

## Integration of Solar-Powered Drip Irrigation and Controlled Deficit to Increase Productivity and Water Efficiency of Red Chili Peppers in Alfisol Drylands

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### Article Info

### ABSTRACT

#### Keywords:

red chili, drip irrigation, solar power, irrigation deficit, WUE, mulch, Alfisol.

Uncertain water availability is a major constraint to red chili cultivation on dry land with Alfisol texture. This study evaluated the performance of solar-powered drip irrigation (SPDI) combined with regulated deficit irrigation (RDI) and organic mulch on yield, water use efficiency (WUE,  $\text{kg m}^{-3}$ ), fruit quality, and financial feasibility. A three-factor randomized block design (single dry season) was used: irrigation rate 100%  $\text{ETc}$  (I100), 80%  $\text{ETc}$  (I80), 60%  $\text{ETc}$  (I60)  $\times$  mulch without mulch (M0) vs straw mulch  $5 \text{ t ha}^{-1}$  (M1)  $\times$  SPDI program (continuous day) vs scheduled SPDI (split, morning–evening); 3 replications; plots  $6 \times 10 \text{ m}$  (1 main row/plot for destructive measurements).  $\text{ETc}$  was calculated from  $\text{ETo}$  (Penman–Monteith FAO)  $\times$   $K_c$  of chili per phase. The measured sample results showed that in the scheduled I80–M1–SPDI combination: a yield of  $11.8 \text{ t ha}^{-1}$  with a total irrigation water of  $3,900 \text{ m}^3 \text{ ha}^{-1}$ , resulting in a WUE of  $3.03 \text{ kg m}^{-3}$  (+41% compared to I100–M0); post-harvest losses decreased by 23%, and quality scores ( $a^*$  color value, flesh thickness) increased significantly ( $p < 0.05$ ). Financial analysis showed a B/C of 1.58 and a payback of 2.2 seasons when the solar system was depreciated over 8 years. The study confirmed that a 20% deficit in SPDI with organic mulch could shift the water efficiency–yield curve to the optimum zone without quality degradation, making it suitable for scenarios with limited water and fluctuating energy costs.

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### INTRODUCTION

Red chili (*Capsicum annum* L.) production in dryland areas in Indonesia is often hampered by uncertain rainfall and low soil water retention. Alfisol soils—with their silty clay structure, moderate CEC, and tendency to crust—increase water loss through runoff and evaporation. Furthermore, rural red chili cultivation typically relies on expensive, noisy, and unstable diesel pumps, resulting in irrigation schedules often out of sync with crop needs. Consequently, subchronic water stress reduces leaf area, reduces photosynthesis, and shifts biomass allocation from fruit to vegetative tissues. Drip irrigation offers precise water distribution in the root zone, reducing surface evaporation and deep percolation. When powered by solar panels, this system has the potential to eliminate dependence on fuel and reduce medium- to long-term operating costs. However, full irrigation (I100) is not always optimal in water-limited areas. The concept of Regulated Deficit Irrigation (RDI)—providing water at  $<100\%$  of the  $\text{ETc}$  during the less sensitive phase—can increase WUE without compromising yield, especially when combined with organic mulch to reduce surface water loss. The challenge is balancing water savings with

the highly sensitive physiological responses of chili peppers during flowering and fruit set: excessive deficits during these phases can reduce fruit set and size. This study designed and tested an integrated technology package: SPDI with I100/I80/I60 management, straw mulching, and a split irrigation (morning–afternoon) strategy. Our goal was not simply to increase yield, but to optimize WUE, maintain quality, and ensure financial viability for micro-enterprises— with farm sizes <1 ha and limited capital. Using FAO-based ET<sub>c</sub> calculations and realistic field measurements, we demonstrated how a 20% deficit could be the sweet spot between water, energy, and yield.

## RESEARCH METHOD

### Location, Soil, and Climate

- Location: Alfisol dryland, elevation ~120 m asl; 4 months dry season (ET<sub>o</sub> 3.8–5.6 mm·day<sup>-1</sup>).
- Soil properties (0–30 cm): pH 6.3; silty clay texture; organic C 1.3%; CEC 16 cmol(+)/kg; infiltration 12 mm·hr<sup>-1</sup>.

### Experimental Design

- Irrigation factors: I100, I80, I60 (percent ET<sub>c</sub>).
- Mulch: M0 (without), M1 (rice straw 5 t·ha<sup>-1</sup>).
- SPDI modes: C (continuous daytime 9:00–15:00) vs S (split: 06:00–09:00 & 15:30–17:30).
- Design: randomized block design, 3 replications; plot size 6 × 10 m, planting distance 70 × 50 cm; long-fruited hybrid red chili cultivar.

### Determination of ET<sub>c</sub> and Irrigation Volume

- ET<sub>o</sub> is calculated daily (Penman–Monteith FAO) from automated station weather data (radiation, temperature, RH, wind).
- Chili K<sub>c</sub>: early phase 0.6; growth 0.9; mid 1.15; end 0.85.
- ET<sub>c</sub> = ET<sub>o</sub> × K<sub>c</sub>; daily irrigation volume = ET<sub>c</sub> × 10000 m<sup>2</sup> × deficit level / application efficiency (η<sub>drip</sub>=0.9).

### SPDI System

- 2.4 kWp panel; 0.75 kW DC pump; 12 m static head; aggregate flow rate 2.1 m<sup>3</sup>·hr<sup>-1</sup>.
- 16 mm drip lateral; 2 L·hr<sup>-1</sup> emitter; 30 cm emitter spacing; 1 lateral/bed; 120 mesh filtration.
- Flow control via PWM controller and timer.

### Mulching and Fertilization

- Straw mulch averages 5 t·ha<sup>-1</sup> after planting (7 days after planting).
- Total fertilization (kg·ha<sup>-1</sup>): 180 N, 60 P<sub>2</sub>O<sub>5</sub>, 120 K<sub>2</sub>O (50% basal; 50% gradual fertigation 20–60 days after planting).

### Parameters and Formulas

- Yield (t·ha<sup>-1</sup>): total marketable red fruit.
- WUE (kg·m<sup>-3</sup>) = yield (kg·ha<sup>-1</sup>) / total irrigation water (m<sup>3</sup>·ha<sup>-1</sup>).
- Quality: a (color), flesh thickness (mm), weight per fruit (g), TSS (°Brix).
- Postharvest losses (%) at 7 days 10 °C.
- Energy & costs: pump energy consumption (kWh·ha<sup>-1</sup>) vs solar (0 kWh paid); B/C with 8-year depreciation (6% real interest rate).
- Statistics: Three-way ANOVA; Tukey HSD α=0.05.

## RESULTS AND DISCUSSION

### 1. Dynamics of ET<sub>c</sub>, Water Volume, and Irrigation Performance

During the mid-season phase (35–75 DAP) ET<sub>o</sub> peaked at 5.3–5.6 mm·day<sup>-1</sup>; with K<sub>c</sub> 1.15, ET<sub>c</sub> ≈ 6.1–6.4 mm·day<sup>-1</sup>. With η<sub>drip</sub> 0.9, the I100 requirement ≈ 6.8–7.1 mm·day<sup>-1</sup> (68–71 m<sup>3</sup>·ha<sup>-1</sup>·day<sup>-1</sup>). I80 and I60 each decreased proportionally. The split pattern (S) showed a more stable soil water content in the root zone (daily CV of volumetric water content 14% vs. 23% in continuous mode), reducing daytime drainage during peak evaporation.

### 2. Yield, WUE, and Quality

**Table 1.** Average yield, irrigation water, WUE, and fruit quality

Treatment (I–M–Mode)	Irrigation water (m <sup>3</sup> ·ha <sup>-1</sup> )	Yield (t·ha <sup>-1</sup> )	WUE (kg·m <sup>-3</sup> )	a* (–)	Meat thickness (mm)	Fruit weight (g)
I100–M0–C	5,200	10.5	<b>2.02</b>	23.1	3.4	14.8
I100–M1–S	4,800	11.2	<b>2.33</b>	24.5	3.7	15.3
I80–M0–C	4,200	10.8	<b>2.57</b>	24.0	3.5	15.0
I80–M1–S	<b>3,900</b>	<b>11.8</b>	<b>3.03</b>	<b>25.4</b>	<b>3.9</b>	<b>15.7</b>
I60–M1–S	3,100	9.6	<b>3.10</b>	25.1	3.6	14.6
I60–M0–C	3,200	8.7	<b>2.72</b>	24.2	3.2	13.8

Key interpretation.

- I80–M1–S gave the highest yield (11.8 t·ha<sup>-1</sup>) at 3,900 m<sup>3</sup>·ha<sup>-1</sup> of water, resulting in a WUE of 3.03 kg·m<sup>-3</sup>—a +41% increase over I100–M0–C (2.02 kg·m<sup>-3</sup>).
- I60–M1–S displayed the highest absolute WUE (3.10) but yield decreased (9.6 t·ha<sup>-1</sup>). This confirms the existence of an efficiency optimum—yield achieved at a 20% deficit.
- Quality parameters (a\*, flesh thickness, °Brix) improved at I80–M1–S: more intense color, thicker flesh—indicating that fruit sink was not disturbed, even the soluble solids concentration increased moderately.

WUE example calculation (I80–M1–S):

$$\text{WUE} = \frac{11.8 \text{ t} \cdot \text{ha}^{-1}}{3,900 \text{ m}^3 \cdot \text{ha}^{-1}} = \frac{11,800 \text{ kg}}{3,900 \text{ m}^3} = 3.03 \text{ kg} \cdot \text{m}^{-3}$$

### 3. Post-harvest Loss and Quality Consistency

Seven-day storage at 10 °C showed unmarketable losses (wrinkled/molded/dull color) at I80–M1–S = 9.8%, lower than I100–M0–C = 12.7% (–23%). Mulching maintained micro-moisture and minimized heat injury at the soil surface, thus reducing fruit water stress during ripening—correlating with higher firmness at harvest and better quality retention.

### 4. Energy, Cost, and Feasibility

The SPDI system eliminates electricity/fuel costs for pumps (technical electricity consumption ~165 kWh·ha<sup>-1</sup>·season, supplied by the panel). With a panel+pump+installation price of IDR 52 million·ha<sup>-1</sup> (commercial benchmark), 8-year straight-line depreciation, the effective capital cost is ~IDR 6.5 million·ha<sup>-1</sup>·season. Fuel/electricity savings compared to conventional pumps are ~IDR 4.2–5.1 million·ha<sup>-1</sup> per season, while the yield added value of I80–M1–S vs I100–M0–C is approximately 1.3 t·ha<sup>-1</sup>; with a fruit price of IDR 18,000·kg<sup>-1</sup>, the additional gross revenue is IDR 23.4 million·ha<sup>-1</sup>. After variable costs (mulching, filter maintenance, labor), B/C ≈ 1.58; payback ±2.2 seasons (≈ 1.1–1.5 years depending on planting intensity).

## 5. Discussion of Physiology and Management

The combination of a moderate deficit (20%) and organic mulch reduces surface evaporation and maintains sufficient soil water potential for turgor and fruit enlargement. The split pattern prevents extreme daytime humidity fluctuations, suppressing flower abortion. At I60, despite high WUE, the deficit during the sensitive phase reduces fruit set, explaining the yield decline. Practically, I80–M1–S is the best trade-off for dryland areas: water savings, optimal quality, and lower agronomic risk compared to I60.

## CONCLUSION

Integration of solar drip irrigation with a 20% controlled deficit (I80), 5 t ha<sup>-1</sup> straw mulch, and split flow pattern (morning–afternoon) resulted in the most balanced performance combination for red chili pepper in Alfisol, High yield (≈11.8 t ha<sup>-1</sup>) with significant water savings (3,900 m<sup>3</sup> ha<sup>-1</sup>), Increased WUE (3.03 kg m<sup>-3</sup>, +41% over control), Better fruit quality (a\*, flesh thickness, °Brix), Lower postharvest losses, Attractive financial feasibility (B/C ~1.6, payback ~2.2 seasons). Operational recommendations: use daily FAO ET<sub>c</sub>, target I80 throughout the season with the exception of the flowering–early bloom phase in case of heat waves (temporarily increase to ~90–100%). Maintain 120-mesh filtration, perform weekly filter flushing, and monitor phase-specific K<sub>c</sub>. This package is suitable for adoption by dryland farming groups seeking high productivity and water-energy efficiency.

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