Improving water productivity of sprinkler-irrigated cumin through deficit irrigation in arid areas postprint

Authors: Hari Mohan MEENA, Deepesh MACHIWAL, Priyabrata SANTRA, Vandita KUMARI, Saurabh SWAMI, Hari Mohan MEENA

Date: 2025-07-07T00:00:00+00:00

Abstract

Integrating sprinkler with deficit irrigation system is a new approach to improve crop water productivity and ensure water and food security in arid areas of India. This study undertook a field experiment of sprinkler-irrigated cumin (variety GC-4) with a mini-lysimeter setup at an experimental research farm in Jodhpur, India during 2019–2022. Four irrigation treatments T1, T2, T3, and T4 were designed at irrigation water/cumulative pan evaporation (IW/CPE) of 1.0, 0.8, 0.6, and 0.4, respectively, with three replications. Daily actual crop evapotranspiration (ETc) was recorded and weekly soil moisture was monitored over the crop growth period. Quantities of applied water and drainage from mini-lysimeters were also measured at every irrigation event. Yield of cumin was recorded at crop maturity. Furthermore, change in farmer' s net income from 1-hm2 land was computed based on the cost of applying irrigation water and considering yield variations among the treatments. Results indicated the highest mean seasonal actual ETc (371.7 mm) and cumin yield (952.47 kg/hm2) under T1 (with full irrigation). Under T2, T3, and T4, the seasonal actual ETc decreased by 10.4%, 27.6%, and 41.3%, respectively, while yield declined by 5.0%, 28.4%, and 50.8%, respectively, as compared to the values under T1. Furthermore, crop water productivity of 0.272 ($±$0.068) kg/m3 under T2 was found relatively higher in comparison to other irrigation treatments, indicating that T2 can achieve improved water productivity of cumin in arid areas at an optimum level of deficit irrigation. The results of cost-economics indicated that positive change in farmer' s net income from 1-hm2 land was 108.82 USD under T2, while T3 and T4 showed net losses of 5.33 and 209.67 USD, respectively. Moreover, value of yield response factor and ratio of relative yield reductions to relative ETc deficits were found to be less than 1.00 under T2 (0.48), and more than 1.00 under T3 (1.07) and T4 (1.23). This finding further supports that T2 shows the optimized level of deficit irrigation that saves 20.0% of water with sacrificing 5.0% yield in the arid areas of India. Findings of this study provide useful strategies to save irrigation water, bring additional area under irrigation, and improve crop water productivity in India and other similar arid areas in the world.

Full Text

Improving Water Productivity of Sprinkler-Irrigated Cumin Through Deficit Irrigation in Arid Areas

Hari Mohan MEENA*, Deepesh MACHIWAL, Priyabrata SANTRA, Vandita KUMARI, Saurabh SWAMI
Division of Natural Resources, Indian Council of Agricultural Research (ICAR)-Central Arid Zone Research Institute (CAZRI), Jodhpur 342003, India

Abstract: Integrating sprinkler with deficit irrigation systems represents a novel approach to improve crop water productivity and ensure water and food security in arid regions of India. This study conducted field experiments on sprinkler-irrigated cumin (variety GC-4) using a mini-lysimeter setup at an experimental research farm in Jodhpur, India during 2019–2022. Four irrigation treatments T1, T2, T3, and T4 were designed at irrigation water/cumulative pan evaporation (IW/CPE) ratios of 1.0, 0.8, 0.6, and 0.4, respectively, with three replications. Daily actual crop evapotranspiration (ETc) was recorded and weekly soil moisture was monitored throughout the crop growth period. Quantities of applied water and drainage from mini-lysimeters were measured at each irrigation event. Cumin yield was recorded at crop maturity, and changes in farmer' s net income from 1 hm^2 land were computed based on irrigation water costs and yield variations among treatments. Results indicated the highest mean seasonal actual ETc (371.7 mm) and cumin yield (952.47 kg/hm^2) under T1 (full irrigation). Under T2, T3, and T4, seasonal actual ETc decreased by 10.4%, 27.6%, and 41.3%, respectively, while yield declined by 5.0%, 28.4%, and 50.8%, respectively, compared to T1. Furthermore, crop water productivity of 0.272 ($±0.068)kg/m^{3}$ under T2 was relatively higher compared to other treatments, indicating that T2 can achieve improved water productivity of cumin in arid areas at an optimal deficit irrigation level. Cost-economics analysis indicated a positive change in farmer' s net income from 1 hm^2 land of 108.82 USD under T2, while T3 and T4 showed net losses of 5.33 and 209.67 USD, respectively. Moreover, the yield response factor and ratio of relative yield reductions to relative ETc deficits were less than 1.00 under T2 (0.48), and greater than 1.00 under T3 (1.07) and T4 (1.23). This further supports that T2 represents the optimized deficit irrigation level, saving 20.0% of water while sacrificing only 5.0% yield in arid areas of India. These findings provide useful strategies to save irrigation water, bring additional area under irrigation, and improve crop water productivity in India and other similar arid regions worldwide.

Keywords: cumin crop; crop water productivity; crop evapotranspiration;

deficit irrigation; mini-sprinkler irrigation; yield response factor

1 Introduction

Cumin (*Cuminum cyminum* L.), a native crop of Egypt, is mainly grown in India, followed by North Africa, China, and America (Dar et al., 2019). India is the largest producer of cumin worldwide, contributing 70.0% of global production (Sharma et al., 2019). More than 90.0% of total cumin production in the country comes from two states: Gujarat and Rajasthan (Saranya et al., 2025). Cumin is a small annual herbaceous plant with industrial and medicinal uses (Bettaieb et al., 2011), as its seeds contain oil (10.0%), protein, cellulose, sugar, and mineral elements (Li and Jiang, 2004). The essential oil ratio in cumin ranges between 2.5% and 5.0% depending on climatic and soil conditions. Adapted to dry winter climates, cumin is cultivated primarily for essential oil production or as a seed spice. The essential oil helps the plant adapt to its environment, and higher quantities can be produced when plants are exposed to moisture stress (Olle and Bender, 2010).

Under Indian conditions, cumin is cultivated during the winter season (November–March) in arid climates (Sharma et al., 2019). Farmers grow cumin as a cash crop with irrigation despite water being the most limiting factor in arid agriculture. The irrigated area under cumin has gradually increased in arid lands due to easy access to groundwater supplies, leading to large-scale groundwater extraction. Even though water resource shortages from low precipitation and limited surface water availability are major constraints, extensive cultivation of water-intensive crops like groundnut and castor drives groundwater exploitation, causing water table decline (Harisha et al., 2017; Machiwal et al., 2024). Thus, precious water volumes must be applied judiciously by adopting water-efficient micro-irrigation systems.

Among different irrigation methods for seed spices in arid areas, cumin performs better with sprinkler irrigation as it ensures sensible water utilization and savings (Malhotra et al., 2009). Sprinkler irrigation also increases yield and produce quality by ensuring proper and uniform germination (Ravindran et al., 2006). Deficit irrigation offers another valuable tool for addressing restricted water availability in arid areas. Literature reveals that deficit irrigation saves water and improves productivity for cereals and other crops in arid climates (Kumar et al., 2019; Attia et al., 2021; Kheir et al., 2021; Meena et al., 2021a, b, 2025; Rathore et al., 2021). However, few studies have investigated deficit irrigation for seed spice crops, particularly cumin.

Bondok and El-Sharkawy (2014) compared irrigation water amounts, yield, and yield components of cumin under surface and sprinkler irrigation at deficit and full irrigation levels (60.0%, 80.0%, and 100.0% actual crop evapotranspiration (ETc)) in El Gharbeia Governorate, Egypt. Results revealed 45.5%–47.9% water savings through sprinkler irrigation with 10.2%–12.5% yield increments. Furthermore, yield showed 14.2% and 26.2% decreases while water productivity showed 6.9% and 14.9% increases under deficit irrigation at 80.0% and 60.0% actual ETc, respectively, compared to full irrigation (100.0% actual ETc). Ozer et al. (2020) imposed different deficit irrigation treatments on black cumin (*Nigella sativa* L.) in Turkey based on cumulative pan evaporation (CPE). Results indicated yield reductions of 13.5%, 18.9%, and 30.1% at deficit irrigation levels of 80.0%, 60.0%, and 40.0% CPE, respectively, compared to full irrigation (100.0% CPE) yield of 1413.50 kg/hm^2. However, irrigation water use efficiency under full irrigation was 6.2%, 23.0%, and 37.6% lower than under deficit irrigation at 80.0%, 60.0%, and 40.0% CPE, respectively.

Mehta et al. (2014) irrigated cumin at three intervals (12, 15, and 18 days) using the flooding method, obtaining maximum yield (471.00 kg/hm^2) at the 18-day interval, which also showed higher water productivity (0.236 kg/m^3) compared to 12-day (0.074 kg/m^3) and 15-day (0.139 kg/m^3) intervals. Rao et al. (2010) reported maximum yield (677.50 kg/hm^2) and water productivity (0.311 kg/m^3) for cumin irrigated through micro-sprinklers at IW/CPE of 0.8 compared to IW/CPE of 1.0, 0.6, and 0.4. Jangir et al. (2007) reported water productivity of 0.260 kg/m^3 and yield of 411.00 kg/hm^2 for sprinkler-irrigated cumin with five irrigations. In a semi-arid area of India, drip and micro-sprinkler irrigation saved 68.5% and 58.1% water, respectively, compared to flood irrigation (Singh et al., 2015). Drip irrigation (yield: 319.50 kg/hm^2) and micro-sprinkler irrigation (yield: 314.85 kg/hm^2) improved water productivity by 4.74% and 4.29%, respectively, over flood irrigation (yield: 186.45 kg/hm^2; water productivity: 0.721 kg/m^3). Kunapara et al. (2016) evaluated three deficit irrigation levels (IW/ETc of 0.6, 0.8, and 1.0) on cumin in Junagarh, India, finding maximum yield (1255.78 kg/hm^2) at IW/ETc of 0.8 compared to IW/ETc of 1.0 (1042.83 kg/hm^2) and 0.6 (1098.67 kg/hm^2), while maximum water productivity occurred at IW/ETc of 0.6 (0.555 kg/m^3), followed by IW/ETc of 0.8 and 1.0 (0.476 and 0.316 kg/m^3, respectively). Lal Mehriya et al. (2020) evaluated yield and water productivity under irrigation levels of 40.0%, 60.0%, and 80.0% CPE for drip-irrigated cumin and 80.0% CPE for flood-irrigated cumin, obtaining maximum yield (1066.67 kg/hm^2) at 80.0% CPE under drip irrigation, which was higher than at 60.0% CPE (1062.67 kg/hm^2) and 40.0% CPE (934.67 kg/hm^2) under drip irrigation and at 80.0% CPE (631.00 kg/hm^2) under flood irrigation. Drip irrigation at 40.0% CPE resulted in maximum water productivity (0.570 kg/m^3) and water saving (39.0%), followed by 60.0% CPE (water productivity: 0.480 kg/m^3; water saving: 18.9%).

Many water-saving approaches exist for efficient irrigation in arid areas, including micro-irrigation methods (drip and sprinkler) and deficit irrigation practices. However, literature reveals that studies amalgamating these two strategies are rarely reported for arid areas. This study integrated micro-irrigation and deficit-irrigation approaches, demonstrating successful application in arid India. The experiment aimed to find the optimum deficit irrigation level through a mini-sprinkler system to improve cumin water productivity and explain how crop yield responds to deficit irrigation levels. Additionally, the study computed changes in farmer’ s net income considering deficit irrigation impacts and water savings, evaluating economic feasibility beyond water productivity values. Findings provide useful strategies to save irrigation water in water-scarce regions and may be adopted in other global arid areas to escalate irrigated agriculture economies.

2.1 Overview of the Experimental Site

This study was conducted at an experimental research farm (26°18 N, 73°01 E; 224 m a.s.l.) of ICAR-CAZRI, Jodhpur, Rajasthan, India. The arid climate features high diurnal and seasonal temperature variations, irregular annual and inter-annual precipitation, and long dry seasons with strong winds. Long-term climate conditions (1991-2020) and short-term conditions during study years (2019, 2020, 2021, and 2022) for the five-month crop growth period (November-March) are shown in Table 1 . Mean monthly climatic parameters showed no significant variations during the study period. Precipitation occurs due to western disturbances, with totals of 13.0 mm and 16.4 mm during 2019-2020 and 2021-2022, respectively. Mean monthly relative humidity varied from 39.8% to 55.1% during 2019-2020, 29.0% to 48.1% during 2020-2021, and 26.1% to 57.6% during 2021-2022. Mean monthly minimum temperature ranged from 10.3°C to 17.5°C during 2019-2020, 10.5°C to 19.7°C during 2020-2021, and 10.1°C to 20.8°C during 2021-2022, while maximum temperature ranged from 22.8°C to 30.5°C during 2019-2020, 24.5°C to 36.0°C during 2020-2021, and 21.9°C to 37.0°C during 2021-2022. Mean monthly wind speed was below 1.2 m/s during the crop growth period. Sprinkler irrigation is recommended only when wind speeds are below 2.2 m/s (Mohamed et al., 2019). Kumar et al. (2023) reported that a uniformity coefficient of 75.0% for sprinkler systems under wind speeds between 1.1 and 2.2 m/s with 6 m$×$9 m spacing is appropriate, and a uniformity coefficient of 85.0% under 0.0-1.1 m/s winds is acceptable with the same spacing.

Soil at the experimental site originated from rhyolite and was subsequently modified through alluvial and aeolian processes (Kumar et al., 2009). Taxonomically, the soil is classified as coarse loamy, mixed, hyperthermic Camborthids with inherently very low organic carbon (1.6 g/kg) (Kumar et al., 2009). Physical soil properties are summarized in Table 2 .

2.2.1 Crop Experiment

Cumin seeds (variety GC-4) were sown on 23 November 2019, 10 November 2020, and 10 November 2021 at 1.0-1.5 cm depth using a seed drill, with a seeding rate of 10-12 kg/hm^2 and row spacing of 30.0 cm to achieve optimum plant population. Fertilizer was applied at recommended doses of 25 kg N/hm^2 and 20 kg P_2O_5/hm^2 through urea and di-ammonium phosphate (DAP) at sowing using a seed drill (Mehta et al., 2014). Other cultural practices were uniformly adopted across all irrigation treatments according to recommended packages. Crop was harvested at maturity on 20 March 2020, 8 March 2021, and 16 March 2022. Irrigation water was applied using a mini-sprinkler system based on the IW/CPE approach. Four irrigation treatments consisted of full irrigation at IW/CPE of 1.0 (T1) and deficit irrigation at IW/CPE of 0.8 (T2), 0.6 (T3), and 0.4 (T4), replicated thrice. All treatments were irrigated on the same day when CPE in treatment T1 reached 50.0 ($±5.0)mm.DailyevaporationwasmeasuredthroughClass − AopenpanevaporimeterattheAgro − meteorologicalObservatoryofICAR − CAZRI, Jodhpur, neartheexperimentalsite, withdailyvaluessummedtoobtainCPE.Theexperimentcovered0. with net plot size of 7 m$×11m(77m^{2}$) for each treatment and three replicated plots per treatment.

2.2.2 Installation of Mini-Lysimeters

Four mini-lysimeters (50 cm length$×50cmwidth×$55 cm depth) were installed at the experimental site in 2020. Each mini-lysimeter contains a single load cell for actual measurement of water balance components. Field calibration determined the conversion factor for unit weight change in terms of applied water depth, finding that 1.0 kg weight change corresponded to 4.0 mm water depth. The least count of the mini-lysimeter was 0.2 mm (Meena et al., 2015).

2.2.3 Irrigation Application and Uniformity

A pipe network for mini-sprinkler irrigation was installed in the experimental field, operated using a 1 HP centrifugal pump. The network consisted of a main pipe (high-density polyethylene, 63.0 mm diameter, 2.5 kg/cm^2 pressure), screen filter (25.0 m^3/h capacity), linear low-density polyethylene (LLDPE) plain lateral (32.0 mm diameter, 2.5 kg/cm^2 pressure), pressure gauge, sprinkler head, and risers. Each sprinkler head had a twin-nozzle mini-sprinkler (model Monsoon S-10) with nozzle size of 2.5 mm × 1.5 mm. Part-circle mini-sprinklers were used at field corners to avoid unnecessary water losses outside the boundary that occur with full-circle (360°) sprinklers. In part-circle sprinklers, the water jet can be easily adjusted to rotate within any angle range (0°-360°). Each treatment plot (net size 21 m$×11munder3replications)waswateredusingsixmini − sprinklers : fourpart − circlenozzlesatcornersadjustedto90°andtwomid − pointmini − sprinklersat180°.A1malleybetweenadjacentplotsfacilitatedfieldwork, includinginterculturaloperationsando at nozzles, with average single sprinkler discharge of 480 L/h and average system precipitation rate of 4.6 mm/h. Irrigation was required for germinating cumin seeds in sandy loam soil, as the fine seeds are sown at shallow depths (<3 cm) and need moist soil surfaces for optimum germination, requiring at least three irrigations for crop establishment.

The catch can method determined irrigation water depth falling on experimental plots and captured by the root zone, and also determined the uniformity coefficient. In the catch can experiment, 66 cylindrical plastic cans (98.0 mm length$×98.0mmdiameter)wereplacedinagridpattern(2m×2m)overeachtreatmentplot(21m×$11 m) during one irrigation event. Captured water amounts were recorded using a measuring cylinder. Average irrigation application values were used to determine mini-sprinkler nozzle discharge, with average system application rates ranging from 6.0 to 8.0 mm/h. The uniformity coefficient of irrigation application ranged from 70.0% to 75.0%.

2.2.4 Field Observations and Measurements

Field observations began immediately after sowing. Applied irrigation water was monitored based on sprinkler operational hours, with average nozzle discharge cross-checked by monitoring mini-lysimeter weight changes before and after irrigation. Actual ETc and drainage from mini-lysimeters were measured daily by weighing at 08:30 (LST) throughout the three crop growth periods (2019-2020, 2020-2021, and 2021-2022). Daily precipitation was recorded using a non-recording rain gauge at the Agro-meteorological Observatory adjacent to the experimental site. Daily soil temperatures of mini-lysimeters were recorded twice daily at 07:38 and 14:38 for all treatments using soil thermometers at 5 cm depth. Treatment-wise plant growth parameters (plant height, number of branches, crop yield, number of umbels, and number of umblets) were recorded for three randomly selected plants.

2.3 Measurement of Soil Moisture Content

Soil moisture at two depths (0-15 and 15-30 cm) from three plots per treatment was determined weekly and before/after irrigation by collecting samples using an auger. Samples were stored in moisture boxes and immediately transported to the laboratory to avoid moisture loss. Samples were weighed and oven-dried at 105.0°C for 48 h until constant weight. Volumetric water content (mm) was computed by multiplying moisture content (%) by bulk density (g/cm^3) of individual soil layers, then converted to water depth (mm) by multiplying by soil layer depth (mm) (Ali, 2010).

2.4 Computation of Actual ETc

Daily actual ETc from mini-lysimeters was computed using the water balance equation (Doorenbos and Kassam, 1979; Jensen et al., 1990; Allen et al., 1991):

$$ET = P + I - D - R \pm \Delta S$$

where P is precipitation (mm), I is irrigation application (mm), D is drainage from the mini-lysimeter (mm), R is surface runoff (mm), and ΔS is change in soil moisture of the mini-lysimeter tank (mm).

Precipitation was negligible during the crop growth period, and irrigation was applied at controlled rates through mini-sprinklers, so water never overflowed mini-lysimeter surfaces, making surface runoff zero. Daily precipitation was obtained from the rain gauge, and irrigation amounts were computed. Drainage was computed from differences between consecutive daily lysimeter readings (on precipitation/irrigation days and the following day after surplus water drained). No drainage occurred in response to precipitation or irrigation events during the entire study period, indicating soil moisture never exceeded saturation capacity. Therefore, drainage was considered zero. With runoff and drainage absent, consecutive daily mini-lysimeter weights were simply differenced to obtain ΔS on non-irrigation days.

2.5 Assessment of Crop Water Productivity

Crop water productivity is defined as the ratio of economic crop yield to water used through evapotranspiration (Droogers and Bastiaanssen, 2002; Cetin and Akinci, 2022):

$$CWP = \frac{Y}{ET_s}$$

where CWP is crop water productivity (kg/m^3), Y is economic yield (kg/hm^2), and ET is seasonal actual ETc (m^3/hm^2).

2.6 Estimating the Impact of Deficit Irrigation on Cost-Economics of Cumin Cultivation

Deficit irrigation saves water at the cost of yield reduction. This study examined how farmer’ s net income was affected by water savings and yield reductions. Saved water may be used to irrigate additional area, while yield reduction under deficit irrigation can diminish net income, potentially making adoption difficult for farmers. Furthermore, farmer income may not directly correlate with water productivity, causing reluctance to accept water-saving techniques (Pereira et al., 2012). Environmental and economic criteria often contrast, as water-saving approaches may require advanced solutions while economic approaches may reject them (Gonçalves et al., 2011). Therefore, evaluating economic feasibility of the best deficit irrigation treatment considering both costs and benefits became necessary. All economic computations estimated changes in farmer’ s net income from 1 hm^2 land, keeping all other cost and benefit parameters constant except irrigation application cost, crop yield, and total production. It was assumed that saved water could be used to raise irrigated cumin on additional land using the same irrigation practice. The local cumin selling price was considered 1.67 USD/kg (1 USD = 86.87 INR) (https://www.xe.com/currencyconverter/convert/?Amount=1&From=INR&To=USD) accessed 11 February 2025 (Meena et al., 2021c).

2.7 Computation of Crop Yield Response Factor

The response of crop yield to deficit irrigation or moisture stress throughout the growth period was quantified using the crop yield response factor (or crop water production function). The factor for three deficit irrigation treatments was estimated using the formula (Doorenbos and Kassam, 1979):

$$K_y = \frac{1 - Y_a/Y_m}{1 - ET_a/ET_m}$$

where K is the crop yield response factor, Y is actual crop yield (kg/hm^2) under deficit irrigation treatments (T2, T3, T4), Y is maximum crop yield (kg/hm^2) under T1, ET is maximum actual ETc (mm) under T1, ET is actual ETc (mm) under deficit irrigation treatments, and 1 - (Y /Y) is the relative yield reduction corresponding to relative ETc deficit (i.e., 1 - (ET /ET)).

2.8 Statistical Analysis

One-way analysis of variance (ANOVA) evaluated effects of full and deficit irrigation on actual ETc, crop yield, and crop water productivity. The null hypothesis stated that population means of full and deficit irrigation treatments were equal against the alternative of inequality in at least two treatments. Prior to ANOVA, normality and homogeneity of variance assumptions were examined using Shapiro-Wilk and Levene’ s F-tests, respectively (Miller, 1997). Multiple comparisons tested the null hypothesis through pair-wise comparisons of treatment means using Fisher’ s Least Significant Difference (LSD) test. All analyses were performed using R 4.2.2 software.

2.9 Exploring Relationships Among Crop Yield, Actual ETc, and Irrigation Application

This study modeled deficit irrigation impacts on actual ETc and crop yield reductions by exploring relationships among them. Linear empirical relationships among crop yield, actual ETc, and irrigation application were developed for full and deficit irrigation using regression analysis. The strength of these relationships (crop yield–actual ETc, crop yield–irrigation application, and actual ETc–irrigation application) was evaluated using the coefficient of determination (R^2).

3.1 Dynamics of Soil Moisture

Soil moisture under full and deficit irrigation treatments is depicted in Figure 1 [Figure 1: see original paper]. The largest soil moisture variation in the profile due to irrigation occurred under T1 (7.3-34.8 mm), followed by T2 (7.9-29.9 mm), T3 (6.5-22.8 mm), and T4 (4.3-19.5 mm). This occurred because under T1, with adequate soil water, crop roots extracted relatively large water quantities through evapotranspiration, supported by

plentiful annual average solar irradiance (5.2 kW h/m^2) in the hot arid climate (Santra et al., 2021). Similar findings were reported by Hassan and Ali (2016), where soil moisture was 20.3%, 30.0%, 35.2%, and 38.6% lower under deficit irrigation at 20.0% potential evapotranspiration (ETP) compared to irrigation at 40.0%, 60.0%, 80.0%, and 100.0% ETP, respectively. Soil moisture depletion rate from cropped area remains directly proportional to water availability in the soil profile, largely controlled by deficit irrigation as in this study. Accordingly, mean soil moisture at 0-30 cm depth ranked as: 31.3 (\$$\pm6.5)mm(T1) > 28.7(\pm6.0)mm(T2) > 27.9(\pm5.8)mm(T3) > 24.5(\pm5.1)mm(T4)(Fig.1a1–a4).During2020–2021, meansoilmoisturerankedas: 26.3(\pm5.5)mm(T1) > 24.7(\pm5.2)mm(T2) > 22.7(\pm4.7)mm(T3) > 21.4(\pm4.5)mm(T4)(Fig.1b1–b4).During202$
$26.8(\pm5.4)mm(T1) > 25.8(\pm5.2)mm(T2) > 26.5(\pm5.6)mm(T3) > 25.2(\pm\$5.4)$ mm (T4) (Fig. 1c1-c4). Overall, soil moisture depletion was maximum under the largest irrigation deficit (T4) and relatively less under full irrigation (T1) and moderate deficit (T2). Soil moisture dynamics were similar under T1 and T2, and under T3 and T4, indicating that choosing an optimized deficit irrigation level is key to efficient irrigation water management in water-scarce hot arid regions. Sprinkler irrigation can also increase yield and food production quality in undulating areas of western Rajasthan (Ravindran et al., 2006).

3.2 Dynamics of Daily and Seasonal Actual ETc

Mean daily actual ETc values during 2019-2020 were 3.2 (\$$\pm0.1)mm, 2.9(\pm0.1)mm, 2.6(\pm0.1)mm, and2.1(\pm0.1)$
$seeoriginalpaper]).During2020–2021, valueswere3.2(\pm0.1)mm, 2.9(\pm0.1)mm, 2.2(\pm0.1)mm, and1.7(\pm0.1)mm$
mm under T1, T2, T3, and T4, respectively (Fig. 2c1-c4). Water evaporated from the evaporation pan over the entire crop growth period was 405.0, 430.0, and 522.0 mm during 2019-2020, 2020-2021, and 2021-2022, respectively, indicating bare soil evaporation. Water used in evapotranspiration was highest (360.0-380.0 mm) under T1, followed by T2 (327.0-338.0 mm), T3 (249.0-294.0 mm), and T4 (188.0-240.0 mm). Actual ETc values closely followed CPE from vegetative to reproductive stages due to good canopy cover, resulting in high actual ETc. The initial phase (20-25 days after sowing (DAS)) was considered the establishment stage, when water loss occurred mainly through evaporation rather than transpiration due to low canopy cover (5.0%-10.0%). After establishment, crop canopy expanded from 50-60 DAS, increasing transpiration during the crop development stage. Maximum canopy cover (40.0%-55.0%) occurred from 85-100 DAS (middle stage). Finally, crop matured from 105-125 DAS (final stage) when leaves turned yellow due to chlorophyll loss. These findings align with those for black cumin (*Nigella sativa* L.) in similar Iranian climatic conditions, where mean actual ETc was low (15.0 mm) at the initial stage, increased to 103.7 mm during crop development, and decreased to 21.1 mm at maturity (Ghamarnia et al., 2014). Similar patterns were reported for coriander, with low actual ETc during 0-30 DAS, gradual increase during 70-100 DAS, and decrease during 100-110 DAS (Ghamarnia et al., 2013). The time plot of evapotranspiration generally followed a sigmoid curve mirroring the plant growth curve.

Mean seasonal actual ETc values from pooled data (2019–2022) are shown in Table 3 . Mean seasonal actual ETc was highest (371.8$±10.4mm)underT1, followedby333.0(±5.6)mmunderT2, 2
mm under T4. Literature reports seasonal water requirements for cumin of 335.0–416.4 mm (Khajehpour, 1986; Saeedinia et al., 2018), indicating that water loss through evapotranspiration was influenced by deficit irrigation amounts.

3.3 Dynamics of Crop Yield and Crop Water Productivity

As shown in Table 3, maximum crop yield (952.47$±238.07kg/hm$^{\{2\})occurredunderT1, followedby904.80(\pm216.94)kg/hm}$
under T2, 682.13 ($±160.71)kg/hm^{2}$ under T3, and 468.20 ($±39.29)kg/hm^{2}$
under T4, indicating considerable deficit irrigation impact. A 20.0% deficit in applied irrigation water from T1 to T2 resulted in only 5.0% yield reduction (Table 4), harmonizing with Hassan and Ali (2016) who reported 1.1% and 8.2% cumin yield decreases under drip irrigation at 80.0% ETP compared to 100.0% ETP, with considerably higher reductions beyond 60.0% ETP (22.5% and 27.4% at 40.0% and 20.0% ETP, respectively). Lal Mehriya et al. (2020) reported similar findings, with cumin yield reducing to 1066.67, 1062.67, and 934.67 kg/hm^2 under deficit irrigation at 80.0%, 60.0%, and 40.0% CPE, respectively. Bondok and El-Sharkawy (2014) observed 22.8% and 59.4% yield reductions under deficit irrigation at 80.0% and 60.0% actual ETc, respectively, compared to 100.0% actual ETc.

In contrast, some Indian studies reported highest yield under deficit irrigation at IW/CPE of 0.8 compared to IW/CPE of 1.0 for drip-irrigated cumin in Junagarh District, Gujarat and sprinkler-irrigated cumin in Pali District, Rajasthan (Rao et al., 2010; Kunapara et al., 2016). Similar highest seed yields under IW/CPE of 0.8 were reported for other seed spices (Lakpale et al., 2007). Relatively high yield under IW/CPE of 0.8 in Pali District may be due to soils with higher water holding capacity reducing drought stress, while higher yield under deficit irrigation in Junagarh District may result from drip irrigation continuously replenishing root zone moisture during stress. Micro-irrigation systems (drip, micro- or mini-sprinkler) saved water, energy, and fertilizer by 50.0%–90.0%, 31.0%, and 29.0%, respectively, compared to flood irrigation (Kumar et al., 2021). Drip-irrigated cumin showed superior water productivity over surface and sprinkler irrigation (Singh et al., 2015), possibly because micro-irrigation decreases air temperature and increases relative humidity, reducing vapor pressure deficit and regulating plant physiological processes to enhance water use efficiency and reduce transpiration (Liu et al., 2021).

Crop water productivity was maximum under T2 (0.272$±0.068kg/m$^{\{3\}), followedbyT1(0.257\pm0.069kg/m}$\{3\}), T3(0.2
of sprinkler-irrigated cumin occurred under deficit irrigation at T2. Improved cumin water productivity under reduced irrigation was reported in multiple studies (Bondok and El-Sharkawy, 2014; Hassan and Ali, 2016; Kunapara et al., 2016; Lal Mehriya et al., 2020). For coriander, water productivity also increased under restricted water applications, with maximum productivity under water deficit stress (Aliabadi et al., 2008). This reveals that slight irrigation deficits

can considerably enhance water productivity. However, increasing IW/CPE beyond T2 (to T3 and T4) caused significant yield reductions (28.4% and 50.8%, respectively), somewhat lessening water productivity. Beyond improving water productivity, deficit irrigation may reduce evaporation and percolation losses. Water is the most limiting factor in hot arid climates due to competition between evaporation (high solar radiation and atmospheric demand) and infiltration (poor soil water-holding capacity). Thus, deficit irrigation is an important strategy where saved water may convert additional rainfed (dry) area to irrigated (green) area.

3.4 Impact of Deficit Irrigation on Cost-Economics of Cumin Cultivation

The unit cost of mini-sprinkler irrigation was 0.33 USD/($hm^2 \cdot mm$) (Meena et al., 2021a), meaning 0.33 USD to apply 1.0 mm water depth over 1 hm^2. Deficit irrigation saved 20.0% (T2), 40.0% (T3), and 60.0% (T4) water compared to full irrigation (T1), reducing irrigation water application costs by 12.74, 32.62, and 50.53 USD, respectively (Table 4). Utilizing saved water to raise crops on additional area could generate added monetary benefits of 175.86 USD under T2, 414.53 USD under T3, and 550.35 USD under T4. However, deficit irrigation caused yield reductions of 5.0% (T2), 28.4% (T3), and 50.8% (T4) relative to T1, resulting in monetary losses of 79.79, 452.49, and 810.55 USD, respectively. These cost-economics computations revealed positive change in farmer' s net income from 1 hm^2 land under T2 (108.82 USD) but losses under T3 (5.32 USD) and T4 (109.67 USD), indicating T2 was economically advantageous regardless of water productivity values.

3.5 Response of Actual ETc, Crop Yield, and Crop Water Productivity to Deficit Irrigation

Shapiro-Wilk' s test revealed normal distribution of dependent variables (actual ETc and crop yield) ($P>0.05$). Levene' s F-test confirmed equal variances across groups ($P>0.05$). One-way ANOVA showed statistically significant differences ($P<0.05$) among T1, T2, T3, and T4 for actual ETc and crop yield. Pair-wise comparisons using Fisher' s LSD post-hoc test (Table 3) showed no significant difference in water transferred to the atmosphere through evapotranspiration among T1 (371.7 mm), T2 (333.0 mm), and T3 (272.7 mm), despite T3 being about 100.0 mm less than T1. Similarly, no significant difference occurred between T3 and T4 for actual ETc. However, crop yield values differed significantly among all four treatments. Notably, the 5.0% yield difference between T1 (952.47 kg/hm^2) and T2 (904.80 kg/hm^2) was statistically significant, likely due to large standard deviations in yield under T1 (238.07 kg/hm^2) and T2 (217.94 kg/hm^2) compared to T3 (161.71 kg/hm^2) and T4 (39.29 kg/hm^2) (Table 3). Similar to this study, Hassan and Ali (2016) showed significant differences in cumin yield at different irrigation levels. Lal Mehriya et al. (2020) reported highest seed yield of drip-irrigated cumin under deficit irrigation at 80.0% CPE, followed by 60.0% CPE in arid Rajasthan. Hassan and Ali (2014) reported significant differences in coriander yield at different irrigation levels. Lower water productivity at high irrigation levels may be due to greater water loss through actual ETc than corresponding seed yield increases (Kamkar et al., 2011). The large variation in crop yield was likely due to relatively low yields in the first experimental year caused by stones, pebbles, and concrete in the soil during initial cultivation and poor germination.

3.6 Tolerance of Cumin Crop to Water Stress Under Deficit Irrigation

Crop yield response factor results revealed a positive linear relationship between crop yield and applied irrigation water (Fig. 3 [Figure 3: see original paper]). The yield response factor, represented as the slope between relative yield reduction and relative ETc deficit, was 0.48, 1.07, and 1.23 under T2, T3, and T4, respectively (Table 5), suggesting high sensitivity to water stress beyond T2 deficits. This supports earlier findings that T2 deficit irrigation was advantageous over full irrigation (T1), improving water productivity with 5.0% yield reduction and 20.0% water savings. The overall crop yield response factor was 0.89 for all treatments based on cumulative three-year data (Fig. 3), indicating cumin crop tolerance to water stress under deficit irrigation in arid lands.

3.7 Impacts of Deficit Irrigation Treatments on Actual ETc and Crop Yield

Linear regression analyses exploring relationships among crop yield, actual ETc, and applied irrigation water are presented in Figures 4 and 5. A very strong linear relationship ($R^2 = 0.93$-0.98) existed between crop yield and actual ETc (Fig. 4a [Figure 4: see original paper]). Similarly, a strong linear relationship ($R^2 = 0.79$-0.94) occurred between crop yield and applied irrigation water for pooled data across four treatments (Fig. 4b). Both relationships indicated that crop yield increases with higher actual ETc and irrigation water amounts. Linear regression between actual ETc and irrigation water also showed a very strong relationship ($R^2 = 0.86$) (Fig. 5 [Figure 5: see original paper]), indicating greater water loss through actual ETc under higher irrigation application due to high atmospheric water demand in the hot arid climate.

4 Conclusions

This study integrated two water-saving approaches—micro-irrigation (mini-sprinkler) and deficit irrigation—to improve cumin water productivity in arid Rajasthan, India. Actual ETc under deficit irrigation was determined through lysimetry, and changes in farmer' s net income were computed considering irrigation water costs and yield reductions. The highest crop yield (952.41 kg/hm^2) occurred under T1, with 5.0%, 28.4%, and 50.8% reductions under T2, T3, and T4, respectively. Thus, T2 represented the optimal deficit irrigation level, saving 20.0% water compared to full irrigation with minimal yield reduction. The highest crop water productivity (0.272 ± 0.068 kg/m^3) occurred under T2, with slightly lower values under T1 (0.257 ± 0.069 kg/m^3), T3 (0.253 ± 0.071 kg/m^3), and T4 (0.218 ± 0.048 kg/m^3). Net income computations from 1 hm^2 land revealed added benefits from reduced irrigation costs and additional crop production using saved water under T2 (108.82 USD gain) versus losses under T3 (5.32 USD) and T4 (109.67 USD). Findings indicate that water productivity in hot arid areas can be maximized by creating slight water deficits in the crop root zone while sacrificing minor yield. The integrated mini-sprinkler deficit irrigation strategy proved successful and may be useful in other global water-scarce drylands to save water resources and expand irrigated area. Since water-intensive crops like groundnut, fennel, onion, and carrot have increased in India' s western arid region where water resources are limited, these findings are applicable for sustaining arid agriculture. This study employed deficit irrigation with mini-sprinklers; future research could explore integration with other pressurized systems such as surface and subsurface drip irrigation.

Conflict of interest: The authors declare no known competing financial interests or personal relationships that could have influenced this study.

Acknowledgements: The authors thank ICAR-Central Arid Zone Research Institute (CAZRI), Jodhpur for facilities, and anonymous reviewers and editors for constructive comments.

Author contributions: Conceptualization: Hari Mohan MEENA, Deepesh MACHIWAL, Priyabrata SANTRA; Methodology: Hari Mohan MEENA, Deepesh MACHIWAL, Vandita KUMARI; Formal analysis and investigation: Hari Mohan MEENA, Deepesh MACHIWAL; Writing - original draft: Hari Mohan MEENA, Deepesh MACHIWAL; Writing - review and editing: Deepesh MACHIWAL, Priyabrata SANTRA, Saurabh SWAMI, Vandita KUMARI. All authors approved the manuscript.

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Note: Figure translations are in progress. See original paper for figures.