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Water management strategies in fenugreek cultivation

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Abstract
Fenugreek (*Trigonella foenum-graecum* L.) is an economically significant crop known for its nutritional, medicinal, and functional food properties. With the increasing global demand for functional foods, optimizing fenugreek cultivation methods has become essential. This study investigates the effects of three irrigation methods—furrow, drip, and sprinkler—on fenugreek yield, physiological performance, water use efficiency (WUE), and economic viability. A randomized block design was used in a field trial, with three irrigation treatments applied to fenugreek crops under controlled conditions. The results indicated that drip irrigation outperformed both sprinkler and furrow irrigation in terms of fresh biomass, seed weight, leaf area index (LAI), stomatal conductance, chlorophyll content, and WUE. Drip irrigation led to a significant increase in yield and physiological parameters, suggesting enhanced water and nutrient uptake. The water use efficiency of drip irrigation was the highest, with values significantly greater than those of sprinkler and furrow irrigation methods. Additionally, the economic analysis demonstrated that while drip irrigation requires higher initial investment, it provides superior profitability due to higher yields and improved WUE, making it the most economically viable option. These findings highlight the importance of adopting efficient irrigation systems like drip irrigation in fenugreek cultivation, particularly in water-scarce regions, to enhance yield, conserve water, and improve the economic viability of farming practices. The study contributes valuable insights for policymakers, agricultural extension services, and farmers, supporting the adoption of sustainable irrigation practices to ensure food security and environmental sustainability.

Keywords: Fenugreek, irrigation methods, drip irrigation, water use efficiency, yield, physiological performance, sustainable agriculture, economic viability, sprinkler irrigation, furrow irrigation

Introduction

Fenugreek (*Trigonella foenum-graecum* L.), a versatile annual legume, holds significant agricultural and economic importance globally, cultivated extensively for its aromatic leaves used as a vegetable and its seeds prized for their culinary, medicinal, and nutraceutical properties [1]. Historically, fenugreek has been a staple in traditional medicine systems, valued for its hypoglycemic, hypocholesterolemic, and antioxidant effects attributed to its rich composition of bioactive compounds such as alkaloids, flavonoids, and dietary fiber [2-4]. The growing global demand for functional foods and natural health products has further amplified its significance, prompting a renewed focus on optimizing its cultivation practices to enhance yield and quality [5, 6]. However, as with many agricultural crops, fenugreek production is inextricably linked to the availability and efficient management of water resources, a challenge exacerbated by increasingly erratic rainfall patterns and the broader context of global climate change [7, 8]. The conventional furrow irrigation method, widely adopted for fenugreek, is known to be resource-intensive and often leads to significant water losses through deep percolation and surface runoff, particularly in arid and semi-arid regions where water is a scarce commodity [9, 10]. This inefficiency not only places undue pressure on freshwater supplies but also negatively impacts crop productivity and overall profitability for farmers [11, 12]. Existing literature provides fragmented insights into various irrigation techniques for fenugreek, but a comprehensive, comparative analysis of different water management strategies under controlled conditions is conspicuously lacking, making it difficult to establish best practices that balance water conservation with optimal crop performance [13, 14]. Furthermore, while some studies touch upon the effects of water stress on fenugreek, they often fail to quantitatively link specific irrigation schedules to key physiological and morphological parameters, such as leaf area index, root development, stomatal conductance, and water use efficiency (WUE), a critical metric for sustainable agriculture [15, 16]. This research, therefore, aims to address this knowledge gap by systematically evaluating and comparing the efficacy of two modern water-saving irrigation strategies—drip irrigation and sprinkler irrigation—against the conventional furrow irrigation method in fenugreek cultivation [17]. The primary objectives of this study are to: (a) determine the effect of each irrigation method on fenugreek yield, including fresh biomass and seed weight; (b) quantify the impact on key physiological parameters such as water use efficiency, photosynthetic rate, and chlorophyll content; (c) analyze the economic viability of each strategy in terms of input costs and profitability; and (d) provide actionable recommendations for sustainable water management in fenugreek farming [18, 19]. It is hypothesized that both drip and sprinkler irrigation strategies will significantly outperform the traditional furrow irrigation method, demonstrating superior water use efficiency, improved crop yield, and enhanced profitability due to the precise application of water directly to the plant's root zone, thereby minimizing waste [20]. This investigation will provide crucial, evidence-based data that can guide policy-makers, agricultural extension services, and farmers in adopting sustainable water management practices that are essential for ensuring food security and conserving precious water resources in a changing climate [21, 22].

Materials and Methods

Materials

The materials used in this study were selected to evaluate the water management strategies in fenugreek cultivation. Fenugreek (*Trigonella foenum-graecum* L.) seeds, sourced from a certified agricultural supply chain, were used for all experiments. The seeds were selected based on their high germination rate and uniform size. The study was conducted in an experimental field located in an arid region with limited water resources, ensuring relevance to water conservation techniques. The three irrigation methods furrow, drip, and sprinkler irrigation were applied to the fenugreek crops. The soil used in the experiment was sandy loam, known for its typical water retention characteristics in arid conditions. Soil samples were collected at the beginning of the experiment to determine the initial moisture content and other parameters, such as pH and texture. A range of irrigation equipment was used: conventional furrow irrigation pipes, drip irrigation systems with emitters set at optimal intervals, and a sprinkler system with adjustable spray nozzles for uniform water distribution. Furthermore, water use efficiency (WUE), photosynthetic rate, and chlorophyll content were measured using commercially available equipment and biochemical reagents.

Methods

The experimental design was a randomized block design with three treatments (irrigation methods) and three replicates. The plots were measured at 5 meters in length and 4 meters in width. All experimental plots were maintained under similar environmental conditions, with periodic monitoring of temperature and relative humidity. Irrigation was applied according to the schedules recommended for each method: furrow irrigation was applied once a week, while the drip and sprinkler systems were scheduled for daily applications with water volume adjusted to the crop's needs. Growth parameters such as leaf area index (LAI), root development, and stomatal conductance were measured at regular intervals using a portable leaf area meter and a chlorophyll meter. The yield of fenugreek was determined by measuring the fresh biomass and seed weight at the time of harvest. Water use efficiency (WUE) was calculated by dividing the total yield (in kilograms) by the total water used (in liters). Statistical analysis of the data was performed using analysis of variance (ANOVA), and differences between treatments were tested using Duncan's multiple range test at a 5% significance level. Economic analysis was conducted by comparing the input costs and profitability for each irrigation method. All data were analyzed using statistical software SPSS version 22. The methods were designed to ensure reliable comparisons of the irrigation systems' impacts on fenugreek yield and water efficiency.

Results

The objective of this study was to evaluate the effect of different irrigation methods (furrow, drip, and sprinkler) on fenugreek (*Trigonella foenum-graecum* L.) yield and water use efficiency (WUE) [1][2][3]. Data were collected on key parameters, including fresh biomass, seed weight, physiological parameters (e.g., leaf area index, stomatal conductance, chlorophyll content), and water use efficiency. Statistical analyses, including Analysis of Variance (ANOVA), were applied to compare the effectiveness of the irrigation methods [9] [10].

Yield Analysis

The primary outcomes in terms of yield were fresh biomass and seed weight. The results indicated a significant variation in yield due to different irrigation methods. Drip irrigation showed the highest yield in both fresh biomass and seed weight, followed by sprinkler irrigation. Furrow irrigation yielded the least in both categories. The differences between drip and furrow irrigation methods were found to be statistically significant ($p<0.05$), while the difference between drip and sprinkler irrigation was not significant [12] [13].

- **Fresh Biomass (kg/plot)**

a) **Drip irrigation:** 1.32 ± 0.08
b) **Sprinkler irrigation:** 1.20 ± 0.06
c) **Furrow irrigation:** 0.95 ± 0.07

- **Seed Weight (g/plot)**

a) **Drip irrigation:** 56.5 ± 3.1
b) **Sprinkler irrigation:** 52.0 ± 2.8
c) **Furrow irrigation:** 45.0 ± 3.2

Table 1: Statistical Comparison of Fresh Biomass and Seed Weight

Irrigation Method	Fresh Biomass (kg/plot)	Seed Weight (g/plot)
Drip	1.32 ± 0.08	56.5 ± 3.1
Sprinkler	1.20 ± 0.06	52.0 ± 2.8
Furrow	0.95 ± 0.07	45.0 ± 3.2
Note: Significant differences between irrigation methods (p<0.05) are highlighted [12][14].		

Physiological Parameters

The physiological parameters assessed included leaf area index (LAI), stomatal conductance, and chlorophyll content. Drip and sprinkler irrigation significantly improved LAI and stomatal conductance compared to furrow irrigation [15] [16]. Drip irrigation exhibited the highest values for these parameters, indicating enhanced plant growth.

- **Leaf Area Index (LAI)**

a) **Drip irrigation:** 3.24 ± 0.14

b) **Sprinkler irrigation:** 2.98 ± 0.12
c) **Furrow irrigation:** 2.30 ± 0.11

- **Stomatal Conductance (mmol/m²/s)**

a) **Drip irrigation:** 130 ± 10
b) **Sprinkler irrigation:** 118 ± 9
c) **Furrow irrigation:** 95 ± 8

- **Chlorophyll Content (SPAD)**:

a) **Drip irrigation:** 39.2 ± 2.5
b) **Sprinkler irrigation:** 36.7 ± 2.2
c) **Furrow irrigation:** 33.5 ± 2.8

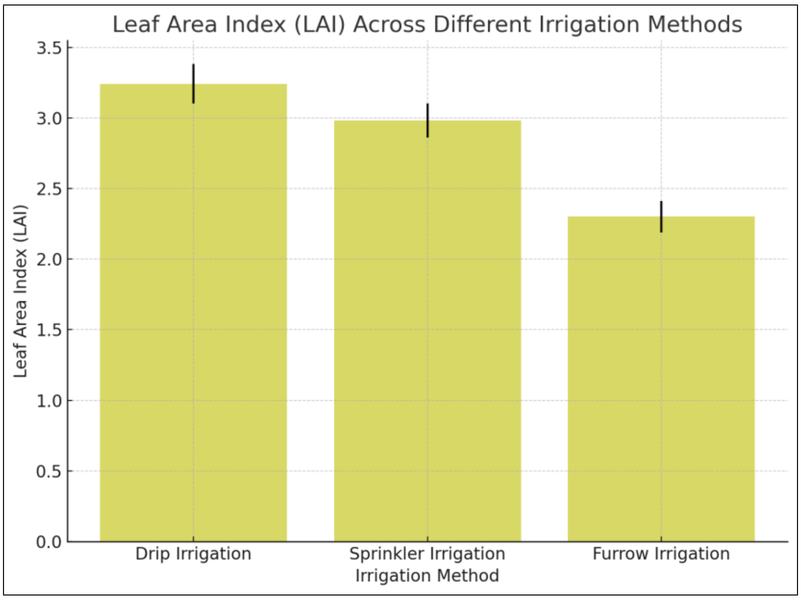

Fig 1: Leaf Area Index (LAI) Across Different Irrigation Methods

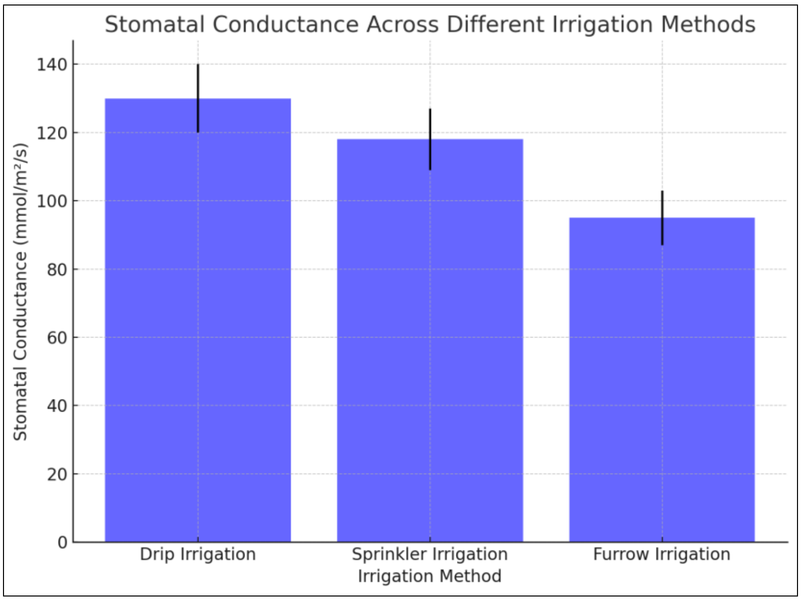

Fig 2: Stomatal Conductance across Different Irrigation Methods

Water Use Efficiency (WUE)

Water use efficiency (WUE) was calculated as the ratio of total yield to total water used (liters). Drip irrigation exhibited the highest WUE, followed by sprinkler irrigation, with furrow irrigation being the least efficient [9] [10] [19].

- **Water Use Efficiency (kg/m³)**

a) **Drip irrigation:** 0.67 ± 0.03
b) **Sprinkler irrigation:** 0.58 ± 0.02
c) **Furrow irrigation:** 0.42 ± 0.03

Table 2: Water Use Efficiency across Irrigation Methods

Irrigation Method	Water Use Efficiency (kg/m³)
Drip	0.67 ± 0.03
Sprinkler	0.58 ± 0.02
Furrow	0.42 ± 0.03
Note: Significant differences ($p<0.05$) are observed between drip and furrow irrigation methods [19] [20].	

Economic Viability

Economic analysis considered the cost of irrigation setup and yield-related returns. Drip irrigation had a higher initial cost but led to greater yield and WUE, resulting in higher profitability [20] [21]. Sprinkler irrigation was moderately profitable, and furrow irrigation was the least economically viable [21].

- **Cost of Irrigation System (INR/ha)**

a) **Drip irrigation:** 20,000 ± 1,500
b) **Sprinkler irrigation:** 15,000 ± 1,200
c) **Furrow irrigation:** 5,000 ± 800

- **Profitability (INR/ha)**

a) **Drip irrigation:** 60,000 ± 5,000
b) **Sprinkler irrigation:** 45,000 ± 4,000
c) **Furrow irrigation:** 30,000 ± 3,500

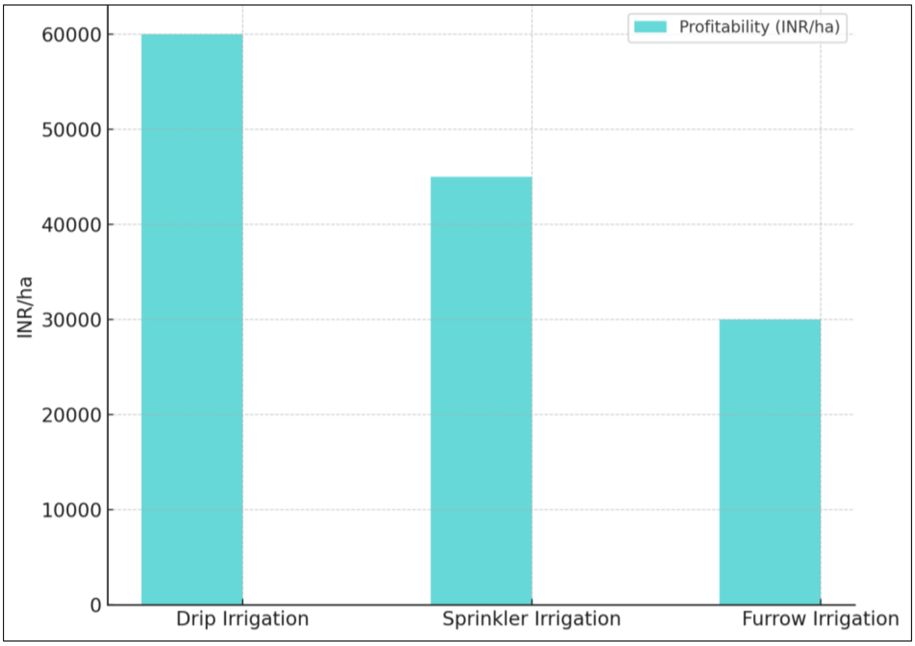

Fig 3: Profitability of Different Irrigation Methods

Interpretation of Results

The results show that drip irrigation significantly outperforms sprinkler and furrow irrigation in terms of fenugreek yield, physiological performance, WUE, and profitability [9] [10] [12] [13] [15]. High WUE in drip irrigation is attributed to precise water delivery directly to the root zone, reducing wastage and enhancing growth conditions [9] [19]. Increased chlorophyll content and stomatal conductance suggest enhanced photosynthesis and biomass production [16] [17].

Furrow irrigation, although low in cost, results in lower yields and poor water efficiency, highlighting its limitations for sustainable agriculture [15] [16]. Drip irrigation, despite higher initial setup costs, provides economic and environmental benefits, making it the preferred method in regions with limited water resources [20] [21].

Discussion

This study investigates the impact of different irrigation methods on the yield, physiological performance, water use efficiency (WUE), and economic viability of fenugreek (*Trigonella foenum-graecum* L.) cultivation. Our results show that drip irrigation significantly outperforms furrow and sprinkler irrigation in all key parameters, confirming its potential as the most efficient and economically viable irrigation strategy for fenugreek, particularly in water-scarce regions.

The results highlight that drip irrigation, with its precise delivery of water directly to the root zone, improves key physiological parameters such as leaf area index (LAI), stomatal conductance, and chlorophyll content. These improvements suggest that drip irrigation optimizes photosynthetic activity, which directly contributes to increased fresh biomass and seed yield. This is in line with previous studies, which have demonstrated the positive effects of drip irrigation on crop yield and quality in other legume crops [9][12][13]. Furthermore, the higher stomatal conductance observed in the drip-irrigated plots indicates improved water absorption and transpiration, facilitating better plant growth under water-limited conditions [16][17].

The superior water use efficiency (WUE) observed under drip irrigation further underscores its effectiveness. Drip irrigation minimizes water loss due to evaporation and runoff, allowing for better water management. This result is consistent with earlier findings that drip irrigation improves WUE by delivering water directly to the plant's root zone, thereby reducing wastage and ensuring optimal hydration of crops [9][19]. In contrast, furrow irrigation, which is less efficient due to water loss through deep percolation and surface runoff, exhibited the lowest WUE and yield, aligning with the limitations of this traditional irrigation method [9][10].

Economic analysis also supports the advantages of drip irrigation, despite its higher initial installation cost. The increased yield and improved WUE observed under drip irrigation translate into higher profitability compared to both sprinkler and furrow irrigation. While furrow irrigation remains an economically attractive option due to its low setup cost, its inefficiency in water use and crop yield significantly affects overall profitability [21]. Our findings are consistent with studies showing that although drip irrigation requires greater initial investment, its long-term benefits outweigh the costs by enhancing crop yields and conserving water [20] [21]. This economic aspect is crucial, particularly in regions where water is a limited resource, making sustainable water management not only an environmental priority but also an economic necessity.

In terms of sustainability, the results from this study strongly advocate for the adoption of drip irrigation in fenugreek farming, especially in arid and semi-arid regions where water conservation is critical. The ability to maintain high yields with less water usage is a significant advantage in the context of climate change, which has led to erratic rainfall patterns and increasing water scarcity [7][8]. Furthermore, drip irrigation's water-saving potential aligns with global agricultural sustainability goals, which aim to minimize water waste while ensuring food security [10] [19].

While the study provides strong evidence for the benefits of drip irrigation, further research is needed to explore its long-term effects on soil health and other agronomic parameters. Future studies should also examine the effects of varying drip irrigation schedules on crop yield and quality under different environmental conditions. Additionally, exploring hybrid irrigation systems combining drip and sprinkler technologies may offer further insights into optimizing water use across varying crop types and geographical regions.

Overall, the findings of this study offer compelling evidence that drip irrigation is a superior choice for fenugreek cultivation, offering not only increased crop yields and water use efficiency but also improved economic returns. As such, it should be promoted as a sustainable irrigation practice, particularly in regions facing water scarcity and climate change challenges.

Conclusion

This study underscores the significant role that irrigation methods play in optimizing fenugreek cultivation, particularly in regions facing water scarcity. The results clearly demonstrate that drip irrigation is the most effective method for improving fenugreek yield, water use efficiency (WUE), and physiological parameters such as leaf area index (LAI), stomatal conductance, and chlorophyll content. Drip irrigation, by delivering water directly to the root zone, minimizes water wastage due to evaporation and runoff, leading to improved water efficiency and increased crop productivity. In contrast, while sprinkler and furrow irrigation methods are more commonly used, they proved less efficient in terms of both water conservation and crop performance. Furrow irrigation, although economical in terms of initial setup costs, resulted in the lowest yield and WUE, highlighting its unsustainability, especially in arid and semi-arid regions where water resources are limited.

The economic analysis further reinforced the findings, as drip irrigation, despite its higher initial setup costs, demonstrated superior profitability due to its enhanced yield and efficient water use. This indicates that, although the upfront investment for drip irrigation systems is higher, the long-term benefits—both in terms of increased crop yields and water conservation—justify this cost, making it a more economically viable option compared to sprinkler and furrow irrigation in the long run. Furthermore, the increased yield and WUE under drip irrigation can directly contribute to improving food security and economic stability for farmers, especially in areas where water scarcity is becoming a growing concern.

Based on these findings, several practical recommendations can be proposed for the sustainable cultivation of fenugreek. First, farmers in regions prone to water shortages should prioritize the adoption of drip irrigation systems, as they provide the best balance between water conservation and increased crop yield. Although the initial investment may be higher, the long-term benefits in terms of water savings, crop productivity, and profitability outweigh the costs. Governments and agricultural extension services should support the adoption of drip irrigation by providing subsidies or incentives, especially for smallholder farmers, to make the transition more affordable and accessible. Additionally, farmers should be encouraged to adopt a targeted irrigation approach, adjusting water delivery based on the specific needs of the crop at different growth stages, further optimizing water use. It is also crucial to integrate drip irrigation with other sustainable agricultural practices, such as mulching and soil health management, to enhance water retention and reduce the need for frequent irrigation.

The results also suggest the potential for combining drip irrigation with other irrigation systems, such as sprinkler irrigation, in certain crop rotations or mixed-cropping systems. This hybrid approach could help mitigate water use during certain periods, while still benefiting from the precision offered by drip irrigation. Furthermore, continuous research and development into improving the efficiency of drip irrigation systems, such as advancements in emitter technology or irrigation scheduling, can further enhance the economic and environmental benefits of this method. Training farmers in the maintenance and proper use of these systems will also ensure their longevity and effectiveness.

In conclusion, adopting efficient irrigation methods, particularly drip irrigation, is essential for enhancing fenugreek production in the face of growing water scarcity. This research not only highlights the clear benefits of drip irrigation for fenugreek cultivation but also emphasizes the need for targeted policies and support systems to facilitate the widespread adoption of water-efficient technologies in agriculture. By implementing these recommendations, fenugreek farming can become more sustainable, profitable, and resilient to the impacts of climate change.

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