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Evaporation-Based Irrigation Strategy for Tomato Production Using a Solar-Powered Drip Irrigation System

Glenn A. Batoon[1], Catherine A. Bartolome[2], Pinky Melanie DC. Panlasigui[3], Elmer A. Rosete[4]
Campus Research Department, Isabela State University, Echague, Isabela [1,2,3,4]
glenn.a.batoon@gmail.com catherine.bartolome@gmail.com; pinkymelanie.d.panlasigui@isu.edu.ph; elmer.a.rosete@isu.edu.ph

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ABSTRACT

This study evaluated the effects of evaporation-based irrigation scheduling on tomato growth, yield, water productivity, and economic performance using a solar-powered drip irrigation system at the Isabela State University Research Experimental Area, Echague, Isabela. Four irrigation regimes based on Class A pan evaporation were tested: 75% (T1), 100% (T2), 125% (T3), and 150% (T4), arranged in a Randomized Complete Block Design with three replications. Results showed that irrigation level significantly affected plant height, number of leaves, fruit diameter, percent effective flowers, and yield ($p < 0.05$). The highest projected yield was obtained under T4 (1,142.22 kg per 1,000 m^2), although it was statistically comparable to T3 (1,119.23 kg per 1,000 m^2). Treatment 3 achieved the highest water productivity at 6.87 kg m^{-3}, followed by T2 (6.43 kg m^{-3}), T1 (6.39 kg m^{-3}), and T4 (6.29 kg m^{-3}). Economic analysis indicated that the solar-powered drip irrigation system was financially viable, with a benefit-cost ratio of 1.76, a return on investment of 42.03%, and a payback period of 2.38 years. The findings suggest that irrigation scheduling based on 125% of Class A pan evaporation provides an effective balance between yield and water-use efficiency and can serve as a practical climate-resilient irrigation strategy for tomato production in water-limited environments.

Keywords: *solar-powered drip irrigation, tomato yield and growth, pan evaporation irrigation scheduling, water productivity, supplementary irrigation management*

Introduction

Tomato (*Lycopersicon esculentum Miller*), commonly known as "kamatis," is considered one of the most important vegetable crops due to its versatility in usage. It is a rich source of vitamins, minerals, and fiber, as well as a dietary source of antioxidants (DA, 2018). Isabela is among the producers of tomatoes under the following climatic conditions with an average annual precipitation of 1,756.3mm, a season not very pronounced, relatively dry from January to April, and wet for the rest of the year. Farmers grow tomatoes in a wide range of conditions, from dry to wet environments with abundant rainfall. As a result, understanding the water needs of tomatoes is critical for improving irrigation management, maximizing crop yield, and preserving water resources, including weather conditions, crop growth stage, cultivar characteristics, and soil properties, which influence tomato water requirements (Lu et al., 2021).

Essentially, water demand for optimal growth and development depends on the crop species, soil, and weather conditions during the growing season. These water demands of the crop are dynamic, varying both during the day and throughout the growing season (Unsworth, 1975). There is an urgent need to develop effective water management strategies to enhance crop productivity in irrigated agriculture. Tomatoes require a significant amount of water; however, excessive application can lead to excessive biomass accumulation, ultimately reducing their yield (Xiukang et al., 2016).

Irrigation is a method used to provide additional water to crops when natural precipitation is insufficient or unevenly distributed. Agriculture is the largest consumer of water, with irrigation accounting for 70% of global freshwater withdrawals and 90% of water used by consumers (Siebert et al., 2010). Drip irrigation provides an efficient, water-saving method for delivering water and nutrients directly to crop roots, thereby enhancing yields and promoting sustainable agricultural practices. While it faces challenges like high initial costs, especially for smallholder farmers, its benefits include reduced water loss, increased productivity, and minimized disease by keeping leaves dry. The technology is suitable for various conditions, including sloping farms, and requires filtered water to prevent clogging from sediments and dissolved chemicals (FAO, 1985).

Moreover, drip irrigation is beneficial because it allows exact volumes of water to be supplied directly to the root zone at nearly any irrigation frequency. This has the potential to significantly improve water management for crop yield and quality optimization, hence making drip irrigation one of the most water-efficient irrigation application technologies. Furthermore, because of the nature of the systems, less water and nutrients are lost through deep percolation, total water requirements are reduced, evaporation and deep drainage losses are minimal, rainfall is captured and used more effectively, and waterlogged conditions are less likely because plant roots are exposed to both dry air-filled soil and wetted air-reduced soil (Bhattarai et al., 2006).

In addition, research shows that drip irrigation can decrease water usage by 30% to 50% compared to traditional methods like sprinkler irrigation, significantly reducing losses due to evaporation and runoff (Mukherjee et al., 2023). This efficiency benefits farmers economically and helps conserve the environment by reducing runoff and evaporation losses associated with less efficient irrigation methods (Mulhollem et al., 2022).

Furthermore, the adoption of solar-powered drip irrigation systems has been shown to enhance crop quality, yield, and resilience against climatic fluctuations, thereby contributing to improved food security and livelihoods (Singh et al. 2023). The necessity for sustainable irrigation solutions has led to the increasing integration of renewable energy sources, particularly solar power, into irrigation practices. Solar-powered irrigation systems utilize photovoltaic (PV) panels to convert sunlight into electricity, which can then be used to power water pumps for irrigation purposes (WaterSense, 2017). The significance of this irrigation strategy lies not only in its environmental benefits but also in its potential to empower smallholder farmers, particularly in remote and underserved areas. By utilizing solar energy, these systems can operate independently from grid electricity, significantly lowering operational costs and making efficient irrigation technology accessible to farmers who previously faced financial barriers (Cerestia, 2024).

Moreover, tomato farming in the Philippines can be highly profitable, especially for off-season production, ideally between May and September. Whether on a small backyard farm or a large-scale operation, success depends on effective irrigation practices. During the dry season, tomatoes can thrive with proper irrigation; however, many farmers lack the technical knowledge to adequately meet their irrigation needs. To address this problem, using current evaporation data can provide a solution for crop irrigation. The approach is straightforward: establish an appropriate watering schedule, adjust for changes in weather or environmental conditions, and irrigate based on the soil's moisture needs. This method reduces the watering rate when less water is needed, especially during the cooler months. This will save on high fuel costs, prevent overwatering, and ensure optimal plant health. Hence, this study aimed to assess the performance of tomatoes under different irrigation regimes. Specifically, it determined the effect of irrigation on tomato growth and yield, water productivity, and the economic viability of a solar-powered drip irrigation system.

Methods

Experimental Design and Layout

The research was established following a Randomized Complete Block Design with four (4) treatments replicated three (3) times. The area was divided into three equal blocks with four plots. Each plot measured 5.0 meters in length and 0.5 meters in width, with plants spaced 50 centimeters apart per hill. The lateral lines of the drip irrigation system were spaced 0.75 meters apart. Additionally, border plants were planted as buffers. Each plot contained 10 experimental seedlings, resulting in a total density of 120 seedlings across all plots, excluding the border plants. The treatments were based on the different irrigation regimes. They are as follows:

T_1 = 75% pan evaporation

T_2 = 100% pan evaporation

T_3 = 125% pan evaporation

T_4 = 150% pan evaporation

When heavy rainfall provided adequate moisture to plants during the day, there was no need to irrigate. However, if the management-allowable deficit had already reached 40%, irrigation was provided based on the different treatments.

Planting Materials

The Diamante tomato seedlings used in the study were obtained from a reliable source.

Land Preparation

Land preparation for dry seeding typically involved plowing or rotovating, followed by harrowing and leveling of dry and friable soil.

Irrigation System and Water Application

Before the treatments were applied, irrigation was done at field capacity. Once the different treatments were introduced, irrigation was adjusted based on 75%, 100%, 125%, and 150% of evaporation. A solar-powered drip irrigation system was utilized to water the plants. It features pressure-compensating emitters with a discharge rate of 5 liters per hour, a 2 hp submersible pump, 12 solar panels (200 watts each), and an elevated tank with a capacity of 1,000 liters. The base area designated for each tomato plant is 30.5 cm x 30.5 cm, which corresponds to one square foot. The formula for calculating the volume of water and the time needed for irrigation is shown below.

Volume of Water (liters) = Rate of Evaporation (%) x Base Area per Plant (cm^{2}) x Evaporation (cm)/1000

$$\text{Time of Irrigation} = \frac{\text{Volume of Water (liters)}}{\text{Discharge of Emitter (liters/hr)}}$$

Soil Physical Properties Determination

The physical properties of the soil were determined using the following formulas:

1. Bulk Density. Soil bulk density determination (BD) was done per replicate. Soil samples were taken by pressing a core sampler into the pot at a depth of 15 centimeters and will be oven-dried for 24 hours at a temperature of 105-110°C. The computation was done using the formula:

$$BD = \frac{W_s}{V_t} \qquad (1)$$

where:
BD = Bulk Density of the Soil, g/cc
Ws = Dry Weight of the Soil Sample, g
Vt = Total Volume of the Soil Sample, cc (equal to the volume of the core sampler)

2. Soil Moisture Content. It was determined using a digital moisture meter, which was taken from the plots at depths of 0 – 20 cms. It was done as the need arose.
3. Field Capacity. The field capacity of the soil samples obtained using core samplers was measured 2-3 days after heavy rainfall. The soil samples were oven-dried for at least 24 hours at temperatures ranging from 105 to 110 °C. The field capacity was computed using the formula:

$$FC = \frac{F_w - ODW}{ODW} \, x\, 100 \qquad (2)$$

where:
FC = field capacity
Fs = fresh weight of the soil sample

ODW = dry weight of the soil sample

4. Permanent Wilting Point. In the absence of tools for determining the soil's permanent wilting point, the following formula was employed to estimate the permanent wilting point.

$$PWP = \frac{FC}{2-2.4} \qquad (3)$$

In this study, the formula used is:

$$PWP = \frac{FC}{2} \qquad (4)$$

where:
PWP = Permanent Wilting Point

5. Available Moisture. It was computed using the formula:

$$AM = FC - PWP \qquad (5)$$

where:
AM = Available Moisture

6. Management Allowable Deficit. In this study, the management allowable deficit is 40% of the available moisture (Maughan et al., 2015), computed using the following formula:

$$MAD = 40\%\ of\ AM \qquad (6)$$

where:
MAD = Management Allowable Deficit

7. Irrigation frequency. It refers to the number of days between irrigations during periods without rainfall. It depends on the consumptive use rate of a crop and on the amount of available moisture in the crop's root zone. It is a function of crop, soil, and climate. Irrigation should start when about 40% of the available moisture has been used in the root zone, where most of the roots are concentrated. The interval that can be safely allowed between two successive irrigations is known as the frequency of irrigation, computed using the following formula:

$$\text{Irrigation Interval} = \frac{\text{Allowable Soil Moisture Depletion}}{\text{Daily Water Use}} \qquad [7]$$

For Clay Loam Soil: F.C. = 22.01%, PWP = 10%, BD = 1.53 g/cc

Root Depth: 30 cm, ET Ratio: 0.60 cm/day

Allowable Soil Moisture Depletion = 40% of Available Soil Water

$$\text{Available Water} = \frac{(22.01-10) \times 1.53}{100} \times 30 \text{ cm} = 5.51 \text{ cm}$$

Allowable Soil Moisture Depletion = 40% x 5.51 = 2.2cm

$$\text{Irrigation Interval} = \frac{2.2 \text{ cm}}{.60 \text{ cm/day}} = 3.66 \text{ days (twice a week)}$$

Data Collection

Tomato yield and growth parameters were recorded and compared among treatments. Plant height and fruit diameter were measured using a meter and a caliper, respectively.

Water Productivity

Water productivity (kg yield m^{-3} water) was calculated as fruit yield divided by the total water input from rainfall plus irrigation (WP_{i+R}).

Data Analysis

The data were analyzed using IRRI STAR Nebula -2.0.1. Whenever the treatment effects were found to be significant, a comparison of treatment means was performed to determine exactly which treatment had a difference in means.

Economic Analysis

In crop production, it is essential to consider the economic benefits gained from the products. The formulas were as follows:

1. Net Present Value (NPV)

$$NPV = Present\ value\ of\ Revenue - Present\ Value\ of\ Cost \quad (7)$$

2. Annual Equivalent Revenue (AER)

$$AER = Annual\ Revenue - Annual\ Cost \quad (8)$$

3. Benefit-Cost Ratio (BCR)

$$BCR = \frac{Present\ Value\ of\ Benefits}{Present\ Value\ of\ Cost} \quad (9)$$

4. Return on Investment (ROI)

$$ROI = \frac{Annual\ Net\ Revenue}{Investment\ Cost} \quad (10)$$

5. Payback Period (PBP)

$$PBP = \frac{Investment\ Cost}{Annual\ Net\ Revenue} \quad (11)$$

Ethical Considerations

The study was conducted following the research guidelines of Isabela State University and adhered to ethical standards in agricultural research. Experimentation was implemented within the desired research area with careful management of water and soil resources to prevent environmental harm. During the study, data collection was recorded accurately and analyzed objectively to ensure the reliability and integrity of the research results.

Results and Discussion

Climatic Conditions During the Study

Figure 1 presents the daily weather conditions recorded during the conduct of the study, based on data obtained from the ISU–PAGASA Agrometeorological Station. The weather parameters monitored included minimum and maximum air temperature, rainfall, and evaporation. The highest maximum temperature recorded during the study was 39.0°C in April, the hottest month of the study period, while the lowest minimum temperature was 19.2°C.

There has been a rare occurrence of rainfall recorded in March and April. However, during the first week of March, the highest rainfall recorded was 45.6 mm. The average evaporation rates for February, March, April, and May were 2.80 mm, 4.04 mm, 5.68 mm, and 5.56 mm, respectively.

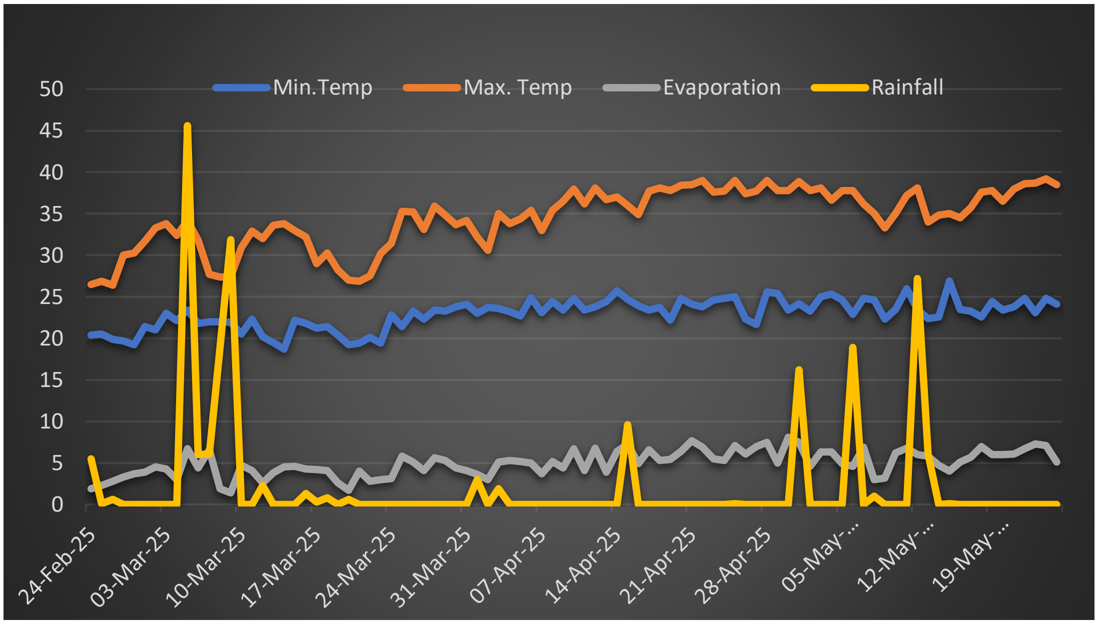

Figure 1. *The Weather Data at ISU-PAGASA*

Soil Physicochemical Properties of the Experimental Area

The physical properties of the soil were determined, showing a field capacity of 22.01%, bulk density of 1.53%, available moisture of 11.99%, management allowable deficit of 7.19%, permanent wilting point of 10%, and apparent specific gravity of 1.53.

The soil chemical properties are shown in Table 1. Based on the results of soil analysis, the soil in the experimental area is slightly acidic; it has medium organic matter (OM) content, moderately high phosphorus, and very high potassium.

Table 1. Soil Chemical Properties of the Soil in the Experimental Area

Soil Sample	pH	Organic Matter (OM), %	Available Phosphorus (P), ppm	Exchangeable Potassium (K), ppm
ISU	5.91	2.97	13.80	91.51

Note: Based on the analysis of the Regional Soils Analytical Services Laboratory

Growth Parameters

1. *Plant Height*

Table 2 shows the average plant height (cm) per treatment at different ages. A statistically insignificant difference ($p > 0.05$) was observed between the treatments at 15 days after treatment (15 DAT). This could be accounted for by the initial soil moisture content, which was adequate to satisfy the crop water requirements of the different treatments, particularly during the vegetative stage, resulting in uniform plant height. However, significant differences ($p < 0.05$) were observed at ages 30DAT and 45DAT. The comparison of means showed that T1 was significantly different from T2, T3, and T4 at 30DAT and 45DAT. Varying irrigation levels may have contributed to differences in plant height. According to Wu et al. (2017), irrigation, fertilization, and growing season had highly significant effects on the plant height of tomato.

Table 2. Plant Height of Tomato under Different Treatments (cm)

Treatment	Days after Transplanting		
	15	**30**	**45**
T1 (75% pan evaporation)	27.61	47.93[b]	77.67[b]
T2 (100% pan evaporation)	27.68	49.13[a]	81.33[a]
T3 (125% pan evaporation)	28.33	51.47[a]	83.59[a]
T4 (150% pan evaporation)	29.44	52.33[a]	83.69[a]
Probability Value	0.48[ns]	0.04*	0.005**
CV%	5.25	3.21	1.94

*Note: ns - not significant at 5% level, * - significant at 5% level, ** - significant at 1% level*

2. *Number of Leaves*

The number of leaves from each replicate per treatment was counted. The average number of leaves, as influenced by the different irrigation regimes, is shown in Table 3. Except for the measurement taken 15 days after transplanting (15 DAT), the number of leaves was significantly influenced by the different treatments. At 15 DAT, the result is consistent with the insignificant effect of irrigation ($p > 0.05$) on the height of the plant. The residual moisture content in each plot was enough to sustain a uniform number of leaves. Similarly, Me et al. (2019) found that increasing irrigation water to 100% ETc significantly increased the number of leaves per tomato plant, directly contributing to above-ground biomass.

Table 3. Number of Leaves of Tomato under Different Treatments

Treatment	Days after Transplanting		
	15	**30**	**45**
T1 (75% pan evaporation)	7.67	10.62[b]	17.18[b]
T2 (100% pan evaporation)	7.78	10.64[a]	17.65[a]
T3 (125% pan evaporation)	7.89	11.92[a]	18.81[a]
T4 (150% pan evaporation)	8.11	12.12[a]	19.33[a]
Probability Value	0.11[ns]	0.017*	0.006**
CV%	2.35	4.42	2.78

*Note: ns - not significant at 5% level, * - significant at 5% level, ** - significant at 1% level*

Yield and Yield Components

1. *Fruit Diameter*

The diameter of the fruits from the experimental crop was measured and recorded after priming, using a caliper. As shown in Table 4, the results were significant ($p < 0.05$), indicating that varying levels of irrigation significantly affect fruit diameter. The comparison of means indicated no significant differences between T1 and T2, as well as between T2, T3, and T4. According to Abdelhady et al. (2024), the elongation of plant cells is typically restricted in dry conditions due to the obstruction of water flow from the xylem to the adjacent elongating cells, which is influenced by irrigation scheduling.

Table 4. Fruit Diameter of Tomato under Different Treatments

Treatment	Fruit Diameter (mm)
T1 (75% pan evaporation)	34.38[b]
T2 (100% pan evaporation)	36.09[ab]
T3 (125% pan evaporation)	39.32[a]
T4 (150% pan evaporation)	39.54[a]
Probability Value	0.033*
CV%	4.87

*Note: * - significant at 5% level*

2. *Percent Effective Flower*

The percent effective flower is calculated as the ratio of the number of developed fruits to the total number of flowers. The relevant data is presented in Table 5. Statistical analysis showed significant differences between the treatments ($p < 0.01$). This implies that the different irrigation regimes significantly affect the percentage of effective flowers. T1 had the lowest mean and significantly differed from T2, T3, and T4, but T3 and T4 showed no significant difference between them.

Table 5. Percent Effective Flower of Tomato under Different Treatments

Treatment	Percent Effective Flower (%)
T1 (75% pan evaporation)	34.69[c]
T2 (100% pan evaporation)	37.74[b]
T3 (125% pan evaporation)	41.77[a]
T4 (150% pan evaporation)	43.25[a]
Probability Value	0.007**
CV%	3.31

*Note: ** - significant at 1% level*

3. *Yield Performance*

The yield of tomatoes is determined by the weight of the fruit. The yield data are presented in Table 6. The results show that treatments with increased irrigation produced significantly higher yields ($p < 0.01$). Among these treatments, T4 achieved the highest yield, followed by T3, T2, and T1.

Table 6. Yield per Hill and Projected Yield per 1000 sq.m. of Tomato under Different Treatments

Treatment	Yield per Hill, g	Projected Yield per 1000 sq. m., kg
T1 (75% pan evaporation)	232.95[b]	776.42[b]
T2 (100% pan evaporation)	268.23[b]	894.01[b]
T3 (125% pan evaporation)	335.80[a]	1,119.23[a]
T4 (150% pan evaporation)	342.67[a]	1,142.22[a]
Probability Value	0.002**	0.002**
CV%	7.17	7.17

*Note: ** - significant at 1% level*

This indicates a significant response in yield associated with varying levels of irrigation. A comparison of the means showed that T3 and T4 had statistically similar yields. Likewise, Somefun et al. (2024) found that effective water management practices are crucial for maximizing tomato yield and reducing the risks associated with climate change. The need for climate-smart irrigation management techniques in agriculture has increased to optimize water use efficiency and enhance crop productivity.

Water Use and Economic Performance

Water Productivity

Water productivity is generally defined as crop yield per cubic meter of water consumed. Treatment 3 obtained the highest water productivity with 6.87 kg/cu. m., followed by T_2 (6.43 kg/cu. m.), T_1 (6.39 kg/ \cu. m. and T_4 (6.29 kg/cu. m.).

Economic Viability of the Irrigation System

1. *Benefit-Cost Ratio (BCR)*

It is a monetary and qualitative statistic that shows the link between the relative costs and benefits of a proposed project. The BCR was 1.76, which is greater than 1, indicating the project had a positive result.

2. *Return on Investment*

It is a metric that determines the system's economic feasibility. The computed ROI (42.03%) was good since it is greater than 10%. A 10% per year return on investment is feasible.

3. *Payback Period (PBP)*

It is the number of years it takes to repay the initial cash investment. The project has a 2.38-year payback period, which is considered feasible since it is lower than 10 years.

Conclusion and Future Works

The study demonstrated that evaporation-based irrigation scheduling integrated with a solar-powered drip irrigation system can effectively support tomato production under dry-season conditions. The findings indicate that an irrigation level equivalent to 125% of Class A pan evaporation provides an optimal balance between crop productivity and water-use efficiency, making it a practical irrigation scheduling approach for tomato cultivation.

The results further highlight the potential of solar-powered drip irrigation as a climate-smart agricultural technology that promotes water conservation, enhances production efficiency, and reduces dependence on conventional energy sources. Its economic feasibility suggests that the technology can contribute to improved farm profitability while strengthening the resilience of smallholder farming systems to water scarcity and climate variability.

However, the findings are limited to a single growing season and the specific environmental conditions of the study area. Future studies should evaluate the performance of evaporation-based irrigation scheduling under different soil types, climatic conditions, and cropping seasons, as well as compare solar-powered drip irrigation with conventional irrigation methods and assess its long-term economic sustainability.

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Conflict of Interest

The authors declare no conflict of interest.

Artificial Intelligence (AI) Declaration Statement

In the preparation of this work, the authors used ChatGPT-4, OpenAI, and Google AI for initial literature review, grammar checking, and text summarization. Beyond that, the authors reviewed and edited the content as necessary and took full responsibility for the publication's content, ensuring that all facts and conclusions were accurate and aligned with the original research.