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Capillary Wick Irrigation Technique: A Sustainable Hydraulic Innovation for Water-Efficient and Climate-Resilient Infrastructure in Arid Regions

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Abstract: Groundwater is a vital resource supporting agriculture, industry, and rural livelihoods. However, changing climatic patterns, erratic rainfall, and unsustainable human activities have accelerated groundwater depletion, posing major challenges to sustainable water management. In response, this study introduces the Capillary Wick Irrigation Technique (CWIT) an innovative, passive irrigation system designed to enhance water use efficiency and promote sustainable agricultural infrastructure, particularly in arid and saline-prone environments. Unlike conventional drip systems, CWIT utilizes capillary action through specially engineered wick structures embedded in a subsurface pipe network, eliminating the need for external energy or technical operation. Experimental trials on fennel crops under controlled saline conditions revealed a distinct hemispherical wetting front, extending vertically up to 50 cm and horizontally up to 30 cm, with soil moisture retained for up to 12 days without additional irrigation. Field studies conducted in Velavadar, Surendranagar District, Gujarat, further validated the technique, showing approximately 17.4% water savings over drip irrigation and nearly 85% compared to traditional surface methods. CWIT also enhanced crop yield efficiency, reduced evaporation and runoff, and supported soil conservation and groundwater recharge. Offering a low-cost, scalable, and environmentally resilient solution, CWIT presents strong potential for integration into rural water systems and climate-resilient farming, particularly in water-scarce regions.

Keywords: Capillary Wick Irrigation, Sustainable Water Management, Soil Moisture Dynamic, Micro-Irrigation Systems, Water Use Efficiency, Climate-Resilient Irrigation.

1. Introduction

Water covers approximately 70% of the Earth's surface, yet less than 1% is directly usable for agricultural activities due to saline oceans, polar ice caps, and inaccessible groundwater reserves [1](World Wildlife, 2021). Agriculture accounts for about 72% of global freshwater withdrawals, surpassing domestic (16%) and industrial (12%) uses [2]. This statistic underscores the critical interdependence between water availability and agricultural sustainability. In India, the issue is exacerbated by the nation's reliance on monsoon-dependent agriculture, with over 60% of cultivated land being rain-fed and hence highly vulnerable to climate variability [3–5].

According to the Food and Agriculture Organization (FAO), approximately 60% of the freshwater used in agriculture is lost due to evaporation, inefficient delivery systems, and inappropriate irrigation scheduling. This inefficiency highlights the pressing need for water-conserving technologies and smarter irrigation methods [1]. Among the many advancements, micro-irrigation techniques such as drip and sprinkler systems have gained global attention for their capacity to enhance water use efficiency and crop productivity while minimizing environmental impacts [5–9].

Despite their benefits, traditional micro-irrigation systems are often financially inaccessible to small and marginal farmers in developing regions. High installation costs, complex maintenance requirements, and energy dependence deter widespread adoption [10,11]. This disparity drives the need for innovative, low-cost, and energy-independent irrigation solutions that align with local socioeconomic conditions.

The Capillary Wick Irrigation Technique (CWIT) emerges as a viable alternative. Unlike pressurized systems, CWIT uses capillary action to draw water through wicks from a water reservoir directly to the plant root zone. This self-regulating mechanism not only reduces water wastage but also negates the need for electricity and intensive manual intervention [12,13]. The simplicity and affordability of this technique make it particularly suitable for smallholder farmers and greenhouse operators.

The benefits of CWIS extend beyond water conservation. Studies demonstrate that Capillary wick irrigation significantly enhances plant health and growth by maintaining consistent moisture levels in the root zone. For instance, [14] reported a 54.6% increase in tomato yield along with an 82.4% reduction in water use compared to conventional basin irrigation. Similarly, [15] assessed the physiological responses of tomato, okra, and chili crops under CWIS, concluding that it maintained optimal water stress conditions conducive to higher productivity.

An important consideration in CWIS design is the choice of wick material, which determines the efficiency of capillary transport. Cotton bonded non-woven (CNW) wicks are widely preferred due to their durability, capillary properties, and availability [1,16,17]. Other innovations, such as optimizing wick diameter, spacing, and the use of subsurface pipe networks, have been introduced to fine-tune the system's performance [1].

Parallel advancements in irrigation technology, including automated and IoT-based systems, are being explored globally to enhance precision agriculture [18–23]. However, such technologies often remain out of reach for low-income farming communities due to infrastructural limitations and technical barriers. Hence, CWIS offers a practical and scalable solution for these underserved groups.

The Surendranagar district in Gujarat presents a critical case for deploying efficient irrigation strategies. The region faces acute water scarcity, receiving only 450 mm of annual rainfall, and suffers from poor soil fertility and high salinity levels. According to the District Krishi Scheme document, nearly 82.8% of cultivable land remains fallow. These challenging conditions amplify the importance of evaluating resource-efficient irrigation techniques like CWIS.

The present study was conducted in Velavadar village, Surendranagar district, with the objective of testing the viability and effectiveness of CWIS under local agronomic conditions. The field trials focused on fennel cultivation; a crop known to be moderately tolerant to salinity. Experimental plots were designed to compare CWIS with the traditional irrigation method. Notably, no fertilizers were used during the trials to ensure that the results reflect only the impact of irrigation technique on crop growth and yield.

The findings of this study contribute to the growing body of knowledge supporting the adoption of CWIT in arid and semi-arid regions, and demonstrate its effectiveness in saline water conditions. By offering a cost-effective, sustainable, and easily adoptable solution, CWIS has the potential to transform agricultural practices among smallholder farmers. Beyond enhancing water use efficiency, the technique also facilitates groundwater recharge by minimizing surface runoff and promotes soil stability, thereby helping to prevent erosion. It aligns well with national and global goals for sustainable agriculture, water conservation, and climate resilience. The research underscores the importance of tailoring irrigation innovations to regional needs and highlights CWIS as a pivotal step toward inclusive technological adoption in water management and rural development.

2. Study Area

The present study was conducted at a farm located in Velavader village, Wadhwan Taluka, within Surendranagar district of Gujarat, India. Geographically, the area falls within Survey of India Toposheet No. 41M and is bounded between latitudes 22° 08′ N to 23° 03′ N and longitudes 70° 58′ E to 72° 12′ E. Surendranagar district spans approximately 10,489 km^2 and comprises 10 administrative talukas encompassing 651 villages and 11 urban centers (Fig. 1). The district lies on the leeward side of the Saurashtra region and is characterized by semi-arid climatic conditions. It features three predominant soil types medium black soils, silty soils, and red sandy soils each with varying implications for agricultural potential and irrigation suitability. Medium black soils, found widely across the central region, are nutrient-rich but shallow, often underlain by basalt or shale bedrock that limits deep-root irrigation. Red sandy soils are dominant in the southeastern, northeastern, and eastern parts of the district, offering better drainage but lower nutrient-holding capacity. In contrast, silty soils are mainly confined to a narrow tract near the Little Rann of Kachchh in the northeastern margin, supporting limited agricultural use due to salinity concerns and poor structural stability.

Water availability for agriculture in the district is primarily dependent on minor reservoirs, tanks, and a limited number of small to medium irrigation projects. The five minor schemes Satapar, Ghanshamgad, Kankvati, Ramgadh, and Vaodi supplement irrigation on a localized scale. Additionally, four medium irrigation schemes Wadhwan-Bhogava-I, Brahmini, Limbdi-Bhogava, and Wadhwan-Bhogava-II contribute a combined gross storage capacity of approximately 139.05 million cubic meters (MCM). However, many of these sources experience seasonal depletion, particularly during the summer months when water tables decline sharply due to limited recharge and high evapotranspiration.

Agricultural practices in Surendranagar are predominantly seasonal and subject to significant water stress. Cotton is the major crop, occupying approximately 59% of the district's gross cropped area, followed by cereals (12%), sesamum (11%), and bajra (8%). The primary source of water for agriculture is the monsoon season, which occurs between June and September. The district receives an average annual rainfall of 587.35 mm, but this value varies widely from year to year. For instance, during the drought years of 2009 and 2012, rainfall dropped to below 300 mm less than 49% of the long-term average highlighting the region's vulnerability to climate variability (Fig. 2). These severe rainfall deficits have historically led to declining groundwater levels and crop failures, prompting a growing reliance on efficient micro-irrigation systems. In addition to erratic rainfall, the region also experiences extreme temperatures. Summer temperatures begin rising in March and can reach up to 46°C by May. These challenging agro-climatic conditions underscore the urgent need for sustainable, water-efficient irrigation solutions such as Capillary Wick Irrigation.

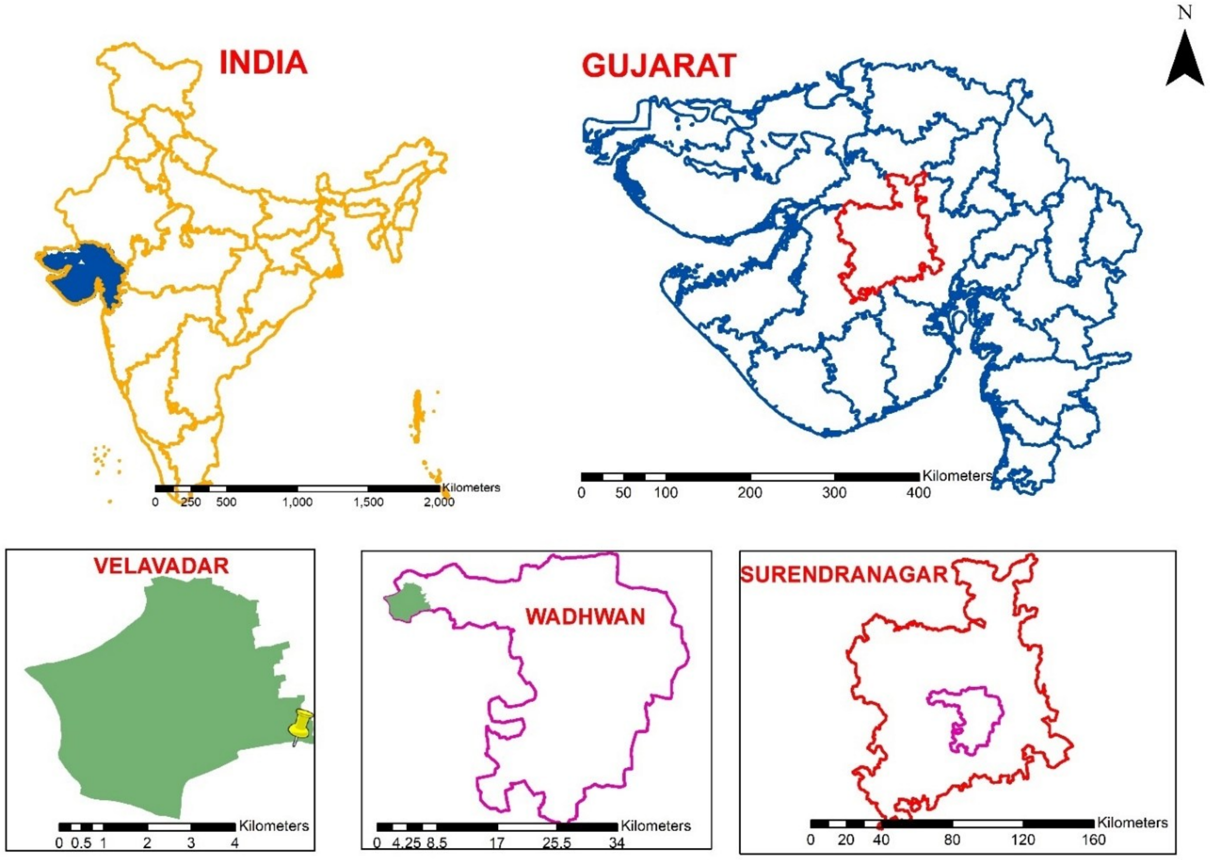

Fig. 1. Location map of Experimental Farm Set-up

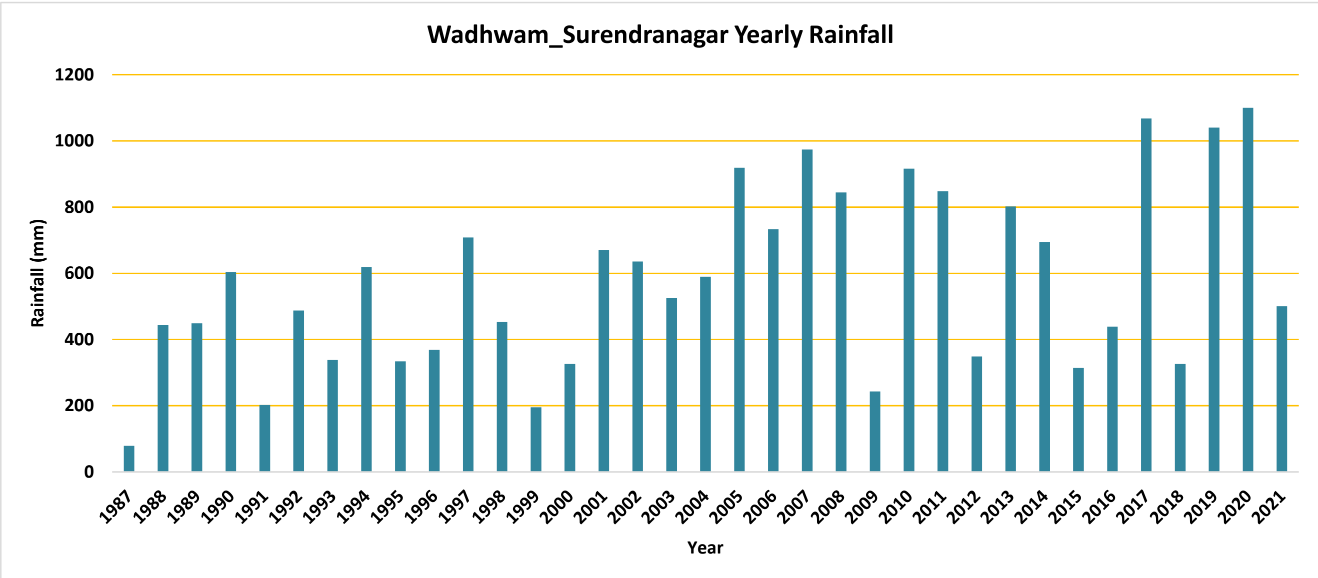

Fig. 2. Yearly Rainfall of Wadhwan Taluka of Surendranagar District

The onset of the southwest monsoon in June brings temporary relief by lowering temperatures and increasing atmospheric humidity. Winters, from November to January, are relatively mild, with daily minimum and maximum temperatures averaging 13°C and 29°C, respectively. Relative humidity during the monsoon exceeds 60%, while in the dry months especially from November to May it drops to 20-30%, further intensifying evapotranspiration losses.

Wind patterns are also seasonally influenced: the district experiences predominantly westerly to southwesterly winds during the monsoon season, transitioning to northerly and northeasterly directions in the post-monsoon and winter months. These climatic conditions, coupled with poor soil moisture retention and unreliable irrigation infrastructure, present formidable challenges for sustaining agriculture, particularly for smallholder farmers.

Given these constraints, the study area presents an ideal setting for evaluating alternative, low-cost, and water efficient irrigation systems like capillary wick irrigation. The semi-arid conditions, limited freshwater availability, shallow soil profiles, and high dependence on rainfall create a practical field laboratory to test the feasibility and effectiveness of such technologies under real world stress conditions.

3. Materials and Methods

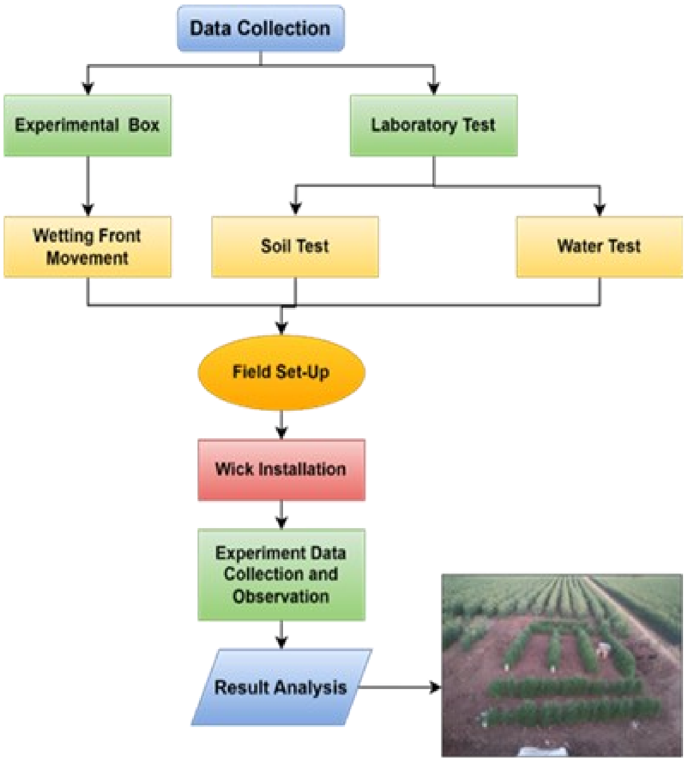

Fig. 3. Methodology flow chart for experimental work

The study utilized a combination of experimental field trials and laboratory analyses to evaluate the performance and feasibility of capillary wick irrigation under both controlled and real-world conditions. The schematic in Fig. 3 illustrates the adopted methodology for applying capillary wick irrigation to row crops.

3.1. Capillary Wick Irrigation Setup

The primary aim was to understand the geometry of wetting depth, breadth, and horizontal spread below the soil surface when using capillary wick irrigation. An experimental test box (60 cm × 60 cm × 60 cm) was developed using agricultural soil, PVC pipes, and wicks of 1 mm diameter. Acrylic sheets were used on one side of the box to visually monitor moisture movement.

Wick Material: Capillary wicks were made from porous materials such as polyester thread. These materials allow for water absorption and lateral distribution via capillary action. Since water moved through the wick by capillary action, salt buildup was low, and clogging did not happen. The process naturally filtered out salts and allowed only moisture to flow, keeping the wick working well throughout the crop cycle.

Pipe Description: PVC pipes were selected for water conveyance due to their cost-effectiveness, resistance to corrosion, and ease of installation.

Soil Used: The experiments employed medium black cotton soil, a commonly cultivated soil type in the Surendranagar region of Gujarat. Based on visual inspection and laboratory texture analysis, the soil was classified as silty clay loam according to the IS 1498 soil classification system. This soil type is characterized by moderate water retention, high clay content, and slow infiltration rates, making it suitable for evaluating capillary-driven irrigation techniques.

Wick discharge and irrigation intervals were designed to promote passive, self-regulated moisture delivery. The study measured vertical and lateral wetting movement from the wick outlet point using the wetting front advancement method, a standard technique to estimate unsaturated hydraulic conductivity in soils.

Laboratory tests such as capillary rise and upward infiltration experiments were conducted to characterize water movement. The essential profile method and the soaking front progression approach were both utilized and compared for determining soil-water dynamics. Observations regarding limitations and efficiency of the setup were noted for practical application (Fig. 4).

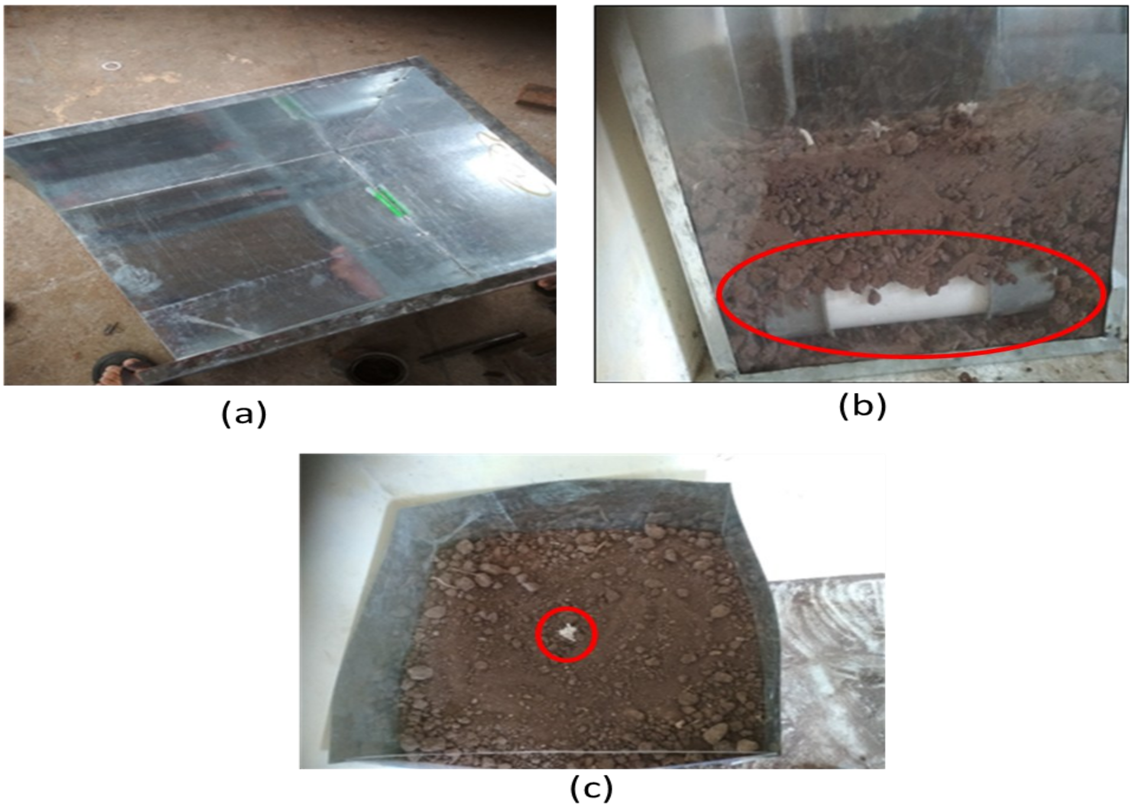

Fig. 4. Experimental box set-up represents (a) Empty Box, (b) Pipe installation (c) Wick installation

3.2. Laboratory Analysis

Soil Testing

Table 1. Soil Quality Parameters

Parameter	Value
OC	0.76 %
K2O	175.00 Kg/Ac
P2O5	27.00 Kg/Ac
EC (1:2)	1.39
PH (1:2)	7.98
S	16.20 ppm
Fe	8.56 (ppm)
Zn	1.20 (ppm)
Cu	1.88 (ppm)
Mn	27.94 (ppm)

Soil samples were collected from three different locations on the experimental farm. Laboratory analyses followed IS 2720 (Part-IV):1985 and IS 460:1978 standards. Testing was conducted at Gujarat State Fertilizer and Chemicals Limited (GSFCL), Morbi (Table 1).

Recommendations included the incorporation of well-decomposed compost and biofertilizers (Azotobacter and phosphate-solubilizing cultures) to enhance soil fertility. Fertilizer applications (NPK, Urea, and DAP) were planned based on soil nutrient levels.

Water Testing

Table 2. Water Quality Parameters

Parameter	Value
CO_3	70 ppm
Cl^-	710 ppm
HCO_3	466 ppm
Na^+	775 ppm
SO_4^{2-}	602 ppm
Mg^{2+}	48 ppm
Ca^{2+}	72 ppm
Electrical Conductivity (μS/cm)	3060
pH	7.33

Water quality was also tested at GSFCL (Table 2). The results indicated high salinity and sodium levels, making the water unsuitable for direct irrigation. It was recommended to apply gypsum as a soil amendment and adopt micro-irrigation systems to mitigate the negative effects on soil health.

3.3. Wetting Front Monitoring

The wetting front, the horizontal and vertical spread of moisture was studied under capillary wick irrigation using a Rapid Moisture Meter (Fig. 5). The device measures water content based on gas pressure produced by the reaction between calcium carbide and free-soil water.

Soil samples were extracted at different depths to analyze moisture distribution post-irrigation. Only the water retained in the soil via capillary action from the underground reservoir was measured.

Fig. 5. Rapid moisture meter used to identify soil moisture for moisture movement in experimental box

3.4. Experimental Farm Setup

The land preparation involved breaking large clumps into smaller pieces using tractors and spades. Steel wires or railings were used to protect the experimental plot from intrusion by stray animals. The alignment of pipes for installation followed the field plan depicted in Fig. 7 and Table 3. Excavation for pipe installation was carried out using a J.C.B. machine, creating trenches measuring 45 cm wide, 45 cm deep, and 6 meters long (Fig. 6-a). Additionally, eight trenches, each measuring 45 cm deep, 45 cm wide, and 8.2 meters long, were excavated for installing PVC pipes (Fig. 6-b). PVC pipes, 6 meters in length with a capacity of 107.750 liters, were installed accordingly (Fig. 6-c). Capillary growth studies were conducted in a glass box using polyester thread wicks, which demonstrated robust capillary action. Polyester wicks of 20 mm and 10 mm diameter were installed at fixed intervals as outlined in the field plan (Fig. 6-d). Materials required for the experiment were sourced from on-farm storage and brought to the site. A 1-meter-long pipe with a 10 cm diameter was used to keep the wicks straight in the soil, which was subsequently removed after filling and leveling the earth (Fig. 6-e and 6-f). The pipes were filled with water (Fig. 6-g), allowing water applied through capillary action via the wicks to reach the fennel seeds (variyali). Fig. 6 (a–g) depicts the actual field setup on the experimental farm. Various arrangements, labeled T4, T3, T2/1, T2/2, T2/3T1/1, T1/2, and T1/3 were tested on eight PVC pipes to see how wick spacing affected crop yield. Plant height, stem diameter, and crop yield were evaluated using these various systems. Experiments were carried out to assess soil wetting patterns using the proposed capillary wick irrigation technique.

Table 3. Capillary Wick Assembly Design

Pipe Name	Pipe Count	Hole Diameter	Center to center distance	Numbers of hole per pipe
T1	3	1.0 cm	30 cm	19
T2	3	2.0 cm	30 cm	19
T3	1	1.0 cm	38 cm	15
T4	1	2.0 cm	38 cm	15

Fig. 6. Field setup for experimental work. (a) Excavation, (b) Tranches as per field plan (c) Pipe installation (d) Wick installation (e) pipe used to make wick straight (f) field set-up (g) water filling in pipe

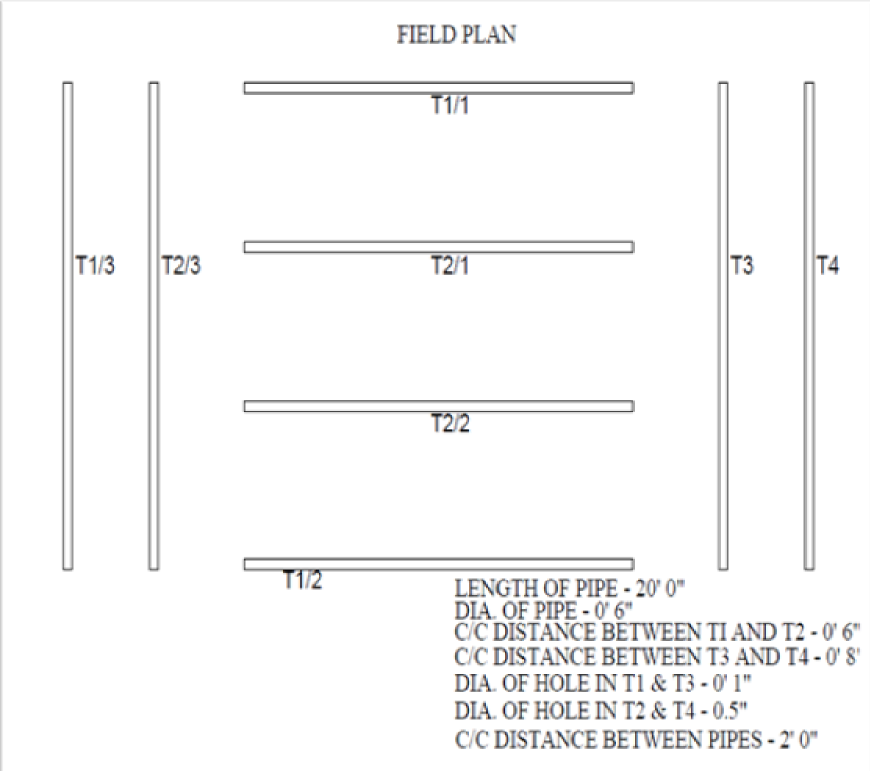

Fig. 7. Layout plan for experimental farm setup

4. Evaluation of Experimental Results

4.1. Soil and Water Quality Analysis

The results from nutrient testing of the soil and quality assessment of the irrigation water revealed that the water exhibited elevated electrical conductivity (E.C.), rendering it unsuitable for conventional agricultural applications. In addition to high salinity, the water contained excessive chloride concentrations. This led to visible salt deposits forming on the exterior of the wicks, which significantly impeded the diffusion rate of water through them.

The high E.C. levels in the soil further underscored poor water availability for crops, potentially causing osmotic stress that limits the uptake of water by plant roots. The maximum soil moisture content recorded using a moisture measurement device was 12.5%, a value close to the upper moisture retention threshold typical of sandy soils. This suggests that despite the challenges posed by poor-quality irrigation water, the soil was able to maintain minimal moisture levels within an acceptable range for short durations.

4.2. Wetting Front Movement

As anticipated, the movement of moisture in the soil displayed more vertical than lateral progression. This vertical dominance in wetting front movement is typical of sandy or loamy soils, where gravity-driven flow is pronounced. Fig. 8 (a–k) illustrate the progressive development of the wetting front in terms of percent moisture content, recorded at intervals of 24, 48, 72, 96, 168, 192, 216, 288, 312, 336, and 360 hours.

By 96 hours, the moisture content had reached the soil's field capacity at depths between 30 to 50 cm from ground level (G.L.). In contrast, this condition was not observed during the initial 24 hours, indicating a delayed saturation phase. Initially, the vertical penetration of water beyond 50 cm was limited, and lateral movement from the wick’s outer wall was also minimal. This difference became more noticeable by the 96-hour mark.

The observed moisture pattern formed a "hemispherical" or ellipsoidal shape, with vertical extension up to 50 cm and horizontal spread of approximately 30 cm from G.L., which is considered an optimal range for effective absorption by plant roots in crops with shallow rooting systems. However, after the 96-hour threshold, the wetting front began to recede and had almost entirely dissipated by the 15th day.

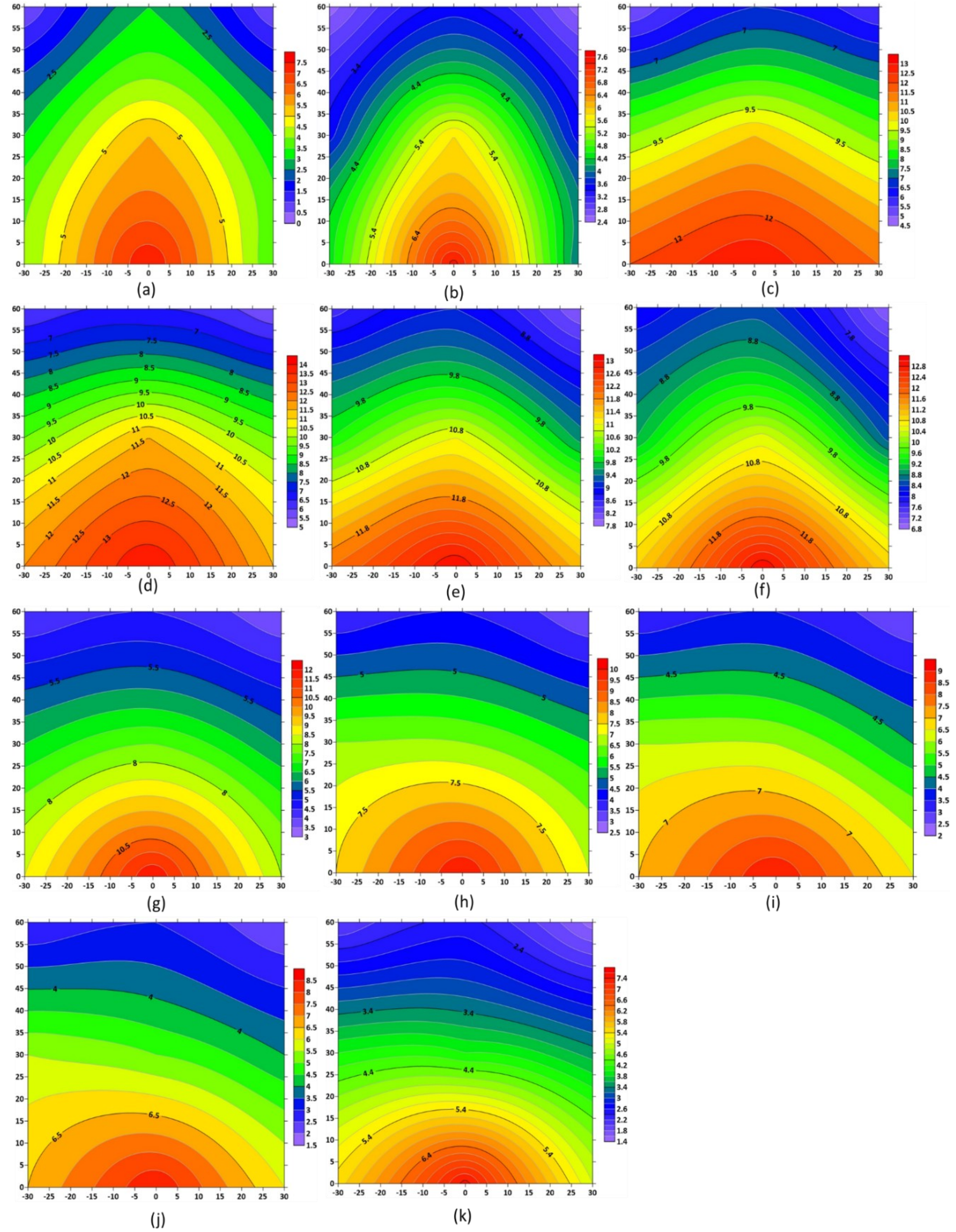

Fig. 8. Movement of Moisture in Experimental box After (a) 24 hours (b) 48 hours (c) 72 hours (d) 96 hours (e) 168 hours (f) 192 hours (g) 216 hours (h) 288 hours (i) 312 hours (j) 336 hours (k) 360 hours

The burial depth of the wick played a pivotal role in influencing the moisture distribution, with deeper placements enabling more extensive downward moisture movement. The wick burial depth used in this experiment was suitable for crops with shallow rooting systems, like fennel and peas (30 to 50 cm), as it matched the observed wetting front depth. This arrangement ensured good moisture distribution in the root zone and allowed for effective infiltration. For practical field-level implementation, farmers are advised to conduct small-scale trials using either candle tests or open excavation methods to visually assess both vertical and lateral water movement patterns.

4.3. Water Application and Crop Water Requirement

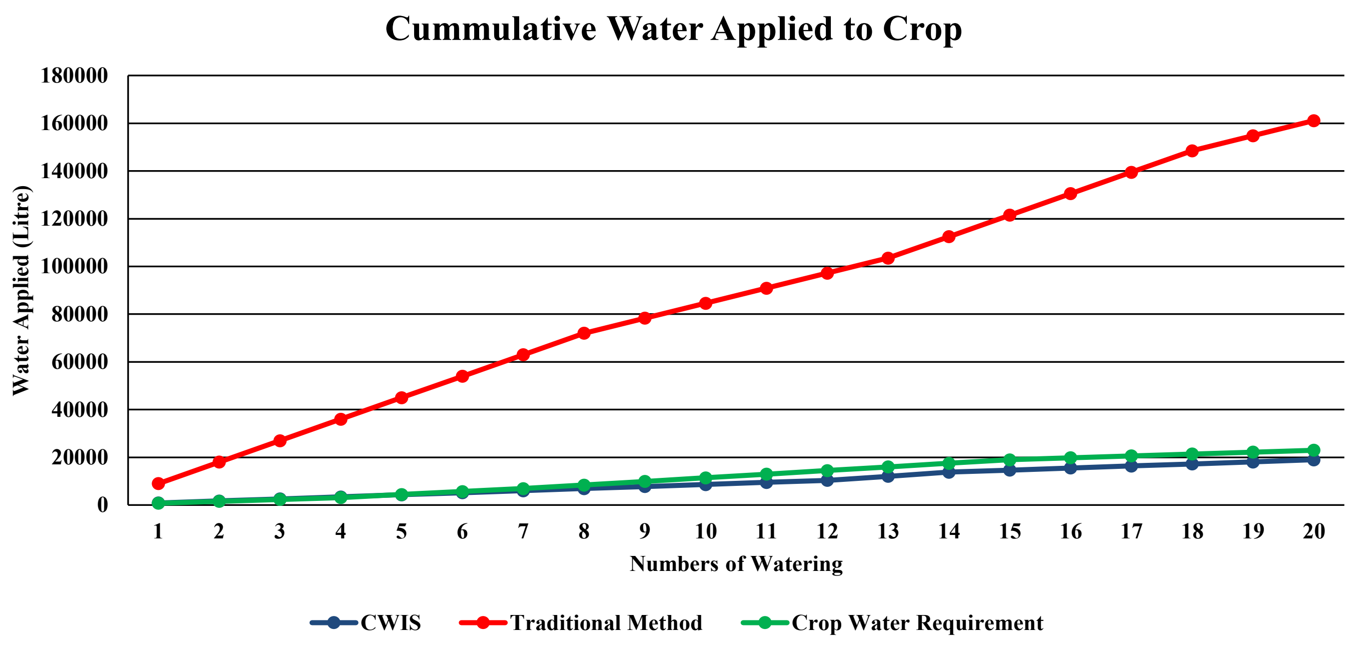

Fig. 9. Comparative graph of cumulative water application under different irrigation techniques over the crop cycle

Water is a critical input for crop production, directly influencing essential physiological processes including respiration, photosynthesis, nutrient uptake, and cell division. This study compares the cumulative water application between traditional farmer irrigation methods and the Capillary Wick Irrigation technique.

The actual water requirement for the fennel crop was estimated using Equations (1) and (2):

$$W_r = C_f \times S \times C_w \times E_{pan} \tag{1}$$

$$C_w = \frac{\text{Wetted Area}}{\text{Plant Area}} = \frac{0.30}{0.60} = 0.5 \tag{2}$$

where:

Wr = Daily water requirement in liter

Epan = Open pan evaporation = 5.34 mm/day (Surendranagar District)

Cf = Crop factor (0.85 – initial, 1.0 – mid, 0.9 – final stage)

S = Plant spacing = 0.3 m²

Cw = Canopy factor

In traditional methods, farmers generally apply more water than required, often leading to wastage and nutrient leaching. In contrast, the CWIT provides precise, demand-based water delivery. Although initial water usage in the CWIT is slightly higher to allow water to rise from a 1.5-foot-deep reservoir via capillary action overall water consumption is significantly lower than traditional practices (Fig. 9). This optimized delivery method supports consistent plant development and improves resilience to water stress by supplying only the essential quantity needed.

4.4. Crop Growth Monitoring: Stem Diameter and Height

Crop growth was assessed using standard tools: digital vernier calipers for stem diameter and measuring tapes for plant height (Fig. 10). Table 4 details the increase in stem diameter over time. Capillary wick treatments T1–T4 generally demonstrated equal or superior stem growth compared to the traditional method. Notably, T3 and T4 outperformed all other treatments, correlating positively with wick diameter and spacing.

Table 4 shows that stem diameter increased consistently throughout the crop cycle. By the 100-day mark, T4 had a stem diameter of 80.69 mm, compared to 82.08 mm recorded under traditional methods. However, the CWIT's organic approach without fertilizer or pesticide inputs offers a sustainable advantage.

Table 5 illustrates height progression. T3 and T4 exhibited height comparable to or exceeding traditional practices. By the end of the crop period (125 days), plants in T3 and T4 reached 170 cm, whereas the traditional method recorded 180 cm. Although slightly lower in height, the wick-irrigated crops maintained uniform growth and demonstrated healthier stem thickness, which is crucial for plant strength and productivity.

Fig. 10. Measuring stem diameter using digital vernier scale

Table 4. The increase in stem diameter with the growth of the crop

		Capillary wick irrigation								Regular farmers method
		The average increase in stem diameter (mm)								Regular farmer method
Sr. No	Crop period	T1/1	T1/2	T1/3	T2/1	T2/2	T2/3	T3	T4	
1	after 12 Days	9.35	9.35	9.35	10.05	10.05	10.05	10.05	10.05	7.45
2	after 28 Days	26.29	26.29	26.29	29.43	29.43	29.43	29.43	29.43	22.63
3	after 46 Days	43.18	43.18	43.18	48.09	48.09	48.09	48.09	48.09	38.18
4	after 59 Days	54.09	54.09	54.09	60.53	60.53	60.53	48.09	48.09	51.07
5	after 74 Days	65.04	65.04	65.04	69.6	69.6	69.6	72.73	72.73	60.53
6	after 100 days	74.84	74.84	74.84	78.15	78.15	78.15	80.69	80.69	82.08
7	after 125 days	76.15	76.15	76.15	81.05	81.05	81.05	84.94	84.94	94.62
8	Crop Spacing (cm)	30	30	30	30	30	30	38	38	30
9	Wick Dia. (cm)	1	1	1	2	2	2	1	2	

Table 5. Increase of height of crop with crop growth

		Capillary wick irrigation								Regular farmers method
		Height of crop (cm)								Regular farmer method
Sr. No	Crop period	T1/1	T1/2	T1/3	T2/1	T2/2	T2/3	T3	T4	
1	after 12 Days	6	6	6	8	8	8	8	8	10
2	after 28 Days	20	20	20	25	25	25	25	25	30
3	after 46 Days	40	40	40	45	45	45	45	45	50
4	after 59 Days	50	50	50	60	60	60	60	60	70
5	after 74 Days	60	60	60	80	80	80	85	85	100
6	after 100 days	120	120	120	140	140	140	150	150	165
7	after 125 days	145	145	145	155	155	155	170	170	180

4.5. Discussion

The principal aim of this study was to evaluate the efficacy of Capillary Wick Irrigation in enhancing crop yield, conserving water, and supporting sustainable water management practices. Compared to conventional farmer practices, this technique demonstrated superior water use efficiency, echoing findings by Heidari et al. (2022), who also reported improved biomass and water efficiency in wick-irrigated systems [24]. The hybrid Mangalam Volleyna fennel variety, selected for its adaptability to the Surendranagar region, exhibited strong growth with a crop duration of 120–130 days.

The working principle of the technique relies on capillary action, whereby water moves against gravity through narrow pores due to cohesive and adhesive forces. This self-regulating technique ensures that moisture is delivered in alignment with plant demand, avoiding over-irrigation and reducing water stress, aligning with Semananda (2018) analysis of capillary irrigation benefits [25].

A significant highlight of the study was the economic analysis: the benefit-cost ratio (B:C) for the CWIT was 2.78 compared to only 0.75 for traditional methods, showcasing its financial viability for sustainable farming. Additionally, the study identified wick diameter and spacing as critical parameters. T3 and T4 configurations (larger diameter and optimal spacing) supported better plant development. Conversely, T1 and T2 (narrower wicks) were more suitable for crops with lower water requirements such as cotton and castor. These results are comparable to those reported by Bhayo et al. (2018), who found significant water savings and productivity gains in wick irrigation technique [26].

Fig. 11 illustrates the experimental plot layout and demonstrates the robust plant growth achieved through CWIT, notably under T4 configurations. The healthy foliage, stem diameter, and plant height in these treatments validate the efficiency of larger wick diameters in supporting water-demanding crops.

The CWIT offers a viable, cost-effective, and environmentally friendly alternative for efficient water use and improved agricultural productivity, particularly in water-scarce regions like Surendranagar. Similar outcomes were documented by junejo (2023), who observed higher yields and better water management in sponge gourd and bitter gourd using wick irrigation [27].

The experimental investigation confirmed that CWIT is a highly effective, sustainable, and low-cost irrigation method, particularly suited to arid and semi-arid regions where water scarcity and irregular rainfall pose significant challenges. The system consistently enhanced crop productivity while significantly improving water use efficiency, achieving up to 85% water savings compared to conventional surface irrigation without compromising yields. These results stem from the elimination of runoff and deep percolation losses, and the substantial reduction in surface evaporation, ensuring optimum use of the available water even under water-stressed conditions. This supports prior findings by Heydari (2022) in maize cultivation under semi-arid conditions [28].

CWIT's passive, energy-independent operation relying solely on capillary action proved especially beneficial for smallholder and resource-limited farmers, as it removes the need for electricity, pumps, or complex mechanical components. The system's self-regulating moisture delivery directly to the root zone reduces water waste and operational oversight while suppressing weed growth and supporting soil health. Over time, as plant roots deepened, the system's responsiveness to moisture demand improved, highlighting its adaptability across various crop types and growth stages.

Fig. 11. Experimental plot with fennel plant growth

Among the configurations tested, the T4 pipe arrangement (optimized for wick diameter and crop spacing) demonstrated superior agronomic performance, particularly in terms of plant height and stem diameter, underscoring the importance of system design in achieving maximum efficiency. Once installed, the subsurface wick network required minimal labor and maintenance, aligning well with the broader goals of labor saving and sustainable farming practices.

Beyond immediate agronomic benefits, CWIT contributes to broader environmental goals by minimizing soil erosion (due to lack of surface water movement), promoting groundwater recharge, and improving soil-plant moisture dynamics. Its suitability for shallow to moderately deep-rooted crops including a wide range of vegetables such as tomatoes, onions, carrots, and zucchinis makes the system flexible for diverse agroclimatic conditions.

The findings indicate strong potential for CWIT as a scalable, climate-resilient irrigation strategy that aligns with national and global water conservation goals. Future research should focus on optimizing design parameters for specific crop-soil combinations, integrating the system with renewable energy-based fertigation, and evaluating durability of CWIT. Moreover, policy support through inclusion in micro-irrigation subsidy programs and climate smart agriculture initiatives could accelerate adoption and maximize the system's benefits for water-stressed farming communities. Ultimately, this study contributes to the effective management of water resources, helping to mitigate the impacts of irregular rainfall and enabling the optimum use of available water, reducing dependency on groundwater and improving water-use efficiency in farming technique.

5. Conclusion

This study establishes the Capillary Wick Irrigation Technique (CWIT) as a sustainable, low-cost, and energy-independent hydraulic innovation suitable for water-efficient infrastructure in arid and semi-arid regions. Through both controlled and field trials, CWIT demonstrated significant improvements in crop yield and water use efficiency, achieving up to 85% water savings compared to conventional irrigation methods, while requiring minimal technical expertise or operational input. The subsurface delivery system, driven by capillary action, effectively reduces evaporation and runoff losses and contributes to groundwater recharge and soil conservation by limiting surface water movement and erosion. Among the tested configurations, the T4 pipe arrangement proved most effective, highlighting the importance of design optimization.

CWIT is well-suited for shallow to moderately deep-rooted crops and adaptable to various soil types and agro-climatic zones, including arid, semi-arid, and saline-prone areas. Its affordable, energy-independent design makes it particularly beneficial for climate-resilient planning in farming communities with limited resources. By addressing key challenges such as erratic rainfall, declining groundwater levels, and rising agricultural input costs, CWIT offers a scalable and sustainable solution that aligns with broader goals of water resource management and rural development.

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