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Evapotranspiration-Based Production Functions and Water Productivity of Strawberry under Mulching and Protected Cultivation

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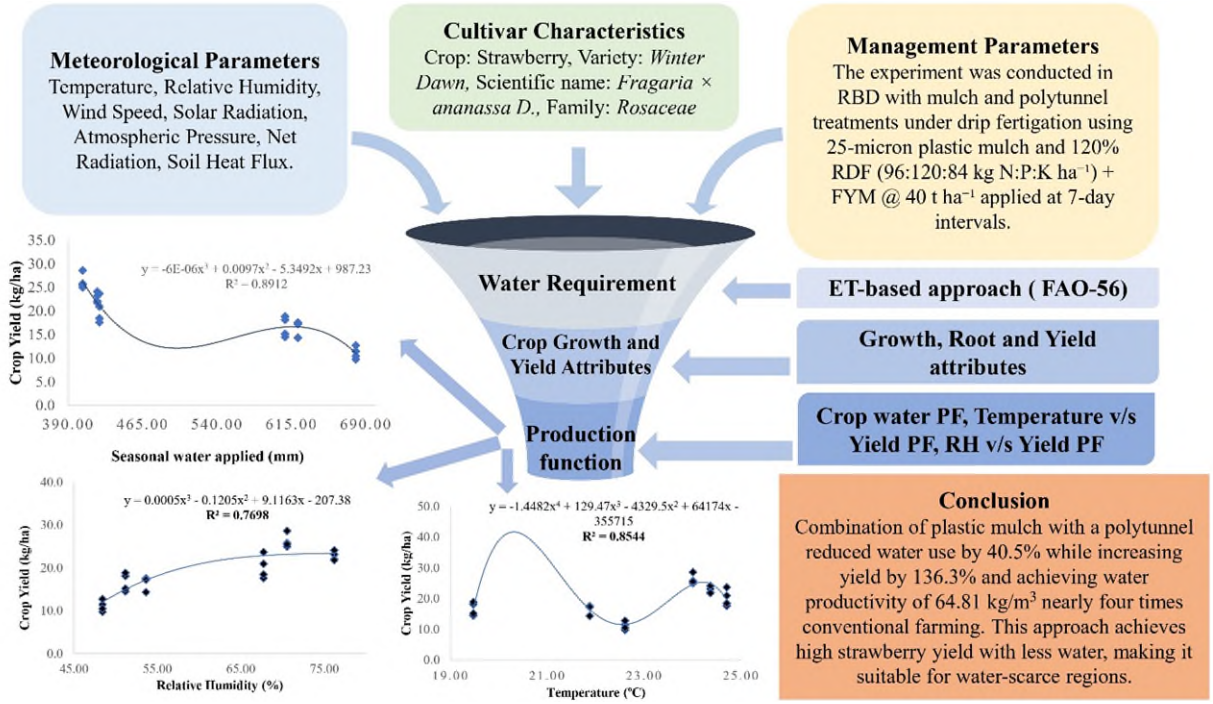
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Evapotranspiration-Based Production Functions and Water Productivity of Strawberry under Mulching and Protected Cultivation

Abstract



Protected cultivation can modify crop water use, yet quantitative relationships between evapotranspiration and strawberry yield remain insufficiently defined. This study developed evapotranspiration-based production functions for strawberry cultivar Winter Dawn under six treatments: control, plastic mulch, straw mulch, polytunnel, plastic mulch with polytunnel, and straw mulch with polytunnel. Daily crop evapotranspiration was estimated using the Penman–Monteith method, and marketable yield, water productivity, and crop yield response factor were evaluated. Plastic mulch with polytunnel reduced seasonal crop evapotranspiration from 679.62 to 404.37 millimetres, representing a 40.5% reduction compared with the control. The same treatment increased marketable yield from 11.09 to 26.21 tonnes per hectare and improved water productivity from 16.32 to 64.81 kilograms per cubic metre. A cubic production function best described the evapotranspiration–yield relationship, with a coefficient of determination of 0.8912. Polytunnel treatments showed low crop yield response factors, indicating reduced yield sensitivity to lower evapotranspiration under modified microclimatic conditions. These results demonstrate that integrating plastic mulch with polytunnel cultivation can improve strawberry yield while substantially reducing consumptive water use in water-limited subtropical regions.

Keywords: Evapotranspiration, Mulching, Polytunnel cultivation, Production function, Strawberry, Water productivity

Highlights:

- Plastic mulch with polytunnel reduced crop evapotranspiration by 40.5%.
- Marketable yield increased by 136.3% over the control.
- Water productivity reached 64.81 kg m^{-3}.

- Cubic yield function explained 89.1% of variation.
- Polytunnel cultivation reduced yield sensitivity to water use.

1. Introduction

Fresh water is among the most critical and increasingly constrained natural resources in agricultural production (Elliott *et al.*, 2014; Ingrao *et al.*, 2023). As global demand for food continues to rise alongside accelerating climate variability, water scarcity has emerged as a central challenge to sustainable crop production, particularly in regions dependent on irrigation (He and Rosa, 2023). Horticulture, which accounts for a disproportionately large share of agricultural water use relative to its cultivated area, faces mounting pressure to improve water-use efficiency without compromising yield or quality(Megha Raghavan, 2025). In this context, developing scientifically grounded, quantitative frameworks that link water consumption to crop productivity has become an urgent priority for irrigation management research.

Strawberry (*Fragaria* × *ananassa* Duch.) is among the most economically significant horticultural crops cultivated worldwide, commanding high market value and strong consumer demand (Hernández-Martínez *et al.*, 2023). Despite its commercial importance, strawberry presents considerable agronomic challenges from a water management perspective (Martínez-Ferri *et al.*, 2016; Biswas *et al.*, 2024). Its shallow root system, typically confined to the uppermost 20–30 cm of the soil profile, renders the crop highly sensitive to both water deficit and waterlogging, with yield and fruit quality responding sharply to fluctuations in soil moisture status (Kim *et al.*, 2009; Gonzalez-Fuentes *et al.*, 2016; Adak, Gubbuk and Tetik, 2018; Celiktopuz *et al.*, 2023). Protected cultivation systems, including plastic mulch and low-tunnel or greenhouse structures, have expanded the geographic range and seasonal window of strawberry production, but they also alter the microclimate and modify crop water use in ways that are not adequately captured by conventional field-based irrigation guidelines (Santosh, 2021; Menzel, 2025; St Fort *et al.*, 2025; Frakolaki *et al.*, 2026). Precise, location-sensitive water management is therefore essential to achieving optimal productivity in these systems (Roy *et al.*, 2024).

A physically meaningful and widely accepted measure of crop water use is evapotranspiration (ET), which integrates the processes of soil evaporation and plant transpiration into a single flux variable governed by the available energy, atmospheric demand, and crop characteristics (Brouwer and Heibloem, 1985; Allen, 1998). Crop evapotranspiration (ET_c), estimated by combining reference evapotranspiration (ET_o) with crop-specific coefficients (K_c), provides a mechanistically grounded basis for irrigation scheduling that transcends the empiricism of volume-based or calendar-based approaches (Klocke *et al.*, 1990; Prochnow *et al.*, 2012; Sun *et al.*, 2024). The FAO-56 Penman–Monteith method, widely regarded as the international standard for ET_o estimation, offers a robust and physically consistent framework applicable across diverse climatic conditions, provided reliable meteorological data are available(Allen *et al.*, 1998; Vu, Watanabe and Takagi, 2005; Zotarelli *et al.*, 2024). Its adoption in horticultural irrigation research has grown considerably over recent decades, yet its translation into predictive yield functions for high-value crops such as strawberry remains limited (Gavilán, Ruiz and Lozano, 2015; Pereira *et al.*, 2015).

Traditional approaches to irrigation management in strawberry production have relied predominantly on empirical scheduling protocols derived from local field experience or agronomic trials that relate marketable yield to applied

irrigation depth. While such approaches offer practical utility within the specific conditions under which they were developed, they suffer from well-recognized limitations (Itier *et al.*, 1996; Morillo *et al.*, 2015). Irrigation depth, as a management variable, does not account for losses due to deep percolation, runoff, or soil evaporation, and thus does not accurately represent the water actually consumed by the crop. Consequently, yield–irrigation relationships derived from one climatic or soil environment cannot be reliably transferred to another(Itier *et al.*, 1996). Furthermore, relating yield to applied water rather than to actual crop water use precludes the development of transferable, process-based production functions capable of supporting irrigation planning and yield prediction under varying water availability scenarios (Singh *et al.*, 2021; Thomas, Mutayoba and Makungu, 2025).

A production function, in the agronomic sense, describes the quantitative relationship between a crop input — in this case water consumed as ET — and the resulting yield(Keller, 2012; Smith and Steduto, 2012; Varzi, 2016). Classical ET–yield production functions, such as those proposed by Stewart, Jensen, and Doorenbos and Kassam, have been extensively validated for cereal and field crops, providing the basis for deficit irrigation strategies and regional water allocation planning (Jensen, 1968; Stewart *et al.*, 1977; Doorenbos and Kassam, 1979). In addition to water-based production relationships, empirical microclimate–yield functions can also be developed to quantify the influence of environmental variables such as air temperature and relative humidity on crop productivity, particularly under protected or modified field conditions. Such temperature–yield and RH–yield relationships help elucidate the extent to which treatment-induced microclimatic variation contributes to observed yield responses (Robertson *et al.*, 2013; Zhao *et al.*, 2017; Ansarifar, Wang and Archontoulis, 2021; Song *et al.*, 2021). However, their application to horticultural fruit crops, and to strawberry in particular, remains sparse (Igbadun *et al.*, 2007). Most existing studies on strawberry irrigation either focus on agronomic responses to different irrigation treatments without developing functional models, or evaluate water productivity as a ratio of yield to applied water rather than to actual ETc. The absence of rigorously derived ET-based production functions for strawberry under field-protected conditions thus represents a substantive gap in the scientific literature — one that limits the capacity of growers, extension specialists, and water managers to make informed, quantitative decisions about irrigation under conditions of water scarcity.

The present study was undertaken to develop evapotranspiration-based production functions for strawberry grown under protected field conditions. Using ground-based meteorological data and the FAO-56 Penman–Monteith method, reference and crop evapotranspiration were estimated across irrigation treatments imposed during a single cropping season, and the resulting ET*c* values were related to measured marketable fruit yield to derive mathematical production functions. Additional empirical relationships were developed between mean seasonal air temperature and yield, and between mean seasonal relative humidity and yield, to quantify the influence of treatment-induced microclimatic variation on crop productivity.

The study is bounded to a single cultivar of *Fragaria* × *ananassa* Duch. under a defined agro-climatic environment, while economic analysis, long-term climate projections, and biotic or nutritional stresses considered beyond its scope. The outcomes are intended to provide a scientifically defensible and practically applicable basis for ET-driven irrigation scheduling and yield prediction in strawberry production.

2. Materials and Methods

2.1. Experimental data

The experimental field trial was conducted at the Precision Farming Development Center (PFDC), CAET, Rajendra Prasad Central Agricultural University (RPCAU), Pusa, Samastipur, Bihar (25°59′ N, 85°48′ E, at an altitude of 52.92 m above mean sea level) near the southern and western banks of the Burhi Gandak River, during the cropping season of 2023–24. The region experiences a humid subtropical climate, strongly influenced by the southwest monsoon, and is characterized by hot, dry summers and cold winters. Mean annual rainfall is approximately 1270 mm, of which nearly 1026 mm falls during the monsoon period (June–October). Occasional winter precipitation occurs between late December and mid-January. The hottest months (May–June) record mean maximum temperatures of 37.5–40.6°C and mean minimum temperatures of 17.0–21.8°C, while January, the coldest month, records mean maximum and minimum temperatures of 23.1°C and 7.7°C, respectively. Relative humidity ranges from 80–95% during the monsoon to 40–60% in summer. Solar radiation peaks at approximately 650 ly/day in May and reaches its lowest at around 380 ly/day in December.

Meteorological data were recorded from December 22, 2023 to April 28, 2024 at RPCAU's Agrometeorology Division. Total precipitation was 15.74 mm; mean maximum and minimum air temperatures ranged from 15.69–39.2°C and 7.64–21.3°C, respectively; relative humidity ranged from 61.0–98.6% (morning) and 28.9–83.7% (afternoon); and mean daily pan evaporation varied between 0.9–9.2 mm day^{-1}.

Table 1:Weekly meteorological data recorded during experimental period (December, 2023 to April, 2024)

Week No.	Tmax, (^{0}C)	Tmin, (^{0}C)	RH, (%) Morning	RH, (%) Afternoon	Wind speed (km/hr)	Rainfall (mm)
			December			
51	24.2	9.1	97	52	-	0
52	23.9	11.7	97	70	-	0
			January			
1	19.52	11.08	97.43	68.29	6.33	0
2	17.8	10.17	98.57	70	7.4	0
3	15.69	8.98	96.67	83.67	5.42	0
4	16.01	7.64	97.14	74.57	5.54	0
5	22.59	8.25	96.86	55.57	7.17	0.17
			February			
6	22.1	9.7	95.9	57.9	0.0	2.3
7	24.7	11.7	98.4	62.1	0.2	1.9
8	26.2	12.7	92.0	51.9	0.5	2.5
9	26.8	12.6	94.7	52.4	0.1	2.8
			March			
10	26.6	12.1	90.4	47.9	12.8	0.0
11	31.0	13.8	89.9	42.4	12.1	0.0
12	28.4	16.4	92.1	60.3	4.8	6.1

13	31.6	19.9	87.1	55.1	6.4	0.0
			April			
14	36.5	19.3	70.4	31.7	13.8	0.0
15	35.9	19.5	77.1	40.3	4.1	0.0
16	37.9	21.1	76.4	33.9	15.7	0.0
17	39.2	21.3	61.0	28.9	18.0	0.0

Soil samples (0–50 cm depth) were collected from multiple points across the experimental area using a soil auger and composited to create a representative sample for chemical analysis. The soil was rich in nitrogen but deficient in organic carbon, potassium, and phosphorus shown in Table: 2.

Table 2:Physical properties of soil

Soil type		**Sandy clay loam (Sand - 63.02 %), (Silt- 23.25 %), (Clay-13.73 %)**
Particulars		**Content**
pH		8.38
Electrical Conductivity (ds m^{-1})		0.20
Particle density (g cm^{-3})		2.65
Bulk density (g cm^{-3})	At 0-15 cm	1.25
	At 15-30 cm	1.31
Gravimetric moisture content (%)	At 0-15 cm	20
	At 15-30 cm	16
Organic carbon (%)		0.78
Available nitrogen (kg ha^{-1})		155.40
Available phosphorus (kg ha^{-1})		89.56
Available potassium (kg ha^{-1})		165.54

The experiment was conducted on strawberry (*Fragaria* × *ananassa* Duchesne), variety Winter Dawn, belonging to the family Rosaceae. The experimental design adopted was a Randomized Block Design (RBD) comprising six treatments with four replications, resulting in a total of 24 treatment plots. The crop duration extended over 130 days, with plants maintained at a spacing of 35 cm × 30 cm (row-to-row × plant-to-plant). Each raised bed measured 5.375 m in length and 0.8 m in width, and the total field area under experimentation was 31 m^2. Details of the treatments in Tables: 3.

Table 3: Treatment details

Treatments	**Details**
T1	Control
T2	Plastic Mulch
T3	Plastic Mulch + Poly tunnel
T4	Poly tunnel
T5	Straw Mulch
T6	Straw Mulch + Poly tunnel

Two mulching treatments were evaluated: black plastic mulch and paddy straw mulch. The black plastic mulch had a thickness of 25 microns. Planting holes were made in the plastic mulch at a spacing of 0.30 m × 0.35 m, and a pair of drip laterals serving two crop rows was laid beneath the mulch in each plot.

Bed preparation was completed on 21st December 2023, and transplanting was carried out on 22nd December 2023. Healthy runners of the *Winter Dawn* variety of bearing 5–6 true leaves were transplanted. Irrigation was applied immediately after transplanting to facilitate establishment. Nutrients were applied at 120% of the Recommended Dose of Fertilizer, corresponding to 96:120:84 kg N:P:K ha^{-1}, in addition to farmyard manure (FYM) at 40 tonnes per hectare to improve soil organic matter, structure, and microbial activity. Soluble fertilizers were delivered through the drip system (fertigation) at 7-day intervals throughout the crop growth period to ensure a steady, stage-specific nutrient supply. The experimental field was divided into 24 blocks for uniform distribution of the total fertilizer dose across fertigation events. This approach was intended to promote resource use efficiency, minimize nutrient losses, and optimize crop yield while maintaining soil health. Pest and disease management followed standard recommendations for the region. Soil-borne pests, including white grubs and cutworms, were managed by ensuring planting fields were free from infestation prior to transplanting. Malathion (0.05%) was applied as needed upon appearance of hairy caterpillars. Cultural operations including earthing up, weeding, and hoeing were performed at appropriate growth stages, with gap filling carried out in transplanted plots to maintain plant populations.

2.2. Drip Irrigation System

A drip irrigation system was installed using a 500-liter overhead water tank supplied by a 3 HP electric motor, positioned at a height of 4 feet to maintain operating pressure. The main pipeline was 75 mm in diameter and 6 m in length, connected to a 63 mm diameter, 6 m sub-main pipeline. Twelve laterals, each 5.4 m in length and 16 mm in diameter, were connected to the sub-main. Inline emitters with a discharge rate of 2 liters per hour (lph) were spaced 30 cm apart along each lateral, corresponding to the plant spacing. A regulating valve was installed at the head of the mainline to maintain consistent operating pressure. Emitter discharge rates were determined by positioning graduated containers beneath each emitter and allowing water to flow for one hour. The volume of water collected in each container was subsequently measured using a graduated cylinder, and the regulating valve was adjusted until the desired emitter discharge rate was achieved.

2.3. Crop Water Requirement and ET Estimation

2.3.1.Reference Evapotranspiration (ET_0)

Daily reference evapotranspiration was estimated using the FAO-56 Penman–Monteith equation:

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,\frac{900}{T + 273}\,u_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,u_2)}$$

where ET_0 is the reference evapotranspiration rate (mm day^{-1}), R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), T is the mean daily air temperature at 2 m height (°C), u_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), Δ is the slope of the vapour pressure curve (kPa $°C^{-1}$), and γ is the psychrometric constant (kPa $°C^{-1}$).

The supporting parameters were derived as follows. Saturation vapour pressure was computed as:

$$0.6108 \exp\left[\frac{17.27T}{T + 237.3}\right]$$

Actual vapour pressure was obtained from relative humidity measurements:

$$e_s \left[\frac{RH}{100}\right]$$

The vapour pressure deficit (VPD) was given by:

$$(e_s - e_a)$$

The slope of the vapour pressure curve was calculated as:

$$= \frac{4098\left[0.6108 \exp\left(\frac{17.27 \times T}{T \times 237.3}\right)\right]}{(T + 273.3)^2}$$

The psychrometric constant was determined by:

$$= \frac{C_p}{\varepsilon\lambda}$$

where C_p is the specific heat at constant pressure (1.013×10^{-3} MJ kg^{-1} °C^{-1}), P is atmospheric pressure (kPa), and λ is the latent heat of vaporization (2.45 MJ kg^{-1}).

Air temperature and relative humidity were recorded twice daily using a Smart Sensor AR 300 Infrared Thermometer and a Kestrel 4000 pocket weather station, respectively. Wind speed at 2 m height was obtained from the Agrometeorology Division, RPCAU, and solar radiation data for the period December 2023 to April 2024 were sourced from NASA POWER. Soil heat flux (G) was assumed to be negligible on a daily time step, as heat absorbed by the soil during daytime is typically dissipated overnight (Allen *et al.*, 1998; Dohnal *et al.*, 2025).

2.3.2. Crop Evapotranspiration (ETc)

Crop evapotranspiration was estimated using the crop coefficient approach:

$$ET_c = ET_o \times K_c$$

where K_c is the crop coefficient specific to strawberry at different growth stages, as specified in FAO-56 (Allen *et al.*, 1998)(27). The daily crop water requirement for irrigation was subsequently calculated as:

$$WR = ET_c \times \eta_a$$

where η_a is the irrigation application efficiency, assumed to be 100% for the drip system.

2.4. Irrigation and Fertigation Scheduling

Irrigation was scheduled to supply water at 100% ETc for the full irrigation treatment, with other treatments receiving proportionally varied amounts as per the experimental design. Irrigation intervals were set at 7 days during the initial growth stage and reduced to 5 days during peak flowering and fruiting to align with elevated crop water

demand. Fertigation was performed weekly through the drip system using the 3 HP pump to inject soluble nutrients. The operational time of the drip system for each treatment was computed as (Agritech TNAU, 2020):

$$T = \frac{WR}{Q \times N_e}$$

where T is the operation time (hours), WR is the water requirement (liters per plot), Q is the average emitter discharge (lph), and N_e is the number of emitters per plot.

2.5. Statistical Analysis

Data were analyzed using a one-way Analysis of Variance (ANOVA) under the Randomized Complete Block Design (Pincus, 2014). The linear model employed was:

$$Y_{ij} = \mu + \tau_i + \beta_j + \varepsilon_{ij}$$

where Y_{ij} is the observed value, μ is the overall mean, τ_i is the effect of the i^{th} treatment, β_j is the effect of the j^{th} block, and ε_{ij} is the random error term. The F-statistic was computed to assess significant differences among treatment means, with a significance threshold of $\alpha = 0.05$. The sum of squares (SS), degrees of freedom (df), mean squares (MS), and F-values were calculated for each source of variation. All computations were performed using MS-Excel.

2.6. Development of Production Functions

2.6.1.Water Productivity

Water productivity (WP) was calculated as the ratio of total marketable fruit yield to the total volume of irrigation water applied over the growing season (Cai and Rosegrant, 2003; Kijne, Barker and Molden, 2004):

$$WP = \frac{Y}{W}$$

where Y is the total marketable fruit yield (kg) and W is the total irrigation water applied (m^3). Since precipitation during the experimental period was minimal (15.74 mm) and rainfall was excluded from direct crop uptake within the polytunnel treatment, only applied irrigation water was considered in the computation of water productivity.

2.6.2.Crop Water Production Function (ET-Based)

Crop water production functions were developed by relating seasonal crop evapotranspiration (ETc) as a consumptive use index to the corresponding marketable fruit yield across treatment levels. This approach is considered more universally applicable than functions based on applied irrigation depth, as ET integrates the actual water consumed by the crop irrespective of site-specific soil, hydrological, or management conditions (Payero *et al.*, 2008). The best-fit production function was selected on the basis of the highest coefficient of determination (R^2) among linear, quadratic, and power regression models evaluated for the ET_c–yield relationship.

$$Y = f(ET_c)$$

2.6.3.Temperature and RH based Production Function

Temperature–yield and Relative Humidity–yield production functions were developed by relating mean seasonal air temperature and relative humidity (recorded per treatment plot using a Kestrel 4000 pocket weather station) to corresponding marketable fruit yields. For each, the best-fit model (linear, quadratic, or power) was selected based on the highest coefficient of determination (R^2).

3. Results

3.1. Crop Evapotranspiration and Water Application

Seasonal crop evapotranspiration (ETc) varied substantially across treatments, reflecting the influence of mulching and protected cultivation on crop water demand (Table 4). Control recorded the highest seasonal ETc, corresponding to a daily crop water requirement on higher side. In contrast, comibination of Plastic mulch and polytunnel exhibited the lowest ETc, representing a 40.5% reduction of daily water requirement compared to the control.

Table 4:Seasonal crop evapotranspiration and daily water requirement across treatments

Treatments	Seasonal ETc (mm)	Daily Water Requirement (L/plant/day)	Reduction vs Control (%)
T1: Control	679.62	1.351	—
T2: Plastic Mulch	608.41	1.209	10.5
T3: Plastic Mulch + Polytunnel	404.37	0.804	40.5
T4: Polytunnel	421.35	0.837	38.0
T5: Straw Mulch	621.22	1.234	8.6
T6: Straw Mulch + Polytunnel	419.16	0.833	38.3

Polytunnel treatments consistently demonstrated lower ETc values compared to non-polytunnel treatments. This reduction is attributable to the polytunnel's capacity to reduce wind speed to near-zero conditions and maintain elevated relative humidity within the protected environment, thereby suppressing evapotranspiration demand (Lei *et al.*, 2025). Among mulching treatments, plastic mulch proved more effective in reducing water loss compared to straw mulch, owing to the impermeable nature of the plastic surface versus the porous structure of straw(Li *et al.*, 2013). The combination of plastic mulch with polytunnel achieved the greater water conservation, indicating synergistic effects of these interventions on reducing crop water requirement.

Since effective rainfall during the experimental period was negligible, irrigation was applied based solely on ETc values calculated using the FAO-56 Penman-Monteith method combined with stage-specific crop coefficients.

3.2 Microclimate Modification

3.2.1 Soil Surface Temperature

During the initial 50 days, soil temperatures remained stable at 15–20°C across all treatments, followed by a steady increase with pronounced peaks exceeding 30°C around days 85 and 103 (Fig. 1). Control being highest where polytunnel treatments maintained consistently higher temperatures than mulches, where microclimate modifications failed to induce significant soil heating. By day 127, temperatures converged at 30–35°C, with control and T4 recording the highest values while plastic mulch remained lowest.

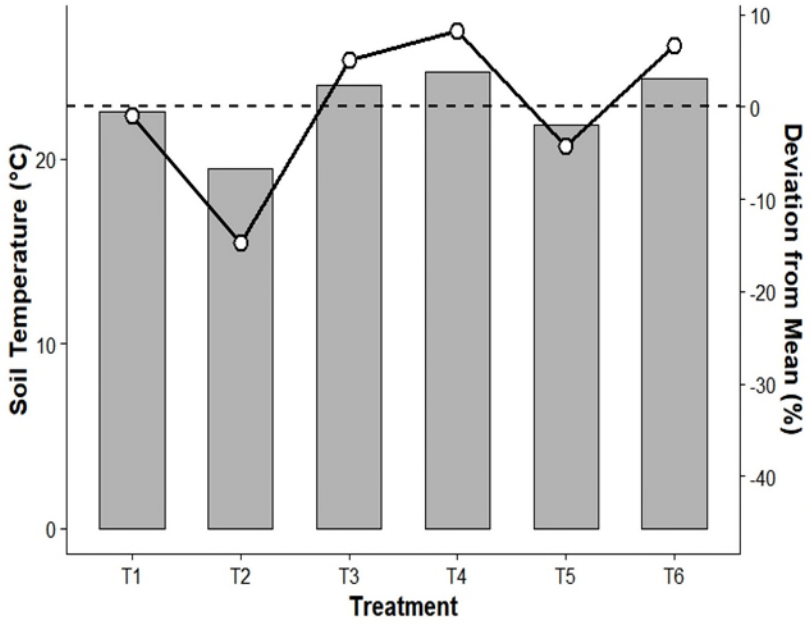


Figure 1: Soil temperature across treatments with mean deviation

The elevated soil temperatures in polytunnel treatments can be attributed to the greenhouse effect created by the polyethylene covering, which trapped incoming solar radiation and restricted convective heat loss, thereby warming the enclosed soil environment (Lei *et al.*, 2025). Conversely, plastic mulch recorded the lowest temperatures as the soil surface lacked direct exposure to solar radiation, limiting radiative heating(Tarara, 2000). T5 exhibited similarly lower temperatures due to the absence of an effective microclimate-modifying structure, leaving the soil susceptible to ambient temperature fluctuations and convective cooling. Mean soil temperature across the experiment was 22.83°C, with deviations ranging from T4 (+8.19%) and T6 (+6.70%) as the warmest treatments, to T2 (-14.72%) as the coldest. T1 (-1.01%) and T5 (-4.21%) remained near average.

These thermal differences likely enhanced soil biological activity, nutrient mineralization, and root development in warmer treatments (T3, T4, T6), potentially improving yields through optimized root expansion and nutrient uptake.

3.2.2 Relative Humidity

Relative humidity (RH) was monitored across polytunnel and non-polytunnel environments over 127 days after planting (Fig. 2). RH varied markedly between the two environments throughout the experimental period, with polytunnel treatments consistently maintaining higher levels (60–100%) compared to non-polytunnel conditions (40–80%), particularly during early and mid-growth stages. Multiple peaks exceeding 80% RH were frequently observed within polytunnels, whereas non-polytunnel treatments rarely surpassed this threshold. Both environments exhibited a gradual decline in RH as the season progressed, converging near 20% toward the end of the experimental period.

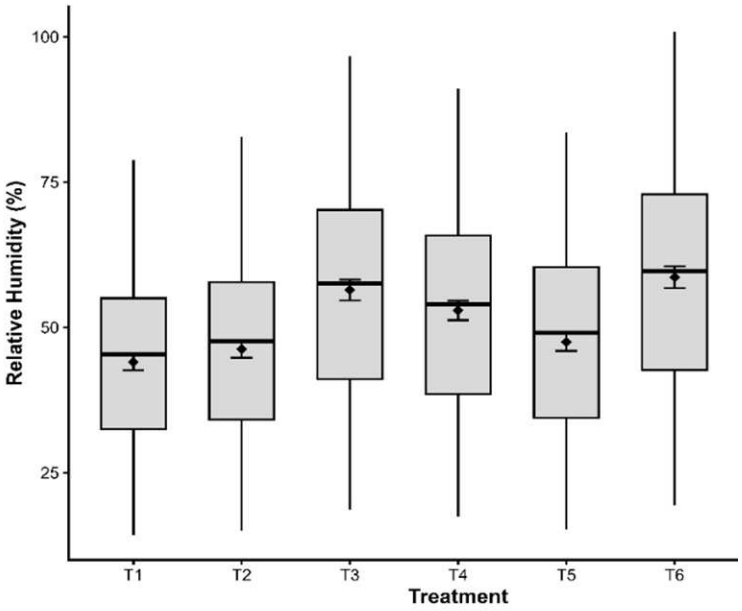


Figure 2: Relative humidity distribution across treatments

The elevated RH within polytunnels can be attributed to the enclosed structure limiting air exchange with the external environment, thereby reducing moisture loss through convective transport. The polyethylene covering restricted wind-driven evaporation from soil and plant surfaces while simultaneously trapping transpired moisture, creating a more humid microclimate. In contrast, the non-polytunnel setup remained exposed to ambient atmospheric conditions, resulting in greater moisture dissipation and consistently lower RH levels (Santosh, Tiwari and Singh, 2017; Lei *et al.*, 2025).

This enhanced moisture environment within polytunnels reduced plant water stress by decreasing vapor pressure deficit (VPD), thereby facilitating improved stomatal function, enhanced photosynthetic activity, and more efficient nutrient uptake. The stable and elevated RH conditions likely supported superior root development, overall growth performance, and potentially higher fruit yields by maintaining a more controlled and favorable microclimate for crop productivity.

3.3. Yield and Fruit Parameters

Fruit size parameters (length and breadth) and individual fruit weight showed numerical differences among treatments, though these were not statistically significant ($CD_{0.05}$ = NS) (Table: 5, Table: 6). Treatment T4 produced fruits with the greatest average length, while T2 exhibited the largest breadth. The control produced the smallest fruits. Average fruit weight ranged from 8.88 g (T1) to 9.30 g (T3), with T3 producing the heaviest individual fruits. Despite the lack of statistical significance, numerical trends suggest that protected cultivation and mulching treatments promoted superior fruit development.

Table 5: Yield, fruit size, and fruit weight across all the treatments. *Values are treatment means. SEm± = standard error of the mean; CD (5%) = critical difference at 5% level of significance; NS = not significant; CV (%) = coefficient of variation.*

Treatment	Yield (t ha⁻¹)	Fruit Length (mm)	Fruit Breadth (mm)	Fruit Weight (g)	Yield/Plant (g)
T1	11.09	23.19	20.85	8.88	116.92
T2	16.64	27.20	21.27	9.08	196.12
T3	26.21	27.10	21.13	9.30	265.95
T4	20.16	27.73	21.19	9.12	228.97
T5	16.62	24.77	21.13	8.96	188.67
T6	22.77	25.57	21.14	9.02	241.08
SEm±	0.870	1.068	1.131	0.516	8.510
CD (5%)	2.623	NS	NS	NS	25.651
CV (%)	9.20	8.24	10.76	11.40	8.25

In contrast, treatment effects were highly significant ($P < 0.01$) for yield and yield per plant (Table: 6). T3 recorded the highest yield, representing a 136.3% increase over the control, and was statistically superior to all other treatments. This was followed by T6 at 105.3% increase and T4 at 81.8% increase. T2 and T5 achieved comparable yields, representing approximately 50% yield improvement over the control. A similar trend was observed for yield per plant, where T3 recorded the maximum value, followed by T6 and T4.

Table 6: Analysis of variance (ANOVA) for strawberry yield, fruit size and weight parameters across treatments. *df = degrees of freedom; ** = significant at P < 0.01; NS = not significant.*

Source	df	Yield	Fruit Length	Fruit Breadth	Fruit Weight	Yield/Plant
Replications	3	4.773	5.385	5.215	0.399	58.571
Treatments	5	112.958**	12.202 NS	0.221 NS	0.083 NS	10947.035**
Error	15	3.030	4.567	5.118	1.067	289.662

The overall ranking of treatments for marketable yield was: T3 > T6 > T4 > T2 ≈ T5 > T1. These results demonstrate that polytunnel cultivation, particularly when combined with plastic mulch, substantially enhances strawberry productivity. The synergistic effect of polytunnel and mulching is evident, as combined treatments consistently outperformed individual interventions, indicating that the integration of microclimate modification through protected cultivation with soil moisture conservation via mulching creates a more favorable environment for maximizing fruit yield(Rathore *et al.*, 2026).

3.4. Water Productivity

Water productivity (WP), calculated as the ratio of marketable yield to total water applied, varied markedly across treatments (Table: 7). T3 demonstrated exceptional water productivity at 64.81 kg/m³ nearly four times greater than the control 16.32 kg/m³. This improvement reflects both substantially reduced water consumption, 40.5% less than control and significantly enhanced yield nearly 136.3% greater than control.

Table 7: Water applied, yield, water productivity (WP), and WP improvement for each treatment.

Treatment	Water Applied (mm)	Yield (kg/ha)	Water Productivity (kg/m³)	WP Improvement vs Control (%)
T1	679.62	11,091	16.32	—
T2	608.41	16,645	27.36	67.6
T3	404.37	26,207	64.81	297.2
T4	421.35	20,163	47.85	193.2
T5	621.22	16,620	26.75	63.9

T6	419.16	22,766	54.31	232.8

T6 achieved the second-highest water productivity 232.8% improvement over control, followed by T4 193.2% improvement. Non-polytunnel mulching treatments showed moderate improvements of approximately 65% over the control but were substantially less efficient than polytunnel-based treatments(Biswas *et al.*, 2015).

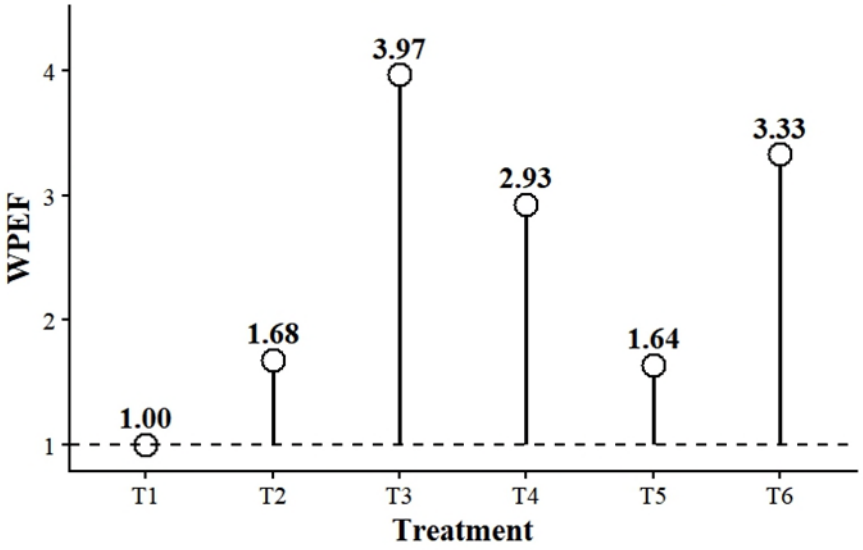


Figure 3: Water Productivity enhanement factor (WPEF)

The Water Productivity Enhancement Factor (WPEF), calculated as the ratio of treatment WP to control WP, provides a dimensionless metric for comparing water use efficiency across treatments (Figure: 3). The WPEF analysis confirms that T3 and T6 produces 3.97 and 3.33 times more yield per unit water respectively compared to control, underscoring the substantial water-saving potential of combined polytunnel and mulch systems. The reduced water application in polytunnel treatments can be attributed to the enclosed structure minimizing evaporative losses, while mulching further conserved soil moisture by reducing surface evaporation, collectively resulting in significantly improved water use efficiency across protected cultivation treatments.

3.5. Production Functions

3.5.1. Crop Water Production Function (ETc-Yield Relationship)

The relationship between seasonal crop evapotranspiration (ETc) and marketable yield was evaluated using linear, quadratic, and cubic regression models. The cubic polynomial function provided the best fit ($R^2 = 0.8912$) and was selected as the crop water production function for strawberry under the experimental conditions (Figure: 4).

$$Y = -6 \times 10^{-6}x^3 + 0.0097x^2 - 5.3492x + 987.23$$

($R^2 = 0.8912$), Where Y represents marketable yield (kg ha^{-1}) and x represents seasonal crop evapotranspiration (mm).

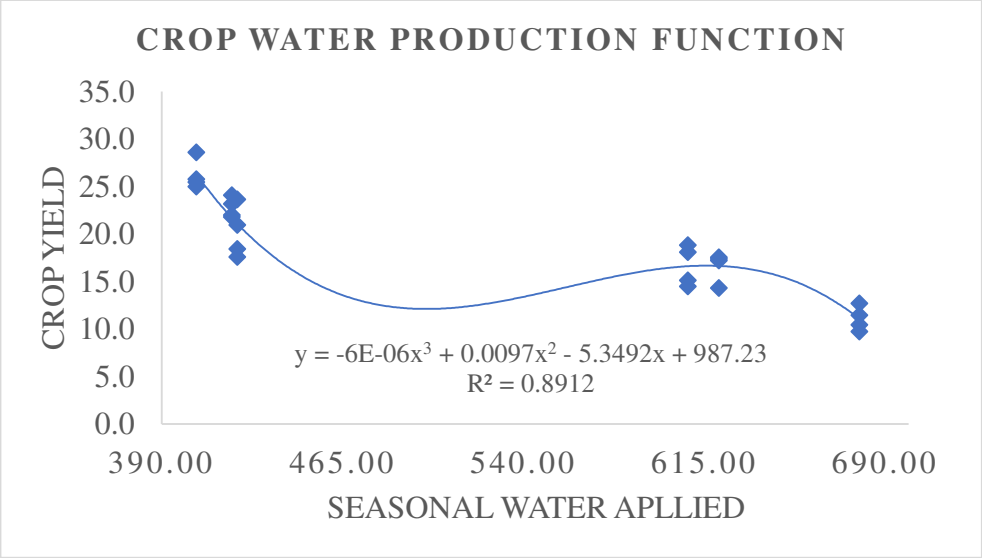


Figure 4: Relation between Crop water Requirement and Crop yield

The production function revealed a non-linear relationship between evapotranspiration (ETc) and strawberry yield, with maximum yields observed at low ETc levels (404–420 mm) under polytunnel conditions, contrary to conventional expectations. A cubic model (R^2 = 0.8912) delineated four phases: (i) high yield at low ETc due to optimized microclimates in polytunnels; (ii) declining yield with increasing ETc (420–600 mm) as microclimate benefits diminish; (iii) moderate yield recovery (600–620 mm) in mulched, open-field treatments; and (iv) yield decline beyond 620 mm, particularly in unmulched controls. These results demonstrate that polytunnel and mulch systems can achieve higher water productivity, challenging the assumption that increased irrigation universally enhances yield(Biswas *et al.*, 2015).

3.5.2. Temperature-Yield Production Function

The relationship between mean seasonal air temperature and marketable yield was evaluated using polynomial regression models (Fig. 3.4). The fourth-order polynomial function provided the best fit (R^2 = 0.8544), confirming temperature as a significant determinant of strawberry yield under the experimental conditions.

Maximum yield occurred at approximately 20°C mean seasonal temperature. Yields increased from 15°C to 20°C but declined sharply beyond 23°C, indicating thermal stress on fruit development. A minor yield recovery was observed at higher temperatures, though productivity remained substantially below the 20°C optimum. This suggests that strawberry cv. *Winter Dawn* is well-adapted to cooler conditions but experiences stress during late-season temperature elevations typical of subtropical Bihar. Polytunnel treatments-maintained conditions closer to the thermal optimum, contributing to superior yields under protected cultivation(Palencia *et al.*, 2013; Bhamini *et al.*, 2017).

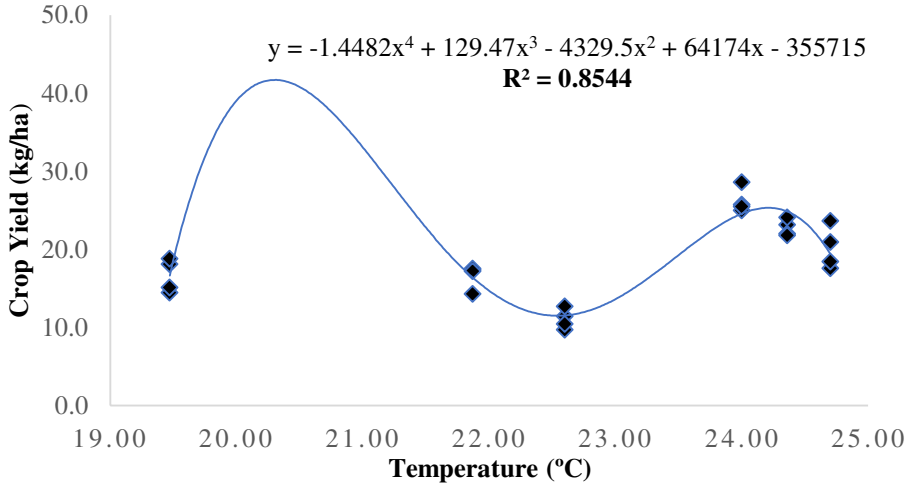


Figure 5: Temperature versus Yield Production Function

The strong coefficient of determination (R^2 = 0.8544) indicates that the fourth-order polynomial function reliably predicts strawberry yield responses to temperature variations. This underscores the value of protected cultivation for controlling microclimate and improving productivity in subtropical conditions

3.5.3. Relative Humidity-Yield Production Function

The relationship between mean seasonal relative humidity (RH) and marketable yield was evaluated using polynomial regression models (Fig. 3.5). The cubic polynomial function provided the best fit (R^2 = 0.7698), indicating a significant though comparatively moderate influence of RH on strawberry yield under the experimental conditions.

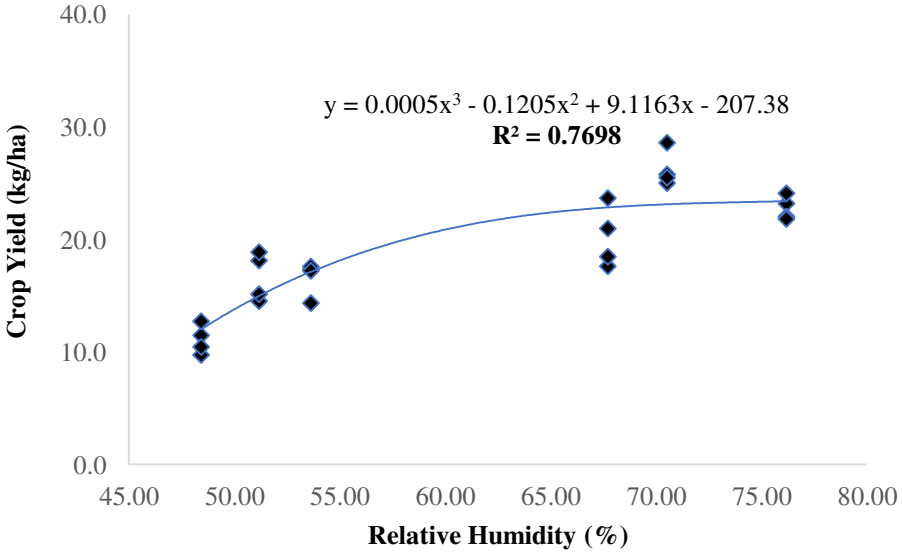


Figure 6: Relative Humidity v/s Yield Production Function

The production function revealed that yield increased progressively with relative humidity up to approximately 65–70%, beyond which diminishing returns were observed(Lieten, 2002). This trend indicates that moderate humidity

levels support optimal plant physiological function, including efficient stomatal regulation, photosynthetic activity, and nutrient uptake. However, excessively high humidity levels (>75%) did not contribute additional yield benefits and may instead promote conditions conducive to fungal disease development, potentially offsetting any physiological advantages of elevated moisture availability(Rossi *et al.*, 2020).

The lower coefficient of determination (R^2 = 0.7698) indicates that while RH influences yield, other factors—including temperature, soil moisture, and nutrient availability—also contribute substantially to yield variation. The function suggests that maintaining RH within 65–70% during critical growth stages optimizes physiological conditions and minimizes disease pressure in protected strawberry cultivation under subtropical conditions.

3.6. Principal Component Analysis

Principal Component Analysis (PCA) was performed to identify the dominant environmental gradients influencing strawberry yield across treatments. The first two principal components collectively explained 98.3% of the total variance, with PC1 accounting for 84.3% and PC2 contributing an additional 14% (Figure: 7).

PC1 was strongly associated with ETc and RH (contributions of ~27% each), representing a water-microclimate gradient that distinguished water-efficient protected cultivation from water-intensive open-field conditions. Temperature and yield contributed approximately 23% and 22% respectively to PC1, indicating that this component captured a holistic environmental-productivity gradient. PC2 was primarily driven by yield (~43%) and temperature (~38%), representing residual temperature-yield interactions not explained by the primary microclimate gradient.

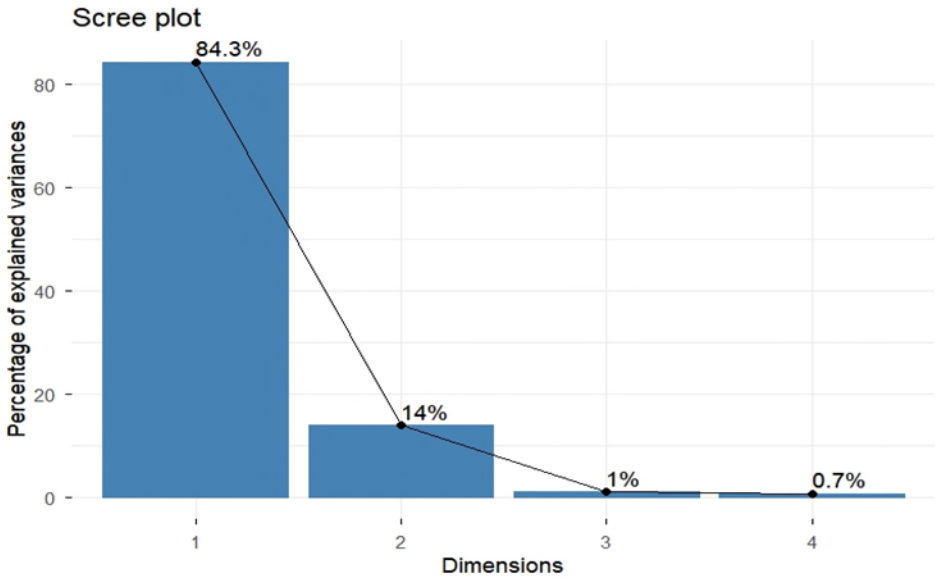


Figure 7: Scree plot- Percentage of explained variances versus Dimensions

The PCA biplot (Figure: 8) revealed clear spatial separation between polytunnel treatments (T3, T4, T6) and non-polytunnel treatments (T1, T2, T5) along PC1. Polytunnel treatments clustered on the positive side of PC1, associated with lower ETc, higher RH, and superior yields, while non-polytunnel treatments occupied the negative side, characterized by higher evapotranspirative demand and lower productivity. The ETc vector was oriented in direct

opposition to yield and RH vectors, confirming the strong inverse relationship between water consumption and crop productivity under the experimental conditions.

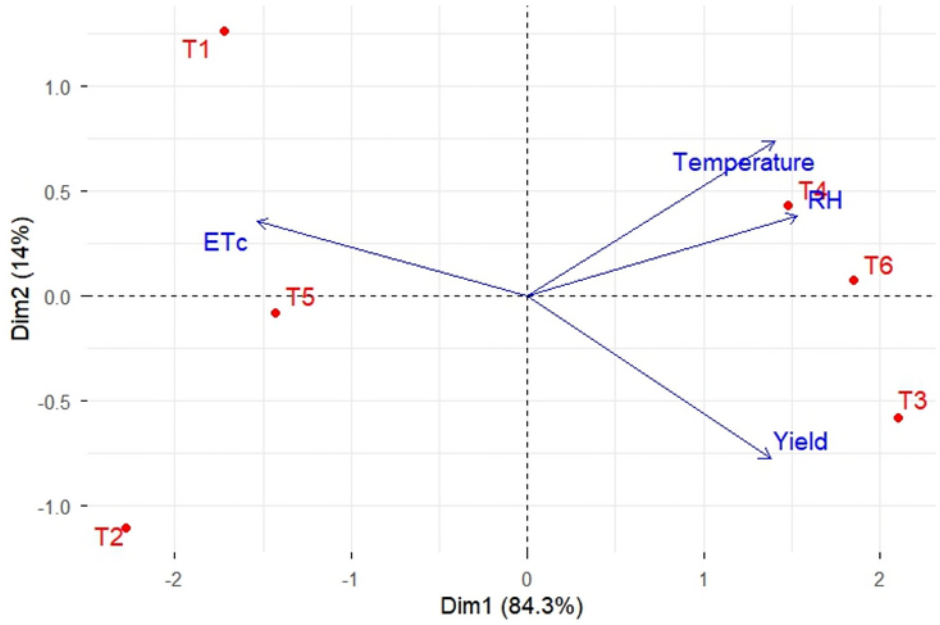


Figure 8:PCA biplot- Environmental Variables and Yield

Treatment T3 (Plastic Mulch + Polytunnel) occupied the extreme positive position on PC1 with the highest yield and lowest ETc, while T1 (control) was positioned at the extreme negative end with the lowest yield and highest water consumption. These findings confirm that the protected microclimate created by polytunnel cultivation—characterized by reduced evapotranspiration, elevated humidity, and optimized temperature—was the principal driver of yield variation across treatments.

4. Conclusion

The research found that combining plastic mulch with a polytunnel was the most effective intervention, reducing seasonal crop water use by 40.5% from 679.62 mm in the control plot to just 404.37 mm. Critically, this significant water saving did not come at the cost of yield. Instead, the modified microclimate within the polytunnel characterized by higher relative humidity and warmer soil temperatures created ideal growing conditions. This resulted in a dramatic yield increase to 26.21 t ha^{-1} under T3, a 136.3% improvement over the control yield of 11.09 t ha^{-1}. Consequently, water productivity soared. Combination of plastic mulch and polytunnel system achieved a water productivity of 64.81 kg of fruit per cubic meter of water, nearly four times the efficiency of conventional open-field cultivation (16.32 kg m^{-3}). The analysis revealed an unconventional, cubic relationship between ETc and yield (R^2 = 0.8912), where maximum yields were achieved at the lowest levels of water consumption, challenging the traditional assumption that more water always leads to higher output. The calculated crop yield response factor (Ky) further confirmed the system's resilience; yields under polytunnels were insensitive to reduced ET, whereas open-field plots showed high vulnerability to water stress. In summary, integrating protected cultivation with ET-based irrigation

scheduling decouples yield from high water consumption, offering a powerful strategy for sustainable, high-productivity strawberry farming in water-scarce regions.

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Competing Interests

The authors declare that they have no financial or non-financial competing interests. The authors have no relevant financial or non-financial interests to disclose that are directly or indirectly related to the work submitted for publication.

Ethics Approval

This research was conducted as an agronomic field trial involving the cultivation of strawberry (*Fragaria × ananassa Duch.*) and does not involve human subjects, human participants' data, or biological material requiring ethics committee approval. The experimental field trial was conducted in accordance with the institutional guidelines and standard agricultural research protocols of Dr. Rajendra Prasad Central Agricultural University. All experimental procedures followed standard horticultural and agronomic practices in accordance with the approved research framework of the Department of Soil and Water Conservation Engineering, RPCAU.

References

Adak, N., Gubbuk, H. and Tetik, N. (2018) "Yield, quality and biochemical properties of various strawberry cultivars under water stress," *Journal of the Science of Food and Agriculture*, 98(1), pp. 304–311. Available at: https://doi.org/10.1002/jsfa.8471.

Agritech TNAU (2020) *Minor Irrigation: Drip Irrigation*. Agritech Portal. Available at: https://agritech.tnau.ac.in/banking/pdf/Minor%20Irrigation_Drip%20Irrigation.pdf.

Allen, R. *et al.* (1998) "FAO Irrigation and drainage paper No. 56," *Rome: Food and Agriculture Organization of the United Nations*, 56, pp. 26–40.

Allen, R.G. (1998) "Crop evapotranspiration : guidelines for computing crop water requirements," *FAO Irrig Drain*, 56, pp. 147–151. Available at: https://cir.nii.ac.jp/crid/1570291225073354368.

Ansarifar, J., Wang, L. and Archontoulis, S. V (2021) "An interaction regression model for crop yield prediction," *Scientific Reports*, 11(1), p. 17754. Available at: https://doi.org/10.1038/s41598-021-97221-7.

Bhamini, K. *et al.* (2017) "Influence of Planting Dates and Temperature on Plant Growth, Flowering and Fruiting of Strawberry in Agro Climatic Condition of Bihar, India," *International Journal of Current Microbiology and Applied Sciences*, 6(8), pp. 3184–3191. Available at: https://doi.org/10.20546/ijcmas.2017.609.392.

Biswas, B. *et al.* (2024) "Modelling the impact of different irrigation regimes and mulching on strawberry crop growth and water use in the arsenic-contaminated Bengal basin," *Scientific Reports*, 14(1), p. 9586. Available at: https://doi.org/10.1038/s41598-024-56664-4.

Biswas, S.K. *et al.* (2015) “Effect of drip irrigation and mulching on yield, water-use efficiency and economics of tomato,” *Plant, Soil and Environment*, 61(3), pp. 97–102. Available at: https://doi.org/10.17221/804/2014-PSE.

Brouwer, C. and Heibloem, M. (1985) *Irrigation water management training manual no.3 irrigation water needs*. Available at: https://api.semanticscholar.org/CorpusID:134919637.

Cai, X. and Rosegrant, M. (2003) “World water productivity: current situation and future options.,” pp. 163–178. Available at: https://doi.org/10.1079/9780851996691.0163.

Celiktopuz, E. *et al.* (2023) “Yield, quality and physiological variation of strawberry in response to irrigation regimes and exogenous proline with a cost benefit analysis,” *Plant Physiology and Biochemistry*, 195, pp. 238–246. Available at: https://doi.org/https://doi.org/10.1016/j.plaphy.2023.01.011.

Dohnal, M. *et al.* (2025) “The role of ground heat flux in estimating evapotranspiration by the Penman-Monteith method on mountain meadow,” *Soil and Water Research*, 20(4), pp. 265–273. Available at: https://doi.org/10.17221/24/2025-swr.

Doorenbos, J. and Kassam, A. (1979) *FAO Irrigation and Drainage Paper 33*, *Yield Response to Water*.

Elliott, J. *et al.* (2014) “Constraints and potentials of future irrigation water availability on agricultural production under climate change,” *Proceedings of the National Academy of Sciences*, 111(9), pp. 3239–3244. Available at: https://doi.org/10.1073/pnas.1222474110.

Frakolaki, G. *et al.* (2026) “Comparative climate change impacts of different strawberry cultivation systems in Southeastern Europe: A study across open-field and protected cultivation systems towards sustainable production models,” *Journal of Agriculture and Food Research*, 26, p. 102589. Available at: https://doi.org/https://doi.org/10.1016/j.jafr.2025.102589.

Gavilán, P., Ruiz, N. and Lozano, D. (2015) “Daily forecasting of reference and strawberry crop evapotranspiration in greenhouses in a Mediterranean climate based on solar radiation estimates,” *Agricultural Water Management*, 159, pp. 307–317. Available at: https://doi.org/https://doi.org/10.1016/j.agwat.2015.06.012.

Gonzalez-Fuentes, J.A. *et al.* (2016) “Diurnal root zone temperature variations affect strawberry water relations, growth, and fruit quality,” *Scientia Horticulturae*, 203, pp. 169–177. Available at: https://doi.org/https://doi.org/10.1016/j.scienta.2016.03.039.

He, L. and Rosa, L. (2023) “Solutions to agricultural green water scarcity under climate change,” *PNAS Nexus*, 2(4), p. pgad117. Available at: https://doi.org/10.1093/pnasnexus/pgad117.

Hernández-Martínez, N.R. *et al.* (2023) “Current state and future perspectives of commercial strawberry production: A review,” *Scientia Horticulturae*, 312, p. 111893. Available at: https://doi.org/https://doi.org/10.1016/j.scienta.2023.111893.

Igbadun, H.E. *et al.* (2007) “Evaluation of selected crop water production functions for an irrigated maize crop,” *Agricultural Water Management*, 94(1), pp. 1–10. Available at: https://doi.org/https://doi.org/10.1016/j.agwat.2007.07.006.

Ingrao, C. *et al.* (2023) “Water scarcity in agriculture: An overview of causes, impacts and approaches for reducing the risks,” *Heliyon*, 9(8). Available at: https://doi.org/10.1016/j.heliyon.2023.e18507.

Itier, B. *et al.* (1996) “Applicability and limitations of irrigation scheduling methods and techniques,” in M. Smith et al. (eds.) *Irrigation scheduling: From theory to practice*. Rome: Food and Agriculture Organization, pp. 19–32.

Jensen, M.E. (1968) “Water consumption by agricultural plants,” *Water deficits and plant growth, 2*, pp. 1–22.

Keller, A. (2012) “Evapotranspiration and Crop Water Productivity: Making Sense of the Yield-ET Relationship,” *Impacts of Global Climate Change*. American Society of Civil Engineers (Proceedings), pp. 1–11. Available at: https://doi.org/10.1061/40792(173)528.

Kijne, J., Barker, R. and Molden, D. (2004) “Water productivity in agriculture: limits and opportunities for improvement.” Available at: https://doi.org/10.1079/9780851996691.0000.

Kim, S.K. *et al.* (2009) “INFLUENCE OF WATER STRESS ON FRUIT QUALITY AND YIELD OF STRAWBERRY CVS. ‘MAEHYANG’ AND ‘SEOLHYANG,’” *Acta Horticulturae*. International Society for Horticultural Science (ISHS), Leuven, Belgium, pp. 177–180. Available at: https://doi.org/10.17660/ActaHortic.2009.842.23.

Klocke, N. *et al.* (1990) “G90-992 Evapotranspiration (ET) or Crop Water Use.”

Lei, W. *et al.* (2025) “Study on thermal and humidity environmental characteristics and predictive temperature modeling for power cabins in utility tunnels,” *Thermal Science and Engineering Progress*, 66, p. 104020. Available at: https://doi.org/https://doi.org/10.1016/j.tsep.2025.104020.

Li, S.X. *et al.* (2013) “Effect of plastic sheet mulch, wheat straw mulch, and maize growth on water loss by evaporation in dryland areas of China,” *Agricultural Water Management*, 116, pp. 39–49. Available at: https://doi.org/https://doi.org/10.1016/j.agwat.2012.10.004.

Lieten, P. (2002) “THE EFFECT OF HUMIDITY ON THE PERFORMANCE OF GREENHOUSE GROWN STRAWBERRY,” *Acta Horticulturae*, (567), pp. 479–482. Available at: https://doi.org/10.17660/actahortic.2002.567.101.

Martínez-Ferri, E. *et al.* (2016) “Water relations, growth and physiological response of seven strawberry cultivars (Fragaria×ananassa Duch.) to different water availability,” *Agricultural Water Management*, 164, pp. 73–82. Available at: https://doi.org/https://doi.org/10.1016/j.agwat.2015.08.014.

Megha Raghavan (2025) “Smart water management in horticultural crops: A review,” *Plant Archives*, 25(1). Available at: https://doi.org/10.51470/plantarchives.2025.v25.no.1.241.

Menzel, C.M. (2025) “A review of strawberry under protected cultivation: yields are higher under tunnels than in the open field,” *The Journal of Horticultural Science and Biotechnology*, 100(3), pp. 286–313. Available at: https://doi.org/10.1080/14620316.2024.2449026.

Morillo, J.G. *et al.* (2015) “Toward precision irrigation for intensive strawberry cultivation,” *Agricultural Water Management*, 151, pp. 43–51. Available at: https://doi.org/https://doi.org/10.1016/j.agwat.2014.09.021.

Palencia, P. *et al.* (2013) “Strawberry yield efficiency and its correlation with temperature and solar radiation,” *Horticultura Brasileira*, 31.

Payero, J.O. *et al.* (2008) “Effect of irrigation amounts applied with subsurface drip irrigation on corn evapotranspiration, yield, water use efficiency, and dry matter production in a semiarid climate,” *Agricultural Water Management*, 95(8), pp. 895–908. Available at: https://doi.org/https://doi.org/10.1016/j.agwat.2008.02.015.

Pereira, L.S. *et al.* (2015) “Crop evapotranspiration estimation with FAO56: Past and future,” *Agricultural Water Management*, 147, pp. 4–20. Available at: https://doi.org/https://doi.org/10.1016/j.agwat.2014.07.031.

Pincus, L. (2014) *Statistics 2: RCBD review (with input from M. Bell & R. Plant)*. Agriculture Innovation Program, University of California, Davis. Available at: https://epakag.ucdavis.edu/media/vocational/man-stats-rcbd.pdf.

Prochnow, A. *et al.* (2012) “Water use indicators at farm scale: methodology and case study,” *Food and Energy Security*, 1(1), pp. 29–46. Available at: https://doi.org/10.1002/fes3.6.

Rathore, A.C. *et al.* (2026) "Integration of mulch and liquid fertilizer improves productivity and quality of strawberries in the north-western Himalayas, India," *Frontiers in Agronomy*, Volume 8-2026. Available at: https://www.frontiersin.org/journals/agronomy/articles/10.3389/fagro.2026.1781888.

Robertson, S.M. *et al.* (2013) "Estimating yield response to temperature and identifying critical temperatures for annual crops in the Canadian prairie region," *Canadian Journal of Plant Science*, 93(6), pp. 1237–1247. Available at: https://doi.org/10.4141/cjps2013-125.

Rossi, F.G. *et al.* (2020) "Effect of Water Stress on Reproduction and Colonization of *Podosphaera aphanis* of Strawberry," *Plant Disease*, 104(11), pp. 2973–2978. Available at: https://doi.org/10.1094/pdis-10-19-2172-re.

Roy, S. *et al.* (2024) "Precision water management for resource conservation in India's dryland agriculture: Strategies and technologies," *International Journal of Environment and Climate Change*, 14(8), pp. 464–480. Available at: https://doi.org/10.9734/ijecc/2024/v14i84367.

Santosh, D.T. (2021) "Estimation of irrigation water requirement of strawberry crop under polyhouse and shadenet house conditions," *International Journal of Agricultural Sciences*, 17(2), pp. 617–619. Available at: https://doi.org/10.15740/has/ijas/17.2/617-619.

Santosh, D.T., Tiwari, K.N. and Singh, V.K. (2017) "Influence of different protected cultivation structures on water requirements of winter vegetables," *International Journal of Agriculture Environment and Biotechnology*, 10(1), p. 93. Available at: https://doi.org/10.5958/2230-732x.2017.00004.3.

Singh, M. *et al.* (2021) "A global meta-analysis of yield and water productivity responses of vegetables to deficit irrigation," *Scientific Reports*, 11(1), p. 22095. Available at: https://doi.org/10.1038/s41598-021-01433-w.

Smith, M. and Steduto, P. (2012) "Yield response to water: the original FAO water production function," *FAO Irrigation and Drainage Paper*, (66), pp. 6–13.

Song, X. *et al.* (2021) "Effect of vapor pressure deficit on growth and water status in muskmelon and cucumber," *Plant Science*, 303, p. 110755. Available at: https://doi.org/https://doi.org/10.1016/j.plantsci.2020.110755.

St Fort, J. *et al.* (2025) "Micro-irrigation systems for water conservation during establishment and freeze protection in Florida strawberry production," *Scientia Horticulturae*, 350, p. 114368. Available at: https://doi.org/https://doi.org/10.1016/j.scienta.2025.114368.

Stewart, J.I. *et al.* (1977) "Optimizing crop production through control of water and salinity levels in the soil." Available at: https://digitalcommons.usu.edu/water_rep/67.

Sun, X. *et al.* (2024) "Research on methods for estimating reference crop evapotranspiration under incomplete meteorological indicators," *Frontiers in Plant Science*, 15, p. 1354913. Available at: https://doi.org/10.3389/fpls.2024.1354913.

Tarara, J.M. (2000) "Microclimate modification with plastic mulch," *HortScience*, 35(2), pp. 169–180.

Thomas, B., Mutayoba, E. and Makungu, E. (2025) "Evaluation of crop yield response to water use efficiency in the chauru irrigation scheme, Tanzania," *Journal of Geoscience and Environment Protection*, 13(09), pp. 47–74. Available at: https://doi.org/10.4236/gep.2025.139004.

Varzi, M.M. (2016) "Crop water production functions—A review of available mathematical method," *Journal of Agricultural Science*, 8(4), p. 76. Available at: https://doi.org/10.5539/jas.v8n4p76.

Vu, S.H., Watanabe, H. and Takagi, K. (2005) "Application of FAO-56 for evaluating evapotranspiration in simulation of pollutant runoff from paddy rice field in Japan," *Agricultural Water Management*, 76(3), pp. 195–210. Available at: https://doi.org/https://doi.org/10.1016/j.agwat.2005.01.012.

Zhao, C. *et al.* (2017) “Temperature increase reduces global yields of major crops in four independent estimates,” *Proceedings of the National Academy of Sciences*, 114(35), pp. 9326–9331. Available at: https://doi.org/10.1073/pnas.1701762114.

Zotarelli, L. *et al.* (2024) “Step by Step Calculation of the Penman-Monteith Evapotranspiration (FAO-56 Method): AE459, 2/2010,” *EDIS*, 2010. Available at: https://doi.org/10.32473/edis-ae459-2010.