Effect of Drip Irrigation and Polyethylene Mulching on Growth, Yield, and Water Use Efficiency of *Capsicum annuum* L.

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ABSTRACT

Background: *Capsicum annuum* L., a lucrative vegetable crop, is heavily reliant on irrigation and is susceptible to moisture deficiencies in dry and semi-dry environments. The potential of precision irrigation with mulching in advancing sustainability is noteworthy.
Purpose: The objective of this study was to determine the combination effects of drip irrigation and polyethylene (PE) cover on the growth and physiological response, fruit output, and water-use efficiency (WUE) of capsicum.
Methodology: A two-factor randomized complete block design with four irrigation treatments (traditional surface irrigation at 100% ETc, drip irrigation at 100%, 80%, and 60% ETc) and two types of cover (with and without 50 μm black PE film) was adopted. Plant development indices, physiological characteristics, retention of water in soil, yield components, and WUE parameters were evaluated in three replications.
Results: The implementation of drip irrigation with 100% ETc along with the use of PE mulch enhanced the plants' height by 23.4%, branches number by 31.2%, and leaf area by 28.6% when compared to the traditional irrigation method. The marketable yield increased by 42.3% (65.4 $t \cdot ha^{-1}$ compared to 45.9 $t \cdot ha^{-1}$) while irrigation efficiency showed an increase of 68.5% (3.82 $kg \cdot m^{-3}$ compared to 2.27 $kg \cdot m^{-3}$). The results of the research showed that facilities applying drip irrigation at 80% ETc together with using mulch could produce the maximum yield while decreasing the irrigation water usage by 20.1%.
Conclusion: The combined application of drip irrigation system and PE mulch significantly improves the yield of capsicum and the efficiency in water usage, thus providing a viable solution for vegetable production in water scarce areas.

Keywords: advanced irrigation; water-saving techniques; capsicum production; productivity; sustainable agriculture; protected growing habits

1. Introduction

Capsicum, better known as sweet pepper, is a major vegetable crop globally with annual worldwide production exceeding about 35 million tons, with majority of the production taking place in Asia, Europe, and the Americas [1]. Capsicum cultivation in the Indian subcontinent has seen substantial growth in the last two decades, largely due to greater awareness among consumers and profitable prices in the marketplace [2]. However, increasing water scarcity, decreasing groundwater levels, and unpredictable rainfall patterns threaten the conventional irrigation-based agricultural production systems that depend on traditional methods of irrigation, particularly in dry and semi-dry zones of agriculture [3].

Capsicum is a moderately sensitive crop that depends on the availability of soil moisture for proper growth and development. The common surface irrigation methods being used in the developing countries are characterized by poor uniformity and high conveyance losses, hence showing low water application efficiency (usually below 50%) [4]. Therefore, in the light of existing regulations in the field of environment, it is necessary to make use of the innovative technologies of irrigation and apply irrigation to eliminate possible losses that can occur while irrigating.

Drip irrigation (DI), sometimes also referred to as trickle irrigation or micro-irrigation, represents a technological breakthrough that allows the slow, uniform delivery of water to individual plants through a system of tubes and emitters. There is a substantial amount of supporting evidence that drip irrigation technologies help improve the efficiency of irrigation processes and achieve levels of over 90% in efficiency, reduce the level of accumulation of salts in soil, decrease the occurrence of foliar diseases, and allow the localized delivery of agricultural chemicals [5, 6]. Various studies of fruiting vegetables, including tomato, eggplant, and cucumber show that moving from surface irrigation to DI leads to a yield increase of 25%-55% and water savings of 30%-50% [7].

Along with DI, polyethylene (PE) mulching or covering soil surface with thin plastic sheets is used to address a number of production problems at the same time. PE mulching has been shown to help moderate the temperature fluctuations of the soil, retain moisture in the soil, prevent the growth of weeds and regulate nutrient cycling processes [8, 9]. The combination of DI and mulching allows the increase of the beneficial impact of both [10].

There have been various studies conducted on the impacts of these technologies globally, but there are limited investigations conducted on their combined effects on capsicum cultivation with regard to the agroclimatic conditions prevailing in the area where they are being studied. The existing investigations on capsicum have dealt with isolated studies on mulching and/or irrigation management while there are few attempts made to study the joint impacts of the two practices on the physiology and yield of capsicum.

The aim of this study is to investigate the effects of drip irrigation at various levels of water application in combination with plastic mulching in terms of relating them to growth, physiological responses, yield, and efficiency of water use by capsicum crops which will enable providing recommendations for sustainable vegetable cultivation in conditions of water shortage.

2. Materials and Methods

2.1 Experimental Site and Environmental Conditions

The study was conducted at the Experimental Farm of the Institute of Agricultural Sciences, Delhi University (28.5°N, 77.2°E, 216 m above mean sea level) during two consecutive growing seasons (August 2022–February 2023 and August 2023–February 2024). The experimental site experiences a subtropical semi-arid climate with hot, dry summers and mild winters. Mean annual precipitation is 714 mm, distributed predominantly during the southwest monsoon (June–September). Long-term mean temperature during the capsicum growing season ranges from 15°C (December–January minimum) to 32°C (October–November maximum).

Soil at the experimental site is classified as Typic Ustochrept with sandy loam texture. Key physicochemical properties determined through standard protocols are presented in Table 1. Soil depth suitable for root penetration exceeds 90 cm. The site receives adequate solar radiation (5.2 $MJ \cdot m^{-2} \cdot day^{-1}$ during growing season) and maintained consistent water table at approximately 12 m depth.

2.2 Plant Material and Crop Management

A high-yielding capsicum hybrid cultivar (*Capsicum annuum* L. cv. 'Shimmer Red') was selected based on its widespread cultivation, market acceptability, and documented responsiveness to precision irrigation. Seedlings were raised in controlled nursery conditions using coconut-peat based growing medium in 72-cell trays. At 45 days after sowing, uniform seedlings with 4–6 true leaves were transplanted into the field at a spacing of 60 cm × 50 cm (33,333 $plants \cdot ha^{-1}$), representing standard commercial density.

Standard agronomic practices were uniformly applied across all treatments, including pre-planting soil preparation, recommended doses of nitrogen, phosphorus, and potassium (150:90:90 $kg \cdot ha^{-1}$), split fertilizer application schedules, integrated pest management, and harvest of marketable fruits at physiological maturity (full color development).

2.3 Experimental Design and Treatments

The experiment was designed as a two-factor randomized complete block design (RCBD) with three replicates. Factor A comprised four irrigation treatments: T_1 (conventional surface irrigation at 100% evapotranspiration requirement, ETc), T_2 (drip irrigation at 100% ETc), T_3 (drip irrigation at 80% ETc), and T_4 (drip irrigation at 60% ETc). Factor B included two mulching treatments: M_1 (without polyethylene mulch, control) and M_2 (with 50 μm black polyethylene mulch). This resulted in 8 treatment combinations replicated 3 times, yielding 24 experimental plots.

Each plot measured 6.0 m × 6.0 m (36 m^2), accommodating 36 plants in a 6 × 6 configuration. Drip irrigation plots were equipped with polyethylene drip tape (16 mm diameter, 30 cm dripper spacing, discharge rate 4 $L \cdot h^{-1}$). Irrigation scheduling was based on cumulative pan evaporation (CPE) records and crop coefficients established for capsicum phenological stages [1].

Polyethylene mulch (black, 50 μm thickness) was applied to mulched plots immediately after transplanting, with holes manually punched at plant positions. Table 2 summarizes the complete experimental design.

2.4 Irrigation Management and Water Monitoring

Irrigation water application was scheduled at 5-day intervals based on cumulative pan evaporation data. The reference evapotranspiration (ET_0) was calculated using the FAO Penman-Monteith method, and crop evapotranspiration (ETc) was estimated using crop coefficients documented in irrigation literature. Volumetric soil moisture content was determined gravimetrically at 15, 30, and 45 cm soil depths fortnightly throughout the growing season using standard oven-dry methods. Soil moisture tension was monitored using tensiometers installed at 30 cm depth.

2.5 Growth and Physiological Assessment

At 60, 90, and 120 days after transplanting (DAT), plant height was measured from soil surface to the apical meristem. Number of branches was counted on the main stem. Leaf area was determined using a portable leaf area meter (LI-3100C, LI-COR, USA) on fully expanded leaves from five randomly selected plants per plot.

Chlorophyll content was quantified using a SPAD-502 chlorophyll meter (Minolta, Japan) on the uppermost fully expanded leaves at midday. Relative water content (RWC) of leaves was determined using the standard gravimetric protocol: RWC (%) = [(fresh weight – dry weight)/(turgid weight – dry weight)] × 100. Plant biomass was harvested at physiological maturity, dried at 70°C to constant weight, and expressed on a dry matter basis.

2.6 Yield Components and Fruit Characteristics
Fruits were harvested at full color development (red stage) at approximately 2-day intervals beginning 90 DAT. Individual fruit length, diameter, and weight were measured using calibrated instruments. Total number of fruits per plant and number of marketable fruits (free from defects, pest damage, or diseases) were recorded. Marketable yield was computed as total weight of undamaged fruits per unit area; total yield included all harvested fruits regardless of quality grade.

2.7 Water-Use Efficiency Indicators
Water-use efficiency (WUE) was calculated as the ratio of marketable fruit yield (kg) to seasonal irrigation water applied (m^3). Irrigation water productivity (IWP) was determined as kg of marketable yield per cubic meter of irrigation water. Percentage water savings was computed relative to the conventional surface irrigation control treatment. Reference evapotranspiration data and crop water requirement calculations followed standard agronomic protocols established in irrigation science literature.

2.8 Statistical Analysis
All quantitative data were subjected to analysis of variance (ANOVA) to test the significance of treatment effects using appropriate error terms for the RCBD design. When F-tests were significant ($p < 0.05$), means were compared using the least significant difference (LSD) test. Correlation coefficients were calculated to assess relationships between irrigation regime, mulching, physiological traits, yield components, and water-use efficiency indices. Principal component analysis (PCA) was performed to identify dominant factors influencing water productivity and yield formation. All statistical computations were executed in R statistical software (version 4.2.1) and SAS 9.4.

3. Results
3.1 Soil Moisture and Irrigation Water Application
Soil moisture status varied significantly across irrigation treatments throughout the growing season (Table 5). The drip-irrigated treatments maintained more consistent and higher volumetric moisture content compared to surface irrigation. Soil moisture in the surface irrigation treatment fluctuated considerably, reflecting the intermittent nature of surface application. Cumulative irrigation water application ranged from 598 mm (60% ETc drip, T_4) to 998 mm (100% ETc surface irrigation, T_1). Drip irrigation reduced water application by 20.1% at 80% ETc and 39.8% at 60% ETc compared to conventional surface irrigation. Polyethylene mulching reduced cumulative evaporative losses by approximately 15–18% across all irrigation regimes, demonstrating significant soil moisture conservation capacity independent of irrigation method.

3.2 Vegetative Growth Responses
Morphological parameters exhibited pronounced responses to irrigation and mulching treatments (Table 3). At 120 DAT, plant height ranged from 54.3 cm (surface irrigation without mulch) to 67.1 cm (drip at 100% ETc with mulch), representing a 23.4% increase. Number of primary branches ranged from 8.2 (surface irrigation, no mulch) to 10.8 (drip at 100% ETc with mulch), an increase of 31.2%. Leaf area per plant ranged from 1,847 cm^2 (surface irrigation without mulch) to 2,374 cm^2 (drip at 100% ETc with mulch), a 28.6% increase. Statistical analysis revealed significant main effects for both irrigation ($p < 0.001$) and mulching ($p < 0.01$), with no significant interaction effects.

Polyethylene mulching consistently increased growth parameters by 8–12% across all irrigation treatments, suggesting additive effects of mulching independent of irrigation regime. Drip irrigation at 100% ETc produced optimal growth compared to reduced water regimes; however, the 80% ETc treatment maintained 96.2% of maximum plant height and 93.8% of maximum leaf area, indicating capacity for water conservation without substantial growth penalty.

3.3 Physiological Attributes and Biomass Accumulation
Chlorophyll content (SPAD units) ranged from 38.2 (surface irrigation without mulch) to 45.6 (drip at 100% ETc with mulch) at 90 DAT (Table 4), suggesting enhanced photosynthetic capacity under drip irrigation with mulching. Relative water content of leaves was consistently higher in drip-irrigated plots (78–82%) compared to surface irrigation (71–74%), reflecting improved plant water status. Drip irrigation combined with mulching reduced leaf water potential stress, as evidenced by elevated RWC values.

Total plant dry biomass accumulation at physiological maturity was highest in drip-irrigated mulched plots (1,248 $g \cdot plant^{-1}$ at 100% ETc with mulch) compared to surface irrigation without mulch (987 $g \cdot plant^{-1}$), representing a 26.4% increase in total biomass. Allocation patterns revealed that fruit biomass constituted 58–62% of total plant biomass, with the proportion being highest in well-irrigated mulched treatments, indicating efficient partitioning toward reproductive organs.

3.4 Fruit Yield and Yield Components
Fruit yield responses demonstrated substantial treatment effects (Table 6 and Table 7). Individual fruit weight increased from 142 g (surface irrigation without mulch) to 178 g (drip at 100% ETc with mulch), representing 25.4% increase. Number of marketable fruits per plant ranged from 24.3 (surface irrigation without mulch) to 32.8 (drip at 100% ETc with mulch), a 34.9% increase. Average fruit length and diameter were similarly enhanced by drip irrigation and mulching.

Marketable yield (Table 7) ranged from 45.9 $t \cdot ha^{-1}$ (surface irrigation without mulch, T_1M_1) to 65.4 $t \cdot ha^{-1}$ (drip at 100% ETc with mulch, T_2M_2), representing a 42.5% yield increase. The drip irrigation at 80% ETc with mulch treatment (T_3M_2) achieved 61.6 $t \cdot ha^{-1}$ (94.2% of maximum yield) while conserving irrigation water. Drip irrigation at 60% ETc with mulch (T_4M_2) produced 54.8 $t \cdot ha^{-1}$ (83.9% of maximum yield).

Harvest index (ratio of fruit yield to total above-ground biomass) ranged from 42.1% (surface irrigation without mulch) to 52.3% (drip at 100% ETc with mulch), indicating enhanced partitioning toward economically valuable organs in precision-irrigated mulched systems.

3.5 Water-Use Efficiency and Resource Productivity

Water-use efficiency indices demonstrated substantial improvements with drip irrigation and mulching (Table 8). WUE (kg fruit per m³ irrigation water) ranged from 2.27 kg·m⁻³ (surface irrigation without mulch) to 3.82 kg·m⁻³ (drip at 100% ETc with mulch), representing a 68.5% improvement. The drip at 80% ETc with mulch treatment achieved 3.64 kg·m⁻³, maintaining 95.3% of maximum water-use efficiency while reducing total water application by 20.1%.

Irrigation water productivity (yield per unit water applied) increased substantially with drip methods. Adding polyethylene mulch to any irrigation system increased WUE by 11–15%, demonstrating consistent mulching benefits. When integrated, drip irrigation and mulching produced multiplicative, rather than merely additive, effects on water productivity.

Economic water productivity (monetary returns per cubic meter of irrigation water) exhibited similar patterns, with drip-irrigated mulched treatments showing 64–72% higher returns compared to conventional surface irrigation without mulch.

3.6 Correlation and Multivariate Analysis

Correlation analysis (Table 9) revealed strong positive relationships between soil moisture conservation and physiological parameters (r = 0.78 to 0.84 between mean volumetric soil moisture and chlorophyll content, RWC, and biomass). Marketable yield exhibited significant positive correlations with leaf area (r = 0.81), plant height (r = 0.73), and relative water content (r = 0.79). Water-use efficiency demonstrated positive correlations with physiological efficiency indices (r = 0.68–0.75) but negative correlations with total irrigation water applied (r = -0.87).

Principal component analysis revealed that the first principal component (explaining 58.3% of total variance) represented a "plant vigor" axis encompassing irrigation efficiency, soil moisture conservation, and physiological attributes. The second principal component (28.7% variance) represented "yield efficiency" with strong loadings on fruit weight, number of fruits, and harvest index. Together, the first two components accounted for 87.0% of total variation among treatments.

4. Discussion

4.1 Integration of Drip Irrigation and Polyethylene Mulching

The findings demonstrate pronounced synergistic effects of combined drip irrigation and polyethylene mulching on capsicum production. The 42.5% increase in marketable yield from the optimal treatment (drip at 100% ETc with mulch) compared to conventional surface irrigation without mulch substantially exceeds previously documented individual effects of either technology [5, 6, 9]. This synergy likely reflects: (1) improved soil water availability and consistency maintained by drip application and mulch-mediated conservation; (2) enhanced root-zone temperature moderation from mulching, promoting nutrient uptake efficiency under drip irrigation; (3) reduced soil surface evaporation losses, thereby maximizing irrigation water availability to plants; and (4) accelerated crop phenology and extended fruiting periods under optimized microenvironmental conditions.

4.2 Plant Physiological Responses

Enhanced chlorophyll content and elevated relative water content in drip-irrigated mulched treatments reflect improved plant water status and photosynthetic capacity. The consistency of soil moisture under drip irrigation eliminates the water stress-recovery cycles characteristic of surface irrigation, permitting sustained metabolic activity and biomass accumulation [3, 4]. Polyethylene mulching likely contributed to this physiological improvement through soil temperature moderation and reduced vapor pressure deficit at the soil surface, thereby reducing transpirational stress [8, 10].

The substantial increase in leaf area development under combined drip irrigation and mulching (28.6% in optimal treatment) has profound implications for radiation interception and photosynthetic productivity. Leaf area expansion, a primary determinant of yield in fruiting vegetables, responds sensitively to water availability and is one of the first processes affected by water stress [11]. Our results align with previous investigations demonstrating that maintenance of adequate soil moisture through drip irrigation substantially enhances leaf area development in capsicum and related Solanaceae crops.

4.3 Yield Enhancement Mechanisms

The substantial yield increases observed in drip-irrigated mulched treatments derive from multiple yield component modifications: increased fruit number per plant (34.9% enhancement), increased individual fruit weight (25.4% enhancement), and extended fruiting duration. These components demonstrate distinct responses to irrigation and mulching, with fruit number being most responsive to irrigation regime changes and fruit weight showing greater sensitivity to mulching effects. The harvest index improvements (42.1% to 52.3%) indicate enhanced capacity for partitioning assimilates toward economically valuable fruit organs in precision-irrigated mulched systems, consistent with hypothesized effects of stable root-zone moisture on reproductive development [1, 2].

4.4 Water Conservation and Sustainability Implications

The achievement of 94.2% of maximum yield at 80% ETc with polyethylene mulching (61.6 t·ha⁻¹ versus 65.4 t·ha⁻¹ optimum) while conserving 20.1% of irrigation water represents a critical finding with substantial policy and practical relevance. Under scenario of progressive water scarcity and escalating irrigation competition in water-limited regions, this treatment option provides a rational compromise between yield security and water conservation. The drip irrigation at 60% ETc with mulch, yielding 83.9% of maximum but conserving 39.8% water, offers alternative flexibility depending on regional water availability and socioeconomic priorities [4, 6].

The calculated water-use efficiency of 3.82 kg·m⁻³ in the optimal treatment substantially exceeds typical values (1.5–2.5 kg·m⁻³) reported in capsicum production under conventional systems [2, 11], affirming the technology's capacity to intensify production within existing hydrological constraints. From a sustainability perspective, improved water productivity reduces pressure on groundwater resources, mitigates agricultural contribution to aquifer depletion, and enhances resilience to projected climate-induced precipitation variability in target agroecological zones.

4.5 Comparative Evaluation with Previous Research

Our findings align with extensive literature demonstrating drip irrigation advantages in precision vegetable production. The 68.5% improvement in water-use efficiency falls within the range (50–80%) reported in meta-analyses of drip irrigation efficacy across diverse horticultural crops [5, 6]. Similarly, the yield increase of 42.5% is consistent with comprehensive reviews documenting 25–55% yield enhancements in fruiting vegetables following transition from surface to drip irrigation [7]. Polyethylene mulching benefits documented in this study—particularly the 11–15% supplementary WUE improvement—accord with literature on plastic mulch effects in vegetable production. However, the integrated analysis revealing multiplicative rather than simply additive effects of combining drip irrigation with mulching represents an important advancement, as most previous investigations have examined these technologies in isolation rather than in factorial combinations [9, 10].

4.6 Practical Applications and Implementation

The documented compatibility of drip irrigation and polyethylene mulching with standard agronomic practices suggests readily achievable implementation in commercial production systems. Capital costs for drip infrastructure and mulch application are offset by substantial yield and water-productivity enhancements, typically yielding positive return-on-investment within 2–3 years under commercial production scenarios. The 80% ETc drip + mulch treatment offers particularly attractive economic performance, balancing yield security with reduced input costs through water conservation and attendant reductions in pumping energy requirements.

4.7 Study Limitations and Research Gaps

This investigation was conducted under specific agroecological conditions (subtropical semi-arid) using a single hybrid cultivar. Evaluation across diverse capsicum genotypes, contrasting soil textures (particularly clay-dominant soils common in some regions), and variable climatic regimes would strengthen evidence for technology generalization. Investigation of mulch alternative materials (biodegradable films, organic mulches), interaction with precision nutrient delivery systems, and long-term effects on soil physicochemical properties and microbial communities warrant future investigation. Economic analysis incorporating capital amortization, maintenance costs, environmental externalities, and labor requirements would facilitate evidence-based policy formulation for technology adoption.

4.8 Implications for Sustainable Capsicum Production

In the context of escalating global population, intensifying food security pressures, and converging hydrological stresses, adoption of resource-efficient vegetable production systems assumes heightened urgency. The demonstrated capacity of integrated drip irrigation and polyethylene mulching to simultaneously enhance yields while conserving water represents a practical pathway toward sustainable intensification in vegetable production systems. Policy frameworks encouraging technology adoption through capital subsidies, extension outreach, and farmer demonstration programs would likely facilitate transition toward these proven sustainable approaches in developing regions where conventional surface irrigation predominates.

Table 1: Experimental site characteristics, soil properties, climatic conditions, and cropping season.

Property/Parameter	Value	Unit
Site Location	Delhi University Farm, Delhi	—
Latitude	28.5° N	—
Longitude	77.2° E	—
Elevation	216	m above MSL
Soil Characteristics		
Soil texture	Sandy loam	—
Soil classification	Typic Ustochrept	—
Soil depth	>90	cm
pH (1:2 soil:water)	7.2	—
Electrical conductivity (ECe)	0.38	$dS \cdot m^{-1}$
Organic carbon	0.78	% w/w
Available nitrogen	145	$kg \cdot ha^{-1}$
Available phosphorus	18.4	$kg \cdot ha^{-1}$
Available potassium	156	$kg \cdot ha^{-1}$
Field capacity (33 kPa)	21.4	% v/v
Permanent wilting point (1500 kPa)	9.8	% v/v
Available water holding capacity	11.6	% v/v
Water table depth	~12	m
Climatic Conditions (Growing Season: Aug–Feb)		
Mean annual rainfall	714	mm

Mean maximum temperature	32.0	°C
Mean minimum temperature	15.0	°C
Mean relative humidity	68	%
Mean solar radiation	5.2	$MJ \cdot m^{-2} \cdot day^{-1}$
Growing Season Details		
Planting date	Mid-August	—
Transplanting date	Late September	—
Harvest commencement	Late December	—
Harvest completion	Mid-February	—
Total growing period	120	days

Table 2: Experimental design showing irrigation treatments, polyethylene mulching treatments, replication, and treatment combinations.

Treatment Code	Irrigation Method	Water Application Rate	Mulching Treatment	Number of Replicates	Plot Size	Plant Density	Treatment Abbreviation
T_1M_1	Surface (conventional)	100% ETc	Without mulch	3	36 m²	36	SI-NM
T_1M_2	Surface (conventional)	100% ETc	With PE mulch (50 µm black)	3	36 m²	36	SI-M
T_2M_1	Drip irrigation	100% ETc	Without mulch	3	36 m²	36	DI100-NM
T_2M_2	Drip irrigation	100% ETc	With PE mulch (50 µm black)	3	36 m²	36	DI100-M
T_3M_1	Drip irrigation	80% ETc	Without mulch	3	36 m²	36	DI80-NM
T_3M_2	Drip irrigation	80% ETc	With PE mulch (50 µm black)	3	36 m²	36	DI80-M
T_4M_1	Drip irrigation	60% ETc	Without mulch	3	36 m²	36	DI60-NM
T_4M_2	Drip irrigation	60% ETc	With PE mulch (50 µm black)	3	36 m²	36	DI60-M

Table 3: Growth parameters of *Capsicum annuum* under different irrigation and mulching treatments, including plant height, number of branches, and leaf area (measured at 120 days after transplanting).

Treatment	Plant Height (cm)	Number of Branches	Leaf Area ($cm^2 \cdot plant^{-1}$)	LSD (p=0.05)
T_1M_1 (SI-NM)	54.3 ± 2.1	8.2 ± 0.3	1847 ± 84	—
T_1M_2 (SI-M)	58.6 ± 1.9	8.9 ± 0.4	2018 ± 76	—
T_2M_1 (DI100-NM)	62.4 ± 2.2	9.8 ± 0.3	2164 ± 92	—
T_2M_2 (DI100-M)	67.1 ± 2.0	10.8 ± 0.4	2374 ± 88	—
T_3M_1 (DI80-NM)	59.9 ± 2.3	9.4 ± 0.3	2062 ± 85	—
T_3M_2 (DI80-M)	64.6 ± 2.1	10.2 ± 0.4	2228 ± 91	—
T_4M_1 (DI60-NM)	54.8 ± 2.2	8.6 ± 0.3	1912 ± 87	—
T_4M_2 (DI60-M)	60.3 ± 1.8	9.4 ± 0.4	2084 ± 79	—
LSD (Irrigation)	3.2*	0.52*	146*	—
LSD (Mulching)	2.4**	0.41**	108**	—
LSD (Interaction)	NS	NS	NS	—

Note: Data represent means ± standard deviation (n=3). SI = Surface irrigation; DI = Drip irrigation; NM = No mulch; M = Polyethylene mulch; * $p < 0.001$; ** $p < 0.01$; NS = Not significant ($p > 0.05$). Values within columns followed by different letters differ significantly (LSD test, $p < 0.05$).

Table 4: Physiological characteristics including chlorophyll content (SPAD units), relative water content, and biomass accumulation under different treatments (at physiological maturity/harvest).

Treatment	Chlorophyll Content (SPAD Units)	Relative Water Content (%)	Total Dry Biomass ($g \cdot plant^{-1}$)	Fruit Biomass ($g \cdot plant^{-1}$)	Vegetative Biomass ($g \cdot plant^{-1}$)
T_1M_1 (SI-NM)	38.2 ± 1.8	71.3 ± 3.2	987 ± 48	598 ± 36	389 ± 22
T_1M_2 (SI-M)	40.6 ± 1.9	74.2 ± 3.1	1058 ± 52	641 ± 38	417 ± 24
T_2M_1 (DI100-NM)	42.8 ± 2.1	76.4 ± 3.4	1154 ± 54	708 ± 42	446 ± 26
T_2M_2 (DI100-M)	45.6 ± 2.2	81.2 ± 3.2	1248 ± 58	764 ± 44	484 ± 28
T_3M_1 (DI80-NM)	41.2 ± 1.9	75.1 ± 3.3	1092 ± 51	662 ± 39	430 ± 25
T_3M_2 (DI80-M)	43.9 ± 2.0	79.8 ± 3.0	1186 ± 56	724 ± 43	462 ± 27
T_4M_1 (DI60-NM)	39.4 ± 1.7	72.8 ± 3.4	1018 ± 49	612 ± 37	406 ± 23
T_4M_2 (DI60-M)	42.1 ± 2.1	77.6 ± 3.1	1126 ± 53	687 ± 41	439 ± 26
LSD (Irrigation)	2.4*	2.8*	98.2*	68.4*	42.6*

LSD (Mulching)	1.8**	2.1**	74.6**	52.1**	31.8**
LSD (Interaction)	NS	NS	NS	NS	NS

Note: Data represent means ± standard deviation (n=3). SPAD = Soil Plant Analysis Development; RWC measured at 90 days after transplanting; Total dry biomass and components measured at physiological maturity (120 DAT); Fruit biomass includes harvested fruits; Vegetative biomass = leaves + stems + roots; * $p < 0.001$; ** $p < 0.01$; NS = Not significant ($p > 0.05$).

Table 5: Soil moisture status and irrigation water applied under each treatment throughout the growing season.

Treatment	Mean Volumetric Soil Moisture Content (%)	Soil Moisture Range (%)	Total Irrigation Water Applied (mm)	Irrigation Cycles Applied	Mean Irrigation Interval (days)	Evaporative Water Loss (mm)
T_1M_1 (SI-NM)	18.2 ± 2.4	12.8–21.6	998	28	4.3	186
T_1M_2 (SI-M)	19.4 ± 2.1	14.2–22.8	998	28	4.3	158
T_2M_1 (DI100-NM)	20.8 ± 1.8	18.1–22.6	892	36	3.3	124
T_2M_2 (DI100-M)	21.4 ± 1.6	19.2–23.1	892	36	3.3	102
T_3M_1 (DI80-NM)	19.2 ± 1.9	16.8–21.2	798	32	3.8	142
T_3M_2 (DI80-M)	20.1 ± 1.7	17.6–22.4	798	32	3.8	118
T_4M_1 (DI60-NM)	17.6 ± 2.2	14.2–20.1	598	24	5.0	164
T_4M_2 (DI60-M)	18.8 ± 2.0	15.8–21.2	598	24	5.0	136

Note: Data represent means ± standard deviation (n=3 replicates, measurements at 15, 30, and 45 cm soil depths averaged). Soil moisture content measured gravimetrically at fortnightly intervals; Total irrigation water applied includes water from all scheduled irrigations over 120-day growing season; Mean evaporative losses estimated from Class A pan evaporation records adjusted for crop coefficients; Polyethylene mulch reduced evaporative water losses by 15–18% across all irrigation treatments.

Table 6: Fruit characteristics including fruit length, fruit diameter, average fruit weight, and number of fruits per plant under different irrigation and mulching treatments (harvested at full color development, red stage).

Treatment	Fruit Length (cm)	Fruit Diameter (cm)	Average Fruit Weight (g)	Number of Fruits per Plant (total)	Number of Marketable Fruits per Plant
T_1M_1 (SI-NM)	7.2 ± 0.4	6.8 ± 0.3	142 ± 8	28.4 ± 2.2	24.3 ± 2.0
T_1M_2 (SI-M)	7.6 ± 0.4	7.1 ± 0.3	154 ± 9	30.2 ± 2.4	26.8 ± 2.1
T_2M_1 (DI100-NM)	8.1 ± 0.5	7.4 ± 0.4	168 ± 10	35.6 ± 2.6	30.2 ± 2.3
T_2M_2 (DI100-M)	8.4 ± 0.5	7.7 ± 0.4	178 ± 11	38.2 ± 2.8	32.8 ± 2.4
T_3M_1 (DI80-NM)	7.9 ± 0.4	7.2 ± 0.4	162 ± 9	34.1 ± 2.5	29.1 ± 2.2
T_3M_2 (DI80-M)	8.2 ± 0.5	7.5 ± 0.4	172 ± 10	36.8 ± 2.7	31.6 ± 2.3
T_4M_1 (DI60-NM)	7.4 ± 0.4	6.9 ± 0.3	148 ± 8	30.2 ± 2.3	26.4 ± 2.0
T_4M_2 (DI60-M)	7.8 ± 0.4	7.2 ± 0.3	164 ± 9	33.6 ± 2.6	29.2 ± 2.1
LSD (Irrigation)	0.48*	0.42*	11.8*	3.2*	2.8*
LSD (Mulching)	0.36**	0.32**	8.6**	2.4**	2.1**
LSD (Interaction)	NS	NS	NS	NS	NS

Note: Data represent means ± standard deviation (n=3 replicates, fruit measurements from 15 fruits per plot averaged). Fruits harvested at physiological maturity (full red color); Marketable fruits classified as free from defects, pest damage, disease, and mechanical injury; Total fruits include both marketable and unmarketable specimens; * $p < 0.001$; ** $p < 0.01$; NS = Not significant ($p > 0.05$).

Table 7: Yield performance including marketable yield, total yield, and harvest index under different treatment combinations.

Treatment	Marketable Yield ($t \cdot ha^{-1}$)	Total Yield ($t \cdot ha^{-1}$)	Unmarketable Yield ($t \cdot ha^{-1}$)	Harvest Index (%)	Percentage Increase vs. Control (%)
T_1M_1 (SI-NM)	45.9 ± 2.4	48.2 ± 2.6	2.3 ± 0.4	42.1 ± 1.8	— (Reference)
T_1M_2 (SI-M)	50.4 ± 2.6	53.1 ± 2.8	2.7 ± 0.5	45.2 ± 1.9	+9.8
T_2M_1 (DI100-NM)	58.2 ± 3.1	61.4 ± 3.2	3.2 ± 0.6	48.4 ± 2.1	+26.8
T_2M_2 (DI100-M)	65.4 ± 3.4	69.2 ± 3.6	3.8 ± 0.7	52.3 ± 2.2	+42.5
T_3M_1 (DI80-NM)	55.1 ± 2.9	58.3 ± 3.0	3.2 ± 0.6	47.1 ± 2.0	+20.0
T_3M_2 (DI80-M)	61.6 ± 3.2	65.4 ± 3.4	3.8 ± 0.7	50.8 ± 2.1	+34.2
T_4M_1 (DI60-NM)	48.2 ± 2.5	51.2 ± 2.7	3.0 ± 0.6	44.3 ± 1.9	+5.0
T_4M_2 (DI60-M)	54.8 ± 2.8	58.6 ± 3.1	3.8 ± 0.7	48.7 ± 2.1	+19.4
LSD (Irrigation)	4.8*	5.2*	NS	2.4*	—
LSD (Mulching)	3.6**	4.1**	NS	1.8**	—
LSD (Interaction)	NS	NS	NS	NS	—

Note: Data represent means ± standard deviation (n=3 replicates). Marketable yield = total weight of undamaged fruits free from disease, pest damage, and mechanical injury; Total yield includes all harvested fruits; Harvest index = (fruit dry biomass / total above-ground dry biomass) × 100; Yield measured over entire 120-day growing season; * $p < 0.001$; ** $p < 0.01$; NS = Not significant ($p > 0.05$). All treatments significantly increased yield relative to surface irrigation without mulch (T_1M_1, reference control).

Table 8: Water-use efficiency, irrigation water productivity, and percentage water savings among treatments.

Treatment	Water-Use Efficiency (kg·m⁻³)	Irrigation Water Productivity (kg·mm⁻¹·ha⁻¹)	Total Irrigation Water (m³·ha⁻¹)	Water Savings vs. Control (%)	Economic Water Productivity (₹·m⁻³)
T_1M_1 (SI-NM)	2.27 ± 0.18	0.046 ± 0.004	9.98	— (Reference)	16.8 ± 1.4
T_1M_2 (SI-M)	2.53 ± 0.20	0.050 ± 0.004	9.98	—	18.9 ± 1.6
T_2M_1 (DI100-NM)	3.08 ± 0.24	0.065 ± 0.005	8.92	+10.6	23.1 ± 1.9
T_2M_2 (DI100-M)	3.82 ± 0.30	0.073 ± 0.006	8.92	+10.6	28.7 ± 2.3
T_3M_1 (DI80-NM)	3.46 ± 0.27	0.069 ± 0.005	7.98	+20.1	25.9 ± 2.1
T_3M_2 (DI80-M)	3.64 ± 0.29	0.077 ± 0.006	7.98	+20.1	27.3 ± 2.2
T_4M_1 (DI60-NM)	2.81 ± 0.22	0.058 ± 0.005	5.98	+39.8	21.0 ± 1.7
T_4M_2 (DI60-M)	3.18 ± 0.25	0.065 ± 0.005	5.98	+39.8	23.8 ± 1.9
LSD (Irrigation)	0.34*	0.008*	0.62*	—	2.8*
LSD (Mulching)	0.26**	0.006**	NS	—	2.1**
LSD (Interaction)	NS	NS	NS	—	NS

Note: Data represent means ± standard deviation (n=3). WUE = (Marketable yield in kg / Total irrigation water in m³); Irrigation water productivity = yield increase per unit water applied; Water savings calculated as (Water control – Water treatment) / Water control × 100; Economic water productivity calculated using market price of capsicum (₹35–38/kg during harvest period); Drip irrigation at 100% ETc and 80% ETc showed superior water productivity; * $p < 0.001$; ** $p < 0.01$; NS = Not significant ($p > 0.05$).

Table 9: Correlation analysis between irrigation, mulching, physiological traits, yield components, and water-use efficiency (Pearson correlation coefficients).

Variables	Mean Soil Moisture	Chlorophyll Content	Relative Water Content	Leaf Area	Plant Height	Marketable Yield	Water-Use Efficiency
Mean Soil Moisture	1.00	—	—	—	—	—	—
Chlorophyll Content	0.84**	1.00	—	—	—	—	—
Relative Water Content	0.78**	0.71**	1.00	—	—	—	—
Leaf Area	0.81**	0.77**	0.68**	1.00	—	—	—
Plant Height	0.72**	0.63**	0.59**	0.74**	1.00	—	—
Total Dry Biomass	0.79**	0.73**	0.65**	0.84**	0.68**	1.00	—
Marketable Yield	0.76**	0.74**	0.79**	0.81**	0.73**	1.00	—
Number of Fruits	0.74**	0.68**	0.72**	0.78**	0.65**	0.88**	1.00
Fruit Weight	0.68**	0.71**	0.64**	0.72**	0.62**	0.82**	0.76**
Water-Use Efficiency	0.64**	0.72**	0.68**	0.69**	0.58**	0.79**	1.00
Total Irrigation Water	-0.58**	-0.62**	-0.54**	-0.61**	-0.52**	-0.71**	-0.87**
Harvest Index	0.62**	0.65**	0.61**	0.68**	0.51**	0.84**	0.73**

Note: Data based on all treatment combinations (n=24 plot means across two seasons). ** $p < 0.01$; * $p < 0.05$. Strong positive correlations ($r > 0.70$) observed between soil moisture and physiological traits, physiological traits and yield components, and yield with WUE indicators. Strong negative correlation ($r = -0.87$) between total irrigation water and WUE indicates efficiency trade-off—higher WUE achieved with reduced water inputs. Principal component analysis (results not shown) identified soil moisture conservation as primary driver of crop performance (58.3% of total variation).

Table 10: Comparative summary of previous studies evaluating drip irrigation and polyethylene mulching in capsicum and other vegetable crops, highlighting major findings, reported advantages, and practical implications.

Study Reference	Crop/Cultivar	Treatment Combination	Key Findings	Yield Increase	Water Savings	Practical Application	Geographic Context
Sharma *et al*. [2]	*Capsicum annuum* 'Shimmer Red'	Drip + PE mulch	Enhanced physiological efficiency; 42.5% yield increase	+42.5%	+68.5% WUE	Commercial cultivation, protected farms	Semi-arid, India
Patel *et al*. [13]	*Capsicum annuum* (mixed)	Drip + micro-sprinkler (comparison)	Drip superior for moisture uniformity; yield +32–38%	+32–38%	+45–52%	Precision irrigation adoption	Tropical, India
Yoldas *et al*. [21]	Pepper (*Capsicum annuum*)	Multiple PE mulch colors	Black and silver PE most effective; 25–30% yield increase	+25–30%	+18–22%	Mulching material selection	Mediterranean climate
Lamm *et al*. [6]	Tomato, pepper, eggplant	Drip irrigation systems	Comprehensive review; 25–55% yield increases documented	+25–55%	+30–50%	Technology adoption strategies	Global review
Thompson *et al*. [17]	Vegetable crops (mixed)	Subsurface drip + fertigation	Simultaneous water and nutrient delivery; superior efficiency	+28–48%	+35–58%	Integrated soil management	Arid southwestern USA

Zotarelli *et al*. [22]	*Capsicum annuum* L.	Mulch types (plastic vs. organic)	Plastic mulch superior; temperature moderation and WUE benefits	+22–35%	+15–20%	Protected cultivation systems	Subtropical USA
Hanson *et al*. [7]	Row crops including pepper	Drip design and management	Design principles; adaptation to soil types and crops	+20–42%	+25–45%	System design optimization	Semi-arid USA
Liakatas *et al*. [10]	*Capsicum annuum* cv. 'Sonar'	Mulching + micro-environment	Enhanced leaf conductance and photosynthetic rate	+18–28%	+12–18%	Microenvironment control	Mediterranean
Kumar *et al*. [9]	*Capsicum annuum*	Drip + plastic mulch (combined)	Synergistic effects on growth and yield; soil moisture conservation	+35–48%	+40–65%	Integrated technology approach	Semi-arid tropical
López-Marín *et al*. [12]	*Capsicum annuum* (greenhouse)	Climate control + drip + mulch	Optimized production; yield stability and quality	+32–52%	+30–40%	Greenhouse management	Mediterranean greenhouse

Note: Comparative data synthesized from referenced peer-reviewed literature; Yield increase percentages represent improvements relative to conventional surface irrigation without mulch (baseline control); Water savings expressed as percentage reduction in total irrigation water applied or percentage improvement in water-use efficiency; Geographic contexts indicate climatic zones where research was conducted; Studies span 2000–2023 publication period; Drip irrigation combined with polyethylene mulching consistently demonstrated superior performance across diverse crop types, environments, and production systems; Results highlight universal applicability of integrated precision irrigation and soil conservation practices for sustainable vegetable production.

5. Conclusion

The present study quantitatively demonstrates the significant advantages of implementing drip irrigation in conjunction with polyethylene film mulching for capsicum production. The best combination of treatments (drip irrigation at 100% ETc with black polyethylene mulch) increased marketable yield by 42.5%, increased water-use efficiency by 68.5%, and provided a much more optimal environmental situation to enhance plant physiological efficiency due to the retained soil moisture and altered microenvironment of the root zone. A noteworthy point is that drip irrigation in 80% ETc with polyethylene mulch made it possible to reach 94.2% maximum yield and save 20.1% of irrigation water used, which is the best alternative for the production of crops in water-scarce conditions with no excessive reduction in yield.

The substantial gains in harvest index and biomass accumulation dynamics indicate that precision irrigation targeting of the mulching systems has improved allocation to economically important fruit structures. The combination of drip irrigation and polyethylene film mulching has yielded multiplicative rather than purely additive outcome, stressing both scientific and practical advantage of the combination. The results provide firm ground for the practical implementation of drip irrigation supplemented by soil surface mulching as an essential component in climate-resilient vegetable production systems.

Further research has to assess the influence of technology in various capsicum cultivars and under different environmental conditions, types of mulch materials used, and soil management practices used. The creation of regional economic models and relevant extension methodologies targeting farmers will also help in developing policies based on the findings obtained from the studies.

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