94^{a}	20.92±1.68^{a}	7.83
Germination rate (%)	76±2.51^{a}	75.67±4.63^{a}	69.67±2.33^{a}	10.21
Survival (%)	68.67±2.90^{a}	70.66±4.66^{a}	61.66±3.84^{b}	7.96
Flowering	12.67±1.20^{b}	16.33±2.72^{a}	8.67±1.6^{b}	5.83
Seeding	28±3^{a}	32.33±1.33^{a}	19.33±3.75^{a}	8.36
Yield (gr/m^2)	595±2 ^{a}	465±1.5 ^{b}	400±4.1 ^{c}	214.2
WUE (gr/lit)	0.40±3.1 ^{a}	0.35±2.9 ^{a}	0.27±6.1 ^{b}	0.4

Similar letters indicate no significant difference, and non-similar letters indicate a significant difference.

3.1.

According to the analysis of variance (Table 4), the irrigation method had no significant overall effect on the height of *Medicago sativa* (P > 0.05). However, a more detailed comparison of the treatments revealed significant differences. There was no significant difference in height between the tape and furrow irrigation treatments, but a significant difference was observed between the clay pipe and furrow treatments (Table 5). The highest plant height was recorded in the clay pipe treatment (42.62 cm), while the lowest was in the furrow treatment (34.14 cm). Our findings are consistent with the research of Douh and Boujelben (2010), who demonstrated that subsurface irrigation systems have a highly significant effect on plant height. They found the most elevated plant heights under subsurface drip irrigation, which aligns with our observation that clay pipe irrigation—a subsurface method—led to the tallest plants. This superior performance is likely due to the benefits of subsurface irrigation, such as reduced evaporation, precise water placement in the root zone, and more uniform water application, all of which contribute to enhanced plant growth.

3.2. Basal diameter

The analysis of variance (Table 4) revealed a statistically significant effect of irrigation treatment on the basal diameter of *Medicago sativa* at the 5% level ($P < 0.05$). A comparison of the treatments (Table 5) showed no significant difference between the clay pipe and surface tape irrigation methods. However, both treatments resulted in a significantly larger basal diameter than the furrow irrigation method. The maximum basal diameter was observed in the tape irrigation treatment (18.21 cm), while the minimum was in the furrow treatment (9.98 cm). These findings highlight the importance of consistent water availability for plant growth. As demonstrated by Doltra et al. (2007) and Velez et al. (2007), stem diameter is a key indicator of a plant's water status. The larger basal diameters observed with the tape and clay pipe irrigation methods suggest that these systems effectively maintained a favorable soil moisture level, supporting active growth. This contrasts with the less efficient furrow irrigation, which likely led to periods of water stress. As described by Hinckley & Bruckerhoff (1975) and Antonova et al. (1995), a reduction in stem diameter during the day followed by only partial recovery at night is a clear sign of high evaporative demand and low soil-water availability—a condition likely to be more prevalent under the less precise furrow irrigation method. Thus, the superior performance of tape and clay pipe irrigation in this study can be attributed to their ability to prevent such water stress and promote consistent, active plant growth.

3.3. Canopy cover

The analysis of variance (Table 4) revealed that the irrigation method had a statistically significant effect on the canopy cover of *Medicago sativa* at the 5% level ($P < 0.05$). As shown in Table 5, there was no significant difference in canopy cover between the clay pipe and surface tape treatments. However, both of these methods resulted in significantly larger canopy cover than the furrow irrigation treatment. The maximum canopy cover was observed in the clay pipe irrigation treatment (47.27 cm²), while the minimum was in the furrow treatment (11.55 cm²). Our findings support the conclusion of O'Connell et al. (2009) that canopy cover and potential water use are directly related. The superior canopy cover observed in the drip and clay pipe irrigation treatments is likely due to their ability to maintain a consistently higher soil water content near the plant's base. This favorable moisture level provides optimal conditions for root water absorption and promotes vigorous leaf growth, leading to a larger canopy. In contrast, the less efficient water delivery of furrow irrigation likely resulted in water stress, which limited leaf development and led to a smaller canopy.

3.4. Number of stems

The analysis of variance (Table 4) indicated a significant difference in the number of stems per plant among the different irrigation methods at the 5% level ($P < 0.05$). A comparison of the treatments (Table 5) showed that the maximum number of stems was observed in the clay pipe irrigation treatment (6.51), while the minimum belonged to the furrow irrigation treatment (4.32). Our findings align with research showing that water availability can significantly impact stem development. While some studies, such as that by Abubaker et al. (2014), found that the number of stems was not significantly affected by varying irrigation amounts in the initial season, others, like Islam et al. (1990), reported significant effects. Our results support the latter, suggesting that the precise and consistent water delivery of clay pipe irrigation created conditions more favorable for stem growth. In contrast, the water stress that can occur under furrow irrigation, as highlighted by Caballero et al. (1996), likely hindered stem development and contributed to the lower stem counts observed in that treatment.

3.5. Plant vigor

The analysis of variance (Table 4) indicated a significant difference in plant vigor among the treatments at the 5% level ($P < 0.05$). A post-hoc analysis (Table 5) showed no significant difference between the clay pipe and tape irrigation methods. However, both of these treatments demonstrated significantly higher vigor compared to furrow irrigation. The highest vigor score was recorded in the clay pipe treatment (4.3), while the lowest was in the furrow treatment (2.78). These findings suggest that consistent water availability is crucial for maintaining plant vigor. As noted by Iannucci et al. (2002), drought stress can lead to yield reductions, and our results indicate that furrow irrigation, with its less efficient water delivery, likely subjected plants to greater water stress. The superior performance of the clay pipe and tape irrigation methods highlights their effectiveness in providing the stable water supply necessary for healthy, vigorous plant growth.

3.6. Fresh weight of forage

The difference in fresh forage weight among the treatments was statistically significant at the 1% level (Table 4). The highest fresh forage weight was observed in the clay pipe irrigation treatment (2013 g), and the lowest was found in the furrow irrigation treatment (718.3 g). This outcome can be attributed to alfalfa's high water demands. The significant water losses from surface evaporation in the furrow irrigation method likely led to insufficient water availability, hindering growth. While the text mentions that water availability is higher in tape irrigation than in subsurface irrigation, our results show the highest yield in the clay pipe system, suggesting that its high water use efficiency compensated for any potential differences in total availability. Our findings are consistent with the work of Almarshadi and Ismail (2011), who concluded that alfalfa's fresh forage yield varies significantly depending on the irrigation method used.

3.7. Fresh weight of weed

The analysis of variance (Table 4) showed that the fresh weight of weeds differed significantly among the treatments at the 1% level. The highest fresh weight of weeds was observed with tape irrigation (173.3 g), while the lowest was found in the clay pipe irrigation treatment (70 g). These results highlight the crucial role of irrigation method in weed control. As noted by Drost & Moody (1982) and Anwar et al. (2010), the soil moisture status after planting is a major factor influencing weed flora. The higher weed biomass under tape irrigation is likely due to the widespread wetting of the soil surface, which creates favorable conditions for weed seed germination and growth. In contrast, the subsurface clay pipe system delivers water directly to the root zone of the crop, leaving the soil surface drier. This lack of surface moisture suppresses weed growth, leading to a significant reduction in weed fresh weight. These findings are consistent with the conclusion of Towa and Xiangping (2014) that weed weight is significantly influenced by water management.

3.8.

The analysis of variance (Table 4) revealed that the irrigation method had a significant effect on chlorophyll content at the 5% level ($P < 0.05$). The highest chlorophyll content was observed in the tape irrigation treatment (1.68), while the lowest was in the clay pipe irrigation treatment (0.95).

These findings highlight the complex relationship between water availability and chlorophyll production. While some studies, such as Munné-Bosch and Alegre (2000), found that chlorophyll content decreased with water stress, others have observed the opposite. This seemingly contradictory response, as noted by Cameron (1999), can vary depending on the intensity of the water stress. A decrease in chlorophyll can be a negative consequence of stress, but it can also be an adaptive feature to reduce light absorption and prevent photo-oxidative damage under moderate water deficits (Munné-Bosch & Alegre, 1999).

The higher chlorophyll content in the tape irrigation treatment suggests that the plants experienced less water stress compared to the clay pipe and furrow methods, leading to an increase in pigment concentration. Conversely, the lower chlorophyll content in the clay pipe treatment may indicate a mild level of water stress, to which the plants adapted by reducing chlorophyll. The clay pipe system, with its highly efficient but localized water delivery, might have induced this adaptive response, even while supporting superior growth and yield metrics.

3.9. Stomatal conductance

The analysis of variance (Table 4) revealed no significant overall effect of irrigation method on stomatal conductance at the 5% level ($P > 0.05$). However, a comparison of the treatment means (Table 5) showed that the highest stomatal conductance was observed in the clay pipe irrigation treatment (23.87 mmol/m²s), while the lowest was in the tape irrigation treatment (19.78 mmol/m²s).

These findings, while not statistically significant on a broad scale, still reflect the known relationship between water availability and plant physiology. A decline in soil-water content typically causes a decrease in stomatal conductance, which, in turn, reduces photosynthesis (Tan & Buttery, 1982a,b). The higher stomatal conductance in the clay pipe treatment suggests that this method provided a more consistent and favorable water supply directly to the root zone, allowing the stomata to remain more open for gas exchange. This supports the findings of Tan and Layne et al. (1991), which showed that irrigation methods can significantly impact stomatal conductance. The lower stomatal conductance in the tape irrigation treatment may be a response to the different wetting pattern of that method, potentially leading to periods of slight water stress.

3.10.

The analysis of variance (Table 4) revealed that the irrigation method had no significant overall effect on the germination rate at the 5% level ($P > 0.05$). However, the highest germination rate was observed in the clay pipe irrigation treatment (76%), while the lowest was in the furrow irrigation treatment (69.67%).

These findings, while not statistically significant, support the idea that consistent soil moisture is crucial for successful seed germination. As shown by Morris et al. (2000), irrigation can effectively overcome the negative effects of drought stress on germination. The lower germination rate in the furrow treatment is likely due to high water evaporation from the soil surface, which can lead to intermittent periods of water stress. In contrast, the clay pipe system provides a constant, subsurface water supply directly to the root zone. This minimizes evaporation and maintains a more stable moisture level, creating a more favorable environment for germination, as indicated by the higher rate in this treatment. While some studies, like that of Shock et al. (2007), found that very high water levels could decrease germination, our results suggest that the precise water delivery of the clay pipe system prevented this issue while avoiding the water stress associated with furrow irrigation.

3.11. Plant survival

The analysis of variance (Table 4) revealed a significant effect of the irrigation method on plant survival at the 5% level. The highest survival rate was observed with tape irrigation (70.66%), while the lowest was found in the clay pipe irrigation treatment (58.67%).

These results are particularly interesting given the context of alfalfa's drought tolerance. While alfalfa's deep root system and ability to enter a "drought-induced dormancy" can help it survive extended periods without water, our findings suggest that the initial establishment phase is highly sensitive to the specific irrigation method. As Whitcomb (1986) notes, the establishment phase is critical, and plant survival is heavily dependent on soil moisture. The superior survival rate under tape irrigation is likely due to the broader and more consistent surface wetting, which creates a more uniform moisture profile conducive to root establishment. Conversely, the highly localized and subsurface water delivery of the clay pipe system may have resulted in a less extensive root system during the critical establishment phase, making the plants more vulnerable to stress and leading to a lower survival rate. This suggests a trade-off between the water-saving efficiency of the clay pipe method and the establishment success provided by surface tape irrigation.

3.12. Flowing

The analysis of variance (Table 4) revealed a significant effect of the irrigation method on the number of flowers at the 1% level. The lowest number of flowers was observed in the clay pipe irrigation treatment (8.67), while the highest was in the tape irrigation treatment (26.33).

These findings suggest that, contrary to some studies that report no effect of water stress on flowering time (e.g., Mawanamwenge et al., 1999), the specific irrigation method and its associated water availability can significantly impact the number of flowers produced. The superior flowering in the tape irrigation treatment is likely due to its broader surface wetting, which creates a more uniform and consistent moisture profile. This environment may be more conducive to the physiological processes required for robust flowering compared to the highly localized water delivery of the clay pipe system, which might induce a level of stress that, while leading to high water use efficiency, reduces the plant's reproductive output.

3.13. Seeding

The analysis of variance (Table 4) revealed a significant effect of the irrigation method on the number of seeds produced at the 5% level. The lowest number of seeds was found in the clay pipe irrigation treatment (19.33), while the highest was in the tape irrigation treatment (32.33).

These results are consistent with the findings of Nadjafi and Rezvani (2002), which showed that irrigation can significantly impact seed yield. The higher number of seeds in the tape irrigation treatment likely stems from its ability to provide a more uniform and consistent moisture profile over the soil surface, which is crucial for supporting both vegetative growth and reproductive development. The clay pipe system, while highly efficient at conserving water and promoting vigorous growth, may induce a mild level of water stress that, in turn, reduces the plant's reproductive output and seed production.

3.1.4. Yield

The analysis of variance (Table 4) revealed a significant effect of the irrigation method on crop yield. The highest yield was observed in the clay pipe irrigation treatment (595 g), while the lowest was found in the furrow irrigation treatment (400 g). These results indicate a clear advantage of water-efficient irrigation methods for maximizing yield in arid environments. Unlike the findings of Jha et al. (2016), who reported no significant effect of irrigation methods on dry matter yield, our study showed a substantial difference. The superior yield under clay pipe irrigation is likely due to its efficient delivery of water directly to the plant's root zone, which minimizes water loss and ensures a consistent supply of moisture. This aligns with the observations of Bidondo et al. (2010), who, despite finding no significant difference, noted that plants under subsurface irrigation tended to show higher values across key growth variables. This suggests that while a statistical difference may not always be present, subsurface irrigation methods consistently create conditions more favorable for maximizing crop yield.

3.1.5. Water Use Efficiency (WUE)

Water use efficiency (WUE) is a critical factor in irrigation planning, representing the amount of dry matter produced per unit of water consumed. As Andarzian et al. (2011) and Hou et al. (2007) noted, improving WUE is essential for effective water management. Our analysis of variance (Table 4) revealed a significant effect of the irrigation method on WUE. The highest WUE was observed in the clay pipe irrigation treatment (0.40 g/L), while the lowest was found in the furrow irrigation treatment (0.27 g/L). These findings are consistent with previous research that highlights the superior efficiency of subsurface irrigation in arid environments. For instance, Dastorani et al. (2010) found a considerable difference in efficiency between surface and subsurface systems for pistachio trees, showing a preference for the subsurface method. Similarly, Al-Amoud (2010) concluded that subsurface irrigation systems are highly efficient and durable for date palm trees in arid zones. The significantly higher WUE in our clay pipe system confirms that delivering water directly to the root zone minimizes water loss from evaporation and runoff, making it a particularly effective method for maximizing crop yield in water-scarce regions.

4. Conclusion

The results of this study demonstrate that the irrigation method significantly influences the growth and yield of *Medicago sativa*. Specifically, key parameters such as basal diameter, canopy cover, stem number, plant vigor, fresh forage and weed weights, chlorophyll content, plant survival, flowering, seeding yield, and water use efficiency were all affected by the different irrigation techniques. The clay pipe irrigation method showed superior results for metrics directly related to plant vigor and water efficiency. It produced the highest values for height, basal diameter, stem number, plant vigor, stomatal conductance, germination rate, yield, and most notably, water use efficiency. In contrast, tape irrigation excelled in parameters related to plant establishment and reproductive output, resulting in the highest values for canopy cover, fresh forage and weed weights, plant survival, flowering, and seeding. Conversely, furrow irrigation proved to be the least effective method, as it did not lead to improvements in any of the measured plant parameters. Its poor performance is attributed to significant water losses, making it an unsuitable solution for arid environments. Based on these findings, both clay pipe and tape irrigation are recommended as effective and viable methods for cultivating *Medicago sativa* in arid regions. However, considering the critical issue of water scarcity, the clay pipe irrigation system is particularly promising due to its superior water use efficiency, which offers both economic and environmental benefits. Ultimately, selecting the appropriate irrigation system is a vital step in providing plants with the water needed to optimize the entire growth process, from germination to yield, especially in water-limited areas.

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