



Article

Ridge Regression Modeling of Evaporation Reduction Strategies for Small-Scale Water Storage in Semi-Arid Regions

Kishore Nalabolu ^{1,*} , Madhusudhan Reddy Karakala ¹, Apparao Chodiseti ¹, Bhaskara Rao Ijjurouthu ¹ , Narayanaswamy Gutta ², Nataraj Kolavanahalli Chikkamuniyappa ³, Murali Krishna Chitte ¹, Arun Kumar Kondeti ², Veera Prasad Godugula ⁴, Rajakumar Kommathoti Navaneetha ⁵, Mohana Rao Boyinapalli Venkata ⁶, Ratnaraju Chebrolu ⁷, Srigiri Doppalapudi ⁵ and Shobhan Naik Vankanavath ⁵

- ¹ Department of Agricultural Engineering, Agricultural Research Station, Acharya N. G. Ranga Agricultural University (ANGRAU), Ananthapuramu 515 001, India; k.madhusudhanreddy@angrau.ac.in (M.R.K.); ch.apparao@angrau.ac.in (A.C.); i.bhaskararao@angrau.ac.in (B.R.I.); ch.muralikrishna@angrau.ac.in (M.K.C.)
- ² Department of Agronomy, Agricultural Research Station, Acharya N. G. Ranga Agricultural University (ANGRAU), Ananthapuramu 515 001, India; g.narayanaswamy@angrau.ac.in (N.G.); k.arunkumar@angrau.ac.in (A.K.K.)
- ³ Department of Soil Science and Agricultural Chemistry, Agricultural Research Station, Acharya N. G. Ranga Agricultural University (ANGRAU), Ananthapuramu 515 001, India; kc.nataraj@angrau.ac.in
- ⁴ All India Coordinated Research Project on Farm Implements (AICRP on FIM), Dr. NTR College of Agricultural Engineering, Acharya N. G. Ranga Agricultural University (ANGRAU), Bapatla 522 101, India; g.veeraprasad@angrau.ac.in
- ⁵ College of Agricultural Engineering, Acharya N. G. Ranga Agricultural University (ANGRAU), Madakasira 515 301, India; kn.rajakumar@angrau.ac.in (R.K.N.); d.srigiri@angrau.ac.in (S.D.); v.sobhanaik@angrau.ac.in (S.N.V.)
- ⁶ Department of Irrigation and Drainage Engineering, Acharya N. G. Ranga Agricultural University (ANGRAU), Lam, Guntur 522 034, India; bv.mohanrao@angrau.ac.in
- ⁷ Dr. NTR College of Agricultural Engineering, Acharya N. G. Ranga Agricultural University (ANGRAU), Madakasira 515 301, India; ch.rathnaraju@angrau.ac.in
- * Correspondence: n.kishore@angrau.ac.in

Abstract

In semi-arid areas, water loss from small agricultural water storage facilities is significant, owing to evaporation. A longitudinal study was conducted between 2019 and 2022 at the Agricultural Research Station, Ananthapuramu, located in the semi-arid climate of Peninsular India, which compared 12 distinct treatments designed to reduce evaporation. These treatments included bamboo sheets, agricultural residues, *Azolla* (*Azolla pinnata*), monomolecular alcohol films, and oil-based films, along with an untreated control. Evaporation rates and meteorological data were measured using the depth loss method and automatic weather station. Results indicated substantial treatment effects, such as bamboo sheets decreasing evaporation by 88%, reducing daily loss from 5.2 mm to 0.8 mm, while *Azolla* achieved a 62% reduction (2.8 mm). Organic residues decreased evaporation by 37–47%, and chemical monolayers and oils by 21–42%. Ridge regression models demonstrated strong performance ($R^2 = 0.789\text{--}0.808$), with bamboo sheets exhibiting the lowest Root Mean Square Error (0.127 mm day^{-1}). Economic analysis revealed annual water savings of $4700\text{--}4800\text{ m}^3\text{ ha}^{-1}$ for bamboo sheets and $2300\text{--}2500\text{ m}^3\text{ ha}^{-1}$ for less effective covers. Assuming a baseline water value of $0.20\text{ US\$ m}^{-3}$, annual net benefits ranged from 250 to 900 $\text{US\$ ha}^{-1}$, with Net Present Values spanning from 7000 to 160,000 $\text{US\$ ha}^{-1}$ across various scenarios. Overall, bamboo sheets and *Azolla* were identified as the most effective and economically viable options for mitigating evaporation in semi-arid smallholder water systems. Maximum air temperature ($T_{\max}$) was a key meteorological variable used to model daily evaporation, together with wind speed, followed by relative humidity and sunshine duration.



Academic Editor: Giovanni Rallo

Received: 8 December 2025

Revised: 17 January 2026

Accepted: 22 January 2026

Published: 3 February 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: semi-arid regions; floating covers; chemical monolayers; evaporation reduction efficiency; return on investment

1. Introduction

Water availability is a critical determinant of agricultural productivity on a global scale, impacting food security, rural livelihoods, and ecosystem sustainability [1–3]. Agricultural irrigation accounts for the largest proportion of freshwater withdrawals worldwide, exerting significant pressure on available water resources [4–7]. The increasing population, urbanization, and alterations in rainfall patterns due to global warming have intensified competition among agricultural, domestic, and industrial water users, necessitating a focus on improving water-use efficiency, particularly in agricultural irrigation [4,8,9]. Reducing water loss from small storage systems can directly enhance the water supply, stabilize groundwater levels, and boost agricultural production [3,10,11]. Open water bodies, such as ponds, tanks, and reservoirs, are significant sites of agricultural water loss [12–14]. In semi-arid regions, these water bodies are often integral to small-scale irrigation systems. Experimental studies indicate that the minimum evaporation rate in semi-arid areas is 1000 mm yr^{-1} , although this rate can be considerably higher depending on the climatic conditions [15]. These losses are exacerbated during periods of high crop irrigation demand, thereby increasing reliance on groundwater storage. Evaporation can be reduced by 40–70% using physical covers [16,17], by 20–50% using chemical monolayers [18–21], and by 20–35% using biological covers [22,23]. The effects of oils, lipid films, and microencapsulation on evaporation remain under investigation. Recently, floating photovoltaic systems have been proposed as a dual-function approach that reduces evaporation while generating renewable energy; however, owing to their initial cost, they do not achieve water savings and energy gains sufficient to be viable for smallholder farmers [24–26].

The potential of evaporation reduction technologies is promising; however, there is a need for methods to evaluate their effectiveness under smallholder farming conditions in semi-arid climates. Most existing studies have focused on large reservoirs or controlled environments [16,27–29]. There is a paucity of research comparing evaporation suppression methods under actual conditions, with most studies focusing on their technical effectiveness in terms of cost, material availability, and ease of implementation. This knowledge gap has impacted farmers and water managers searching for viable methods to mitigate evaporative losses in the region. Small farm ponds are essential for supplemental irrigation and crop production, particularly during periods of variable rainfall. This study evaluated the effectiveness and cost viability of various evaporation reduction methods for small farm ponds in semi-arid peninsular India. The materials tested included physical covers (bamboo sheets), chemical monolayers (cetyl and stearyl alcohol), oils (silicone and neem), and biological materials (sawdust, groundnut shells, and *Azolla*). The objectives were to (i) estimate the evaporation reduction efficiency, (ii) determine the relative efficacy considering cost and availability, and (iii) assess the economic viability of mass applications. This study aims to provide evidence to benefit water management strategies at both the farm and policy levels, offering cost-effective solutions to reduce groundwater dependence and enhance water security in semi-arid conditions.

2. Materials and Methods

2.1. Study Area

The study was conducted at the Agricultural Research Station in Ananthapuramu, situated in the arid region of Andhra Pradesh, India (14.67° N , 77.60° E ; 350 m above

mean sea level) (Figure 1). This area is part of the Deccan Plateau and is characterized by gently undulating terrain with significant wind. The predominant land use is agricultural, with major crops including groundnut, millets, pulses, and oilseeds [30,31], grown in red loamy soil. Irrigated agriculture is limited, relying primarily on groundwater and small farm ponds for supplemental irrigation. During the dry season, large areas remain fallow, resulting in low surface roughness and increased wind exposure, which further exacerbates the open-water evaporation losses.

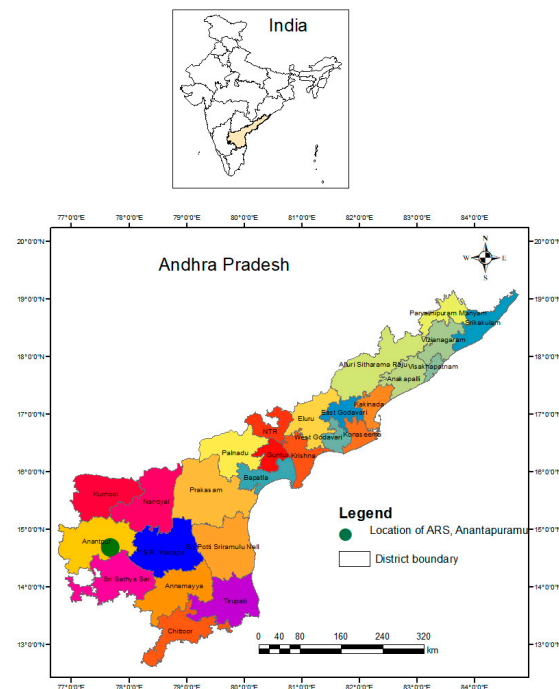


Figure 1. Location of study area.

Climatic Characterization of Study Area

The Ananthapuramu region is characterized by a hot semi-arid climate, marked by irregular monsoon precipitation and high atmospheric evaporative demand. The annual rainfall ranges from 550 to 600 mm, distributed over approximately 34 rainy days, predominantly during the southwest monsoon season [31,32]. The annual potential evapotranspiration surpasses 1500–1800 mm, indicating a significant water deficit [33]. The mean annual temperature is between 27 and 29 °C, with summer maximums exceeding 40 °C, and 130 to 160 days recording temperatures above 35 °C during the period from 2019 to 2022, suggesting prolonged heat stress [30,34]. The study period, from January to March, coincided with peak evaporation and irrigation demand, when evaporation losses were most critical. Winter temperatures are mild and without frost, which is typical of semi-arid tropical regions. The combination of high temperatures, limited precipitation, and sustained evaporative demand frequently results in agricultural droughts. The experiment was conducted during the late Rabi season (January–March) in 2019 and 2022, a period when open-water evaporation intensifies, and farm ponds are utilized for supplemental irrigation [35]. During this time, open-water evaporation increases from 4–5 mm per day in February to 6–7 mm per day in March. Climatological data reveal seasonal variability in the temperature and precipitation (Figure 2). The monthly maximum temperatures ranged from 29.4 °C to 40 °C, with the lowest in January and the highest in March. The daily maximum temperatures varied from 22.2 °C (29 January 2019) to 40.8 °C (30 March 2022). The monthly minimum temperatures ranged between 16 and 23 °C. The average monthly temperature rises from 23.5 °C in January to 32.8 °C in May, then

declines to 23.8 °C in December. Precipitation during winter and early summer is minimal (0–1.5 mm monthly from January to May). Rainfall increases from June, peaking in October with a secondary maximum in September, whereas post-monsoon and winter months remain dry with monthly totals below 2–3 mm, underscoring the necessity for water conservation in farm ponds.

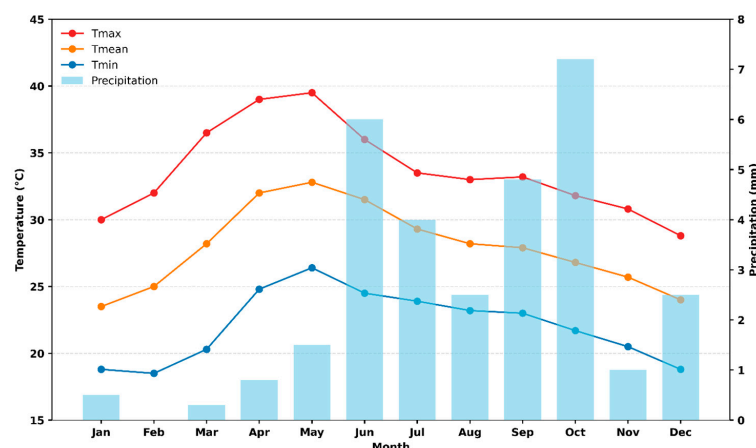


Figure 2. Seasonal variation in mean monthly maximum ($T_{\max}$), minimum ($T_{\min}$), and mean (T_{mean}) air temperature (°C), and precipitation (mm) at the study site. Temperature values are represented by line plots, while precipitation is shown as bars.

2.2. Experimental Design, Meteorological and Evaporation Data Measurement

The experiment assessed twelve treatments, each with three replicates: bamboo sheet; *Azolla* (*Azolla pinnata*); groundnut shell; sawdust; paddy husk; cetyl alcohol; stearyl alcohol; cetyl + stearyl alcohol; silicone oil; neem oil; silicone + neem oil; and control. Each experimental unit consisted of a rectangular cement pan (1.0 m × 0.6 m × 1.0 m) with a water surface area of 0.60 m², filled to a depth of 0.9 m (Figure S1). The bore-well water used had a pH of 7.6, electrical conductivity of 1.74 dS m^{−1}, total dissolved solids of 865 mg L^{−1}, and total hardness of 470 mg L^{−1}, all within the recommended ranges for freshwater systems (pH 6.5–8.5, total hardness ≤ 500 mg L^{−1}, and TDS below the upper permissible limit) [34]. Edge effects reduce wind influence by 30–50% compared to larger ponds, and the efficiency of bamboo may decrease by 10–15% due to wave action [35,36]. Water levels were measured daily at 08:30 using a fixed gauge (resolution 0.1 mm), and pans were refilled to maintain a constant water surface area [37]. The pans were installed on level platforms in an open environment, with boundary fencing to moderate wind and prevent animal intrusion and regular inspections ensured that the pans remained undisturbed, consistent with standard pan evaporation practices. Following standard Class A pan procedures, the water temperature was not recorded daily as all pans experienced the same ambient conditions [33,38–40]. Water quality parameters were not studied to prioritize evaporation quantification and cost analysis under resource constraints, which limits the environmental impact assessment of chemical/oil treatments. Daily evaporation (mm day^{−1}) was quantified using the depth loss method based on water level reductions, with readings corrected for rainfall and refilling. Meteorological data, including maximum air temperature ($T_{\max}$, °C), relative humidity (RH, %), wind speed (WS, km h^{−1}), and sunshine duration (SS, h), were obtained from an automatic weather station located 100 m away. All pans were positioned to ensure uniform environmental exposure, with microclimatic effects from the covers captured in the evaporation responses. Any microclimatic effects induced by the covers, such as alterations in near-surface wind or humidity, were inherently captured in the recorded evaporation responses. Although the lack of microclimatic measurements specific to each treatment is acknowledged as

a limitation, it does not affect the comparative evaluation of the evaporation reduction efficiency among the treatments.

2.3. Different Properties of Material Used for Evaporation Reduction

Twelve distinct treatments were assessed, with one control and 11 materials designed to mitigate evaporation (Figure 3). The fixed and variable unit costs of bamboo sheets are US\$ 75 ha⁻¹ and US\$ 83.2 ha⁻¹, respectively, with an anticipated service life of 3–4 years under semi-arid environmental conditions. Bamboo sheets were installed to cover approximately 95% of the water surface [35]. Routine maintenance practices, such as seasonal inspections and replacement of damaged strips, are conducted as necessary. Organic residue treatments utilized groundnut shells, sawdust, and paddy husks as floating mulches, providing partial shading and disrupting surface airflow. The biological treatment employed *Azolla* (*Azolla pinnata*), a free-floating fern that forms a dense surface mat in association with the nitrogen-fixing cyanobacterium *Anabaena azollae*. *Azolla* was applied at 500 g m⁻² and initially covered approximately 80% of the surface area [41]. Chemical monolayer treatments involved cetyl alcohol (C₁₆H₃₄O) and stearyl alcohol (C₁₈H₃₈O), which were applied as long-chain fatty alcohol films to reduce vapor flux at the air–water interface. [42]. The selected materials, particularly long-chain fatty alcohols and oils, are known to influence surface processes and gas exchange. Cetyl and stearyl alcohol were sprayed in ethanol at rates of 40 mg m⁻² and 45 mg m⁻², respectively. [43]. Oil-based treatments included silicone oil and neem oil, which were used as spreading surface films [44,45]. All treatments were administered at standardized rates, and chemical- and oil-based monolayers were reapplied every four weeks. Silicone oil and neem oil were applied at 50 and 30 mL m⁻², respectively. Agricultural residues were added as groundnut shells at 1.0 kg m⁻², sawdust at 0.8 kg m⁻², and paddy husk at 1.2 kg m⁻². The actual proportions of materials applied were 0.57 m² bamboo sheet, 24 mg cetyl, 27 mg stearyl, 25.5 mg cetyl + stearyl alcohol, 30 mL silicone, 18 mL neem, 14.4 mL silicone + neem oil, 600 g groundnut shell, 480 g sawdust, 720 g paddy husk, and 300 g *Azolla*. Water quality parameters, including EC, salinity, pH, and dissolved solids, were not monitored daily. The experimental design deliberately focused on evaporation measurements and meteorological variables, as the primary aim was to assess the efficiency of surface cover in reducing evaporation and to evaluate its economic performance under semi-arid conditions. The pans were regularly cleaned to remove dust and debris, and any floating material unrelated to the treatment was removed using a fine-mesh scoop; however, assessing their long-term ecological impacts and large-scale deployment was beyond the scope of this study and is recommended for future research.

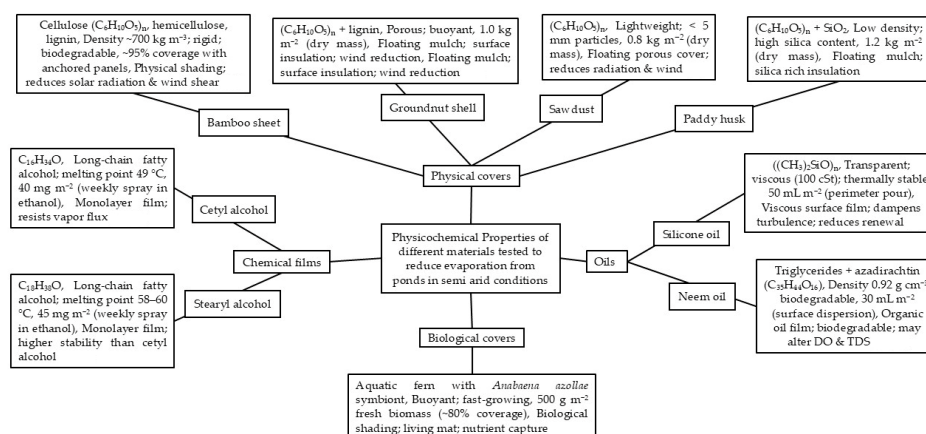


Figure 3. Physicochemical properties, application rates, and mechanisms of different materials tested for evaporation reduction in semi-arid conditions [18–21,35,38,40–42,44,45].

2.4. Cumulative Evaporation and Evaporation Reduction Efficiency Estimation

For each treatment i , the cumulative evaporation over the observation period was calculated by summing the daily evaporation values using Equation (1) [33,39].

$$\text{Cumulative evaporation } (CE_i) = \sum_{d=1}^n E_{i,d} \quad (1)$$

where CE_i is cumulative evaporation (mm day^{-1}), $E_{i,d}$ is the daily evaporation on day d (mm day^{-1}) and n is the total number of days. The Evaporation Reduction Efficiency (ERE) relative to the treatment was estimated using Equation (2) [43,46].

$$\text{Evaporation Reduction Efficiency } (ERE_i)\% = \left(1 - \frac{CE_i}{CE_{control}}\right) \times 100 \quad (2)$$

where CE_i is cumulative evaporation of treatment (i), and $CE_{control}$ is cumulative evaporation from the control tank (mm day^{-1}). This efficiency metric expresses the percentage reduction in seasonal evaporation attributable to each treatment. The use of cumulative seasonal data minimizes day-to-day noise caused by short-term meteorological variability and provides a clearer measure of the overall performance.

2.5. Ridge Regression Modeling

Ridge regression modeling was used to address the issue of multicollinearity among meteorological predictors, a common challenge in evaporation studies that results in unstable ordinary least squares (OLS) coefficients. Prior to model fitting, the dataset was preprocessed. Each column was converted to a numeric data type, and rows with missing entries were removed to maintain the data integrity [47,48]. To meet the requirements of ridge regression, the predictor variables were standardized to have a mean of zero and a standard deviation of one (Z-score normalization). A random 70% of the available observations were used for calibration, with the remaining 30% reserved for validation, ensuring representation of all years in both subsets. This standardization ensures a uniform application of the regularization penalty across coefficients, preventing disproportionate effects on predictors measured on smaller scales [48]. On the calibration subset, a ridge regression model with an L2 regularization parameter $\alpha = 0.373$ was fitted to the data. The ridge penalty was selected based on preliminary trials to balance the bias and variance, avoiding overfitting while retaining the near-linear trend visible in the scatterplots. Model validation was conducted using an independent 30% validation subset that was not used for calibration. Validation performance was then assessed using the same statistics as in calibration: R^2 , Root Mean Square Error (RMSE), and Mean Absolute Error (MAE), which were computed by comparing the predicted and observed evaporation in the validation subset. Ridge regression addresses this issue by introducing a controlled bias to the model estimates, reducing the coefficient variance and enhancing model generalization. The predictive equation for the daily evaporation rate ($\hat{E}$) for each surface cover treatment was calculated using Equation (3).

$$\text{Daily evaporation rate } (\hat{E}) = \beta_0 + \beta_1 T_{max} + \beta_2 RH + \beta_3 U + \beta_4 S \quad (3)$$

where $\hat{E}$ is daily evaporation (mm day^{-1}), T_{max} is maximum air temperature ($^{\circ}\text{C}$), RH is relative humidity (%), U is wind speed (km h^{-1}), S is sunshine duration (h), β_0 is intercept, β_1 , β_2 , β_3 , and β_4 are regression coefficients of maximum temperature ($\text{mm day}^{-1} ^{\circ}\text{C}^{-1}$), relative humidity ($\text{mm day}^{-1} \%^{-1}$), wind speed ($\text{mm day}^{-1} \text{ km}^{-1} \text{ h}$), and sunshine hours ($\text{mm day}^{-1} \text{ h}^{-1}$). Ridge Regression yields stabilized coefficients β_i that quantify the relative importance of each meteorological driver on evaporation. Coefficients approaching zero indicate minimal influence on evaporation under the specified surface

cover, thereby confirming the effectiveness of decoupling. The model performance was evaluated using the coefficient of determination (R^2), Root Mean Square Error (RMSE), and Mean Absolute Error (MAE) using Equations (4)–(6), respectively [49].

$$\text{Coefficient of determination } (R^2) = 1 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (4)$$

$$\text{Root Mean Square Error (RMSE)} = \sqrt{\frac{1}{n} \sum_{i=1}^n (P_i - O_i)^2} \quad (5)$$

$$\text{Mean Absolute Error (MAE)} = \frac{1}{n} \sum_{i=1}^n |P_i - O_i| \quad (6)$$

where P_i is predicted value at observation i , O_i is observed value at observation i , $\bar{O}$ is mean of all observed values, n is the total number of observations, $P_i - O_i$ is individual prediction error, and $|P_i - O_i|$ is absolute error between predicted and observed values.

2.6. Economic Analysis

The economic efficacy of evaporation–reduction treatments for water pans was assessed through discounted cash flow analysis [50–52]. This analysis utilized experimental estimates to calculate water savings, subsequently translating these savings into monetary benefits in comparison to the costs of the treatments. The study focused on a water pan with a water surface area of A (m^2) over 4 years, specifically from January to March 2019–2022. For each treatment, the evaporation depth is determined using Equation (7)

$$\text{Evaporation depth } (\Delta E) = E_{ctrl} - E_{trt} \quad (7)$$

where ΔE is evaporation depth (mm day^{-1}), E_{ctrl} is evaporation in control treatment (mm day^{-1}), and E_{trt} is evaporation of corresponding treatment (mm day^{-1}) is positive when the treatment reduces evaporation relative to the control. The corresponding volume of water saved and gross monetary benefit were obtained by Equations (8) and (9).

$$\text{Volume of water saved } (V_{saved}) = \Delta E \times 10^{-3} \times A \quad (8)$$

$$\text{Gross monetary benefit } (B) = V_{saved} \times P_w \quad (9)$$

where V_{saved} is volume of water saved ($\text{m}^3 \text{ yr}^{-1}$), and A is water surface area (m^2), B is gross monetary benefit of water ($\text{US\$ year}^{-1}$), and P_w is water price ($\text{US\$ m}^{-3}$). Parween et al. (2021) reported that Andhra Pradesh levies area-based irrigation water charges of ₹148.20–1235 ha^{-1} for flow and lift irrigation systems, but the actual price of water during the study years was 0.2 $\text{US\$ m}^{-3}$ [53]. In the analysis of treatment costs, expenses were categorized into fixed and variable components [52,54]. Fixed costs encompassed the initial investment in materials or installation incurred at the commencement of the project, such as the fabrication and placement of the bamboo cover. Variable (recurrent) costs included expenses related to materials, labor, and the re-application of chemical or biological treatments. For treatments requiring multiple applications within the project duration, the per-application cost was determined and aggregated to yield a value using Equation (10).

$$\text{Variable cost } (C_{var}) = C_{mat} + C_{lab} \quad (10)$$

where C_{mat} is the total cost of materials ($\text{US\$ yr}^{-1}$) and C_{lab} is the total labor cost ($\text{US\$ yr}^{-1}$). The combination of a 9% interest rate and 6.5% annual inflation thus reflects a conservative yet realistic approximation of the financing conditions and price dynamics faced by irrigated farmers in Andhra Pradesh during 2019–2022, consistent with

RBI monetary reports, national CPI statistics, and state socio-economic surveys [55,56]. The present value of benefits PV_B , variable costs PV_C and actual discount rate r [50,51] over the project horizon were computed using Equations (11)–(13).

$$\text{Present value of benefit } (PV_B) = \sum_{t=1}^4 \frac{B}{(1+r)^t} \quad (11)$$

$$\text{Present value of costs } (PV_C) = \sum_{t=1}^4 \frac{C_{var}}{(1+r)^t} \quad (12)$$

$$\text{Discount rate } (r) = \frac{1+i}{1+\pi} - 1 \quad (13)$$

where PV_B is present value of benefit (US\$ yr⁻¹), PV_C is present value of variable cost (US\$ yr⁻¹), i is interest rate (%), π is inflation rate (%), t is the period index. The net present value (NPV), benefit–cost ratio (BCR), payback period, return on investment (ROI) of each treatment are calculated using Equations (14)–(17), respectively.

$$\text{Net present value } (NPV) = PV_B - PV_C - C_{fix} \quad (14)$$

$$\text{Benefit cost ratio } (BCR) = \frac{PV_B}{C_{fix} + PV_C} \quad (15)$$

$$\text{Payback period} = \frac{C_{fix}}{B - C_{var}} \quad (16)$$

$$\text{Return on investment } (ROI) (\%) = \frac{NPV}{PV_C} \times 100 \quad (17)$$

A Monte Carlo simulation framework was utilized to evaluate the economic uncertainty related to evaporation–reduction treatments. This simulation conducted 10,000 iterations to assess the uncertainty in the Return on Investment (ROI) for various treatments. The results are presented as probability distributions, illustrating the mean, 5th percentile (P5), and 95th percentile (P95) ROI values for each treatment. This approach indicates that variables such as water price, treatment costs (both fixed and variable), and evaporation reduction efficiency were considered as probabilistic inputs rather than fixed values, resulting in a range of potential economic outcomes. The exceedance curves for Net Present Value (NPV), ROI, and Benefit–Cost Ratio (BCR) further demonstrate the application of a probabilistic method to assess financial risk, revealing that the probability of achieving an NPV greater than zero was essentially 1.0 for the most favorable options. The analysis also incorporated various water price scenarios, ranging from 2.0 to 10.0 US\$.

3. Results

3.1. Evaporation Patterns and Climatic Controls Across Treatments

Daily open water evaporation (control) exhibited a seasonal increase during 2019–2022 from January to March (Figure 4). The control evaporation ranged from 3–5 mm day⁻¹, escalating to 8–11 mm day⁻¹ by the end of March. Peak evaporation reached 11–12 mm day⁻¹ on warmer days, whereas cooler days recorded 3–4 mm day⁻¹. All treatments followed these trends, with reduced levels of significance. During periods of high evaporation (control at 10–11 mm day⁻¹), the treatments demonstrated the following rates: bamboo sheet: 1–2 mm day⁻¹, *Azolla*: 3–4 mm day⁻¹, organic residues: 3–5 mm day⁻¹, and chemical treatments: 5–7 mm day⁻¹. These corresponded to reductions of 80–90% for bamboo, 55–65% for *Azolla*, 35–50% for residues, and 20–40% for chemicals, which is consistent with the seasonal water balance results. Inter-annual variations influenced the curve amplitude, with March 2022 peaks exceeding 10 mm day⁻¹,

whereas 2021 peaked at approximately $9\text{--}10\text{ mm day}^{-1}$. The monthly average evaporation (Figure 5) indicated an increase in control from $4\text{--}5\text{ mm day}^{-1}$ in January to $8\text{--}9\text{ mm day}^{-1}$ in March, with yearly variations of $\pm 0.5\text{--}1.0\text{ mm day}^{-1}$. The treatments exhibited lower monthly averages: bamboo sheet: $1.0\text{--}1.5\text{ mm day}^{-1}$ (January) to $2.0\text{--}2.5\text{ mm day}^{-1}$ (March); *Azolla*: $2.0\text{--}2.5\text{ mm day}^{-1}$ to $3.5\text{--}4.5\text{ mm day}^{-1}$; organic residues: $2.5\text{--}3.5\text{ mm day}^{-1}$ to $4.5\text{--}5.5\text{ mm day}^{-1}$; and chemical treatments: $3.5\text{--}4.5\text{ mm day}^{-1}$ to $5.5\text{--}6.5\text{ mm day}^{-1}$. In March, the control lost $150\text{--}170\text{ mm}$ of water, whereas bamboo and *Azolla* lost $60\text{--}80\text{ mm}$ and $110\text{--}130\text{ mm}$, respectively. All treatments maintained their effectiveness over time and responded to changes in weather. Maximum air temperature and wind speed significantly affected evaporation, whereas relative humidity and sunshine duration had a lesser impact on the daily evaporation rate.

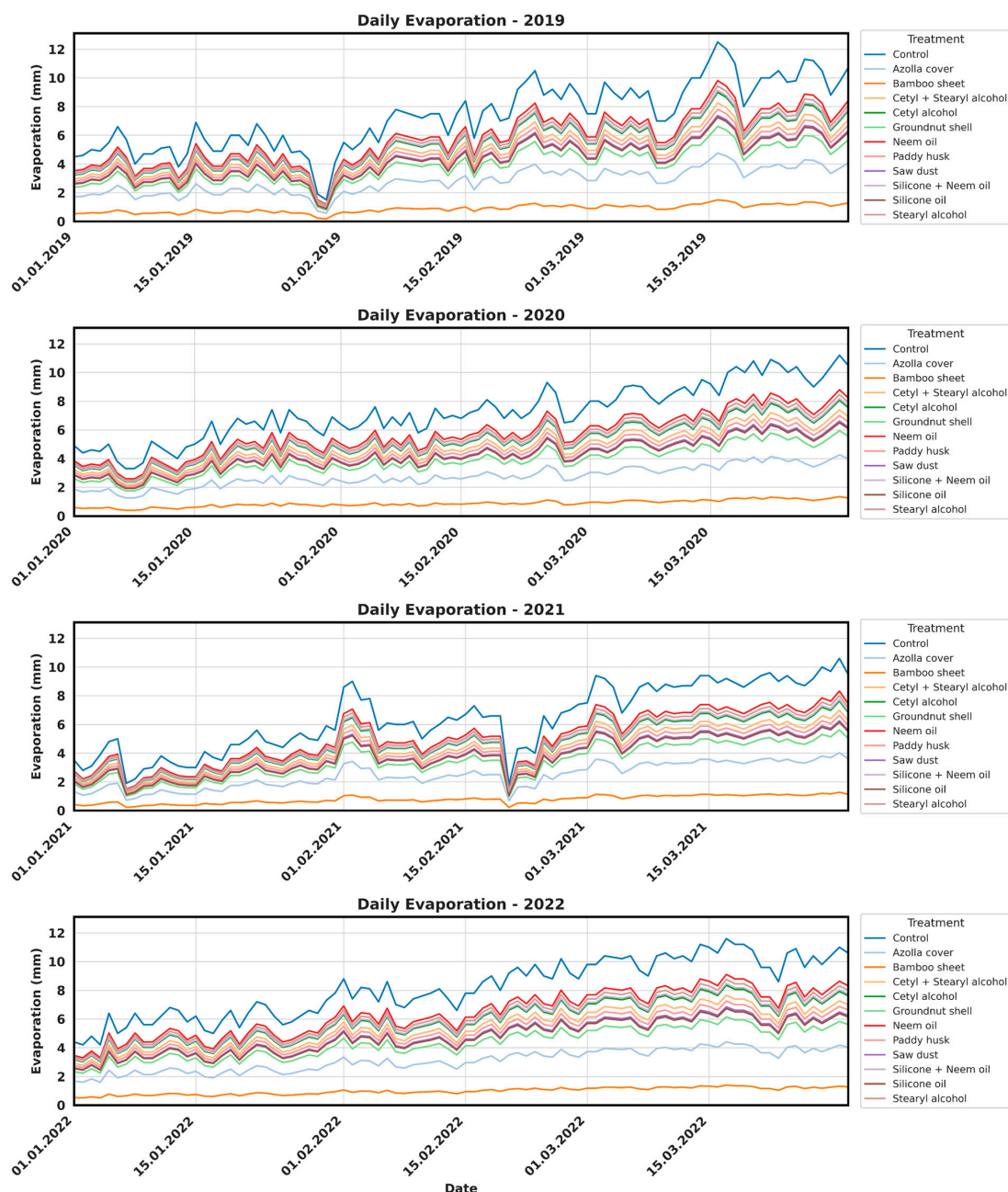


Figure 4. Daily evaporation (mm) under different evaporation reduction treatments for four consecutive years (2019–2022) at ARS, Ananthapuramu.

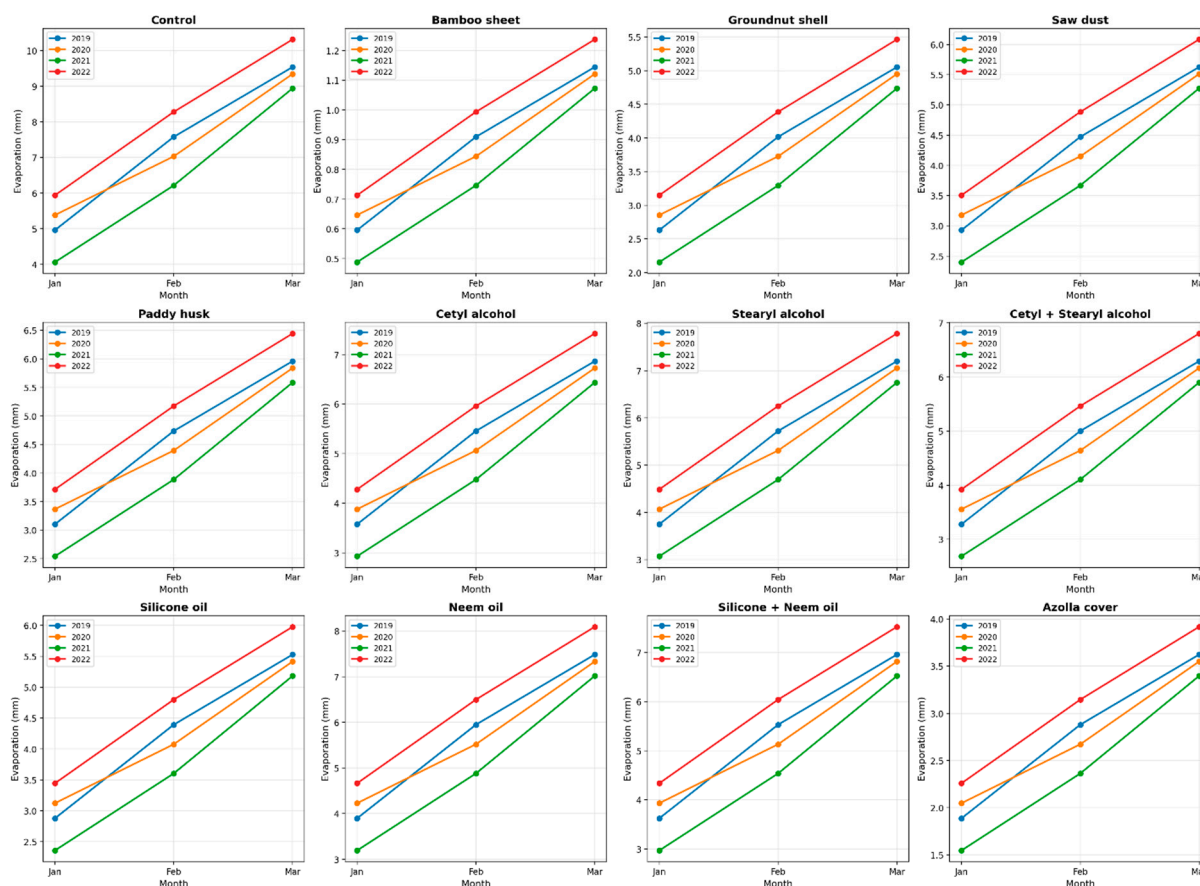


Figure 5. Mean monthly evaporation (mm day^{-1}) for different treatments across four years (2019–2022).

3.2. Weather Parameters on Daily Evaporation Under Different Treatments

The maximum air temperature exerted the most significant influence, followed by wind speed, whereas relative humidity and sunshine hours had comparatively lesser effects. In the open-water control, daily evaporation rates increased with rising maximum temperatures, ranging from $3\text{--}4 \text{ mm day}^{-1}$ to $11\text{--}12 \text{ mm day}^{-1}$ ($24\text{--}40^\circ\text{C}$), corresponding to $0.45\text{--}0.50 \text{ mm day}^{-1} ^\circ\text{C}^{-1}$ (Figure 6). All treatments demonstrated similar patterns at lower temperatures. Bamboo sheets exhibited a slight increase in evaporation ($0.2\text{--}0.3$ to $1.3\text{--}1.4 \text{ mm day}^{-1}$), while *Azolla* showed an increase from $0.4\text{--}0.5$ to $4.0\text{--}4.5 \text{ mm day}^{-1}$. Organic residues and chemical treatments displayed intermediate responses, ranging from $1\text{--}2$ to $6\text{--}7 \text{ mm day}^{-1}$ and $1\text{--}2$ to $7\text{--}9 \text{ mm day}^{-1}$, respectively. The difference between the control and bamboo treatments expanded from $3\text{--}4 \text{ mm day}^{-1}$ under cooler conditions to $10\text{--}11 \text{ mm day}^{-1}$ under hotter conditions. Ridge regression coefficients confirmed the influence of maximum temperature (β_1) across treatments, ranging from 0.283 to $2.257 \text{ mm day}^{-1} ^\circ\text{C}^{-1}$, with the highest value observed in the open-water control ($2.505 \text{ mm day}^{-1} ^\circ\text{C}^{-1}$) (Table 1). Regarding relative humidity, control evaporation decreased from $10\text{--}11 \text{ mm day}^{-1}$ at $40\text{--}45\%$ RH to $4\text{--}5 \text{ mm day}^{-1}$ at $95\text{--}100\%$ RH, as shown in Figure 7. Treatments exhibited similar trends: bamboo showed a slight decline, *Azolla* decreased from $4.0\text{--}4.5$ to $1.0\text{--}1.5 \text{ mm day}^{-1}$, residues from $6\text{--}7$ to $1.5\text{--}2.0 \text{ mm day}^{-1}$, and chemical treatments from $7\text{--}9$ to $2\text{--}3 \text{ mm day}^{-1}$. The RH coefficient (β_2) was negative for all treatments, with the strongest effect observed in neem oil and silicone + neem oil treatments.

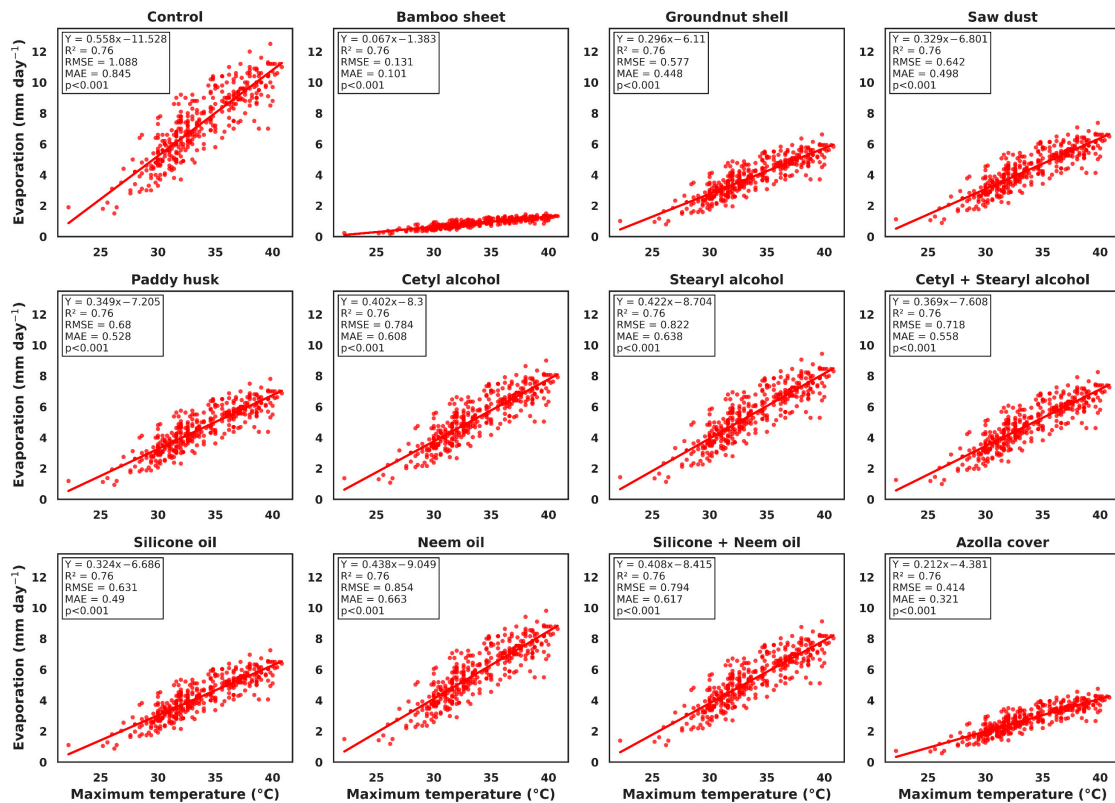


Figure 6. Relationship between maximum air temperature and daily evaporation under different evaporation-reducing treatments during 2019–2022 at the ARS, Ananthapuramu. Solid lines represent fitted ridge regression models, and inset boxes report the corresponding regression equation ($y = mx + c$), coefficient of determination (R^2), root mean square error (RMSE), mean absolute error (MAE) and statistical significance ($p < 0.001$).

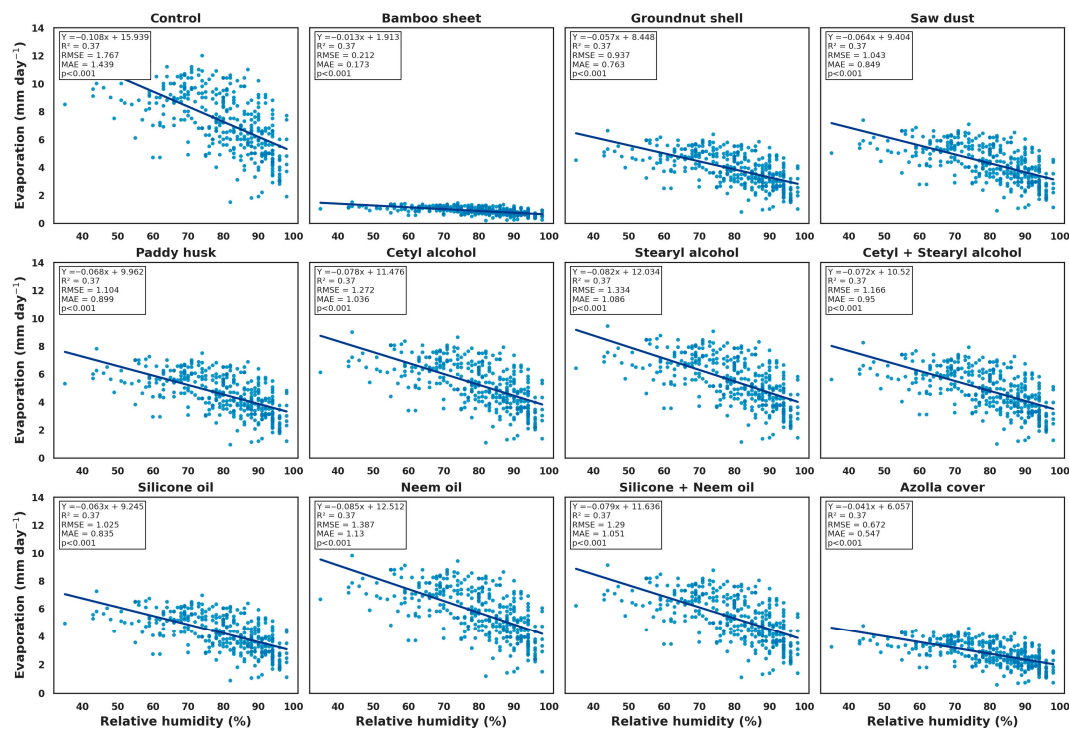


Figure 7. Relationship between relative humidity (%) and daily evaporation (mm).

Table 1. Ridge regression of daily evaporation on weather variables for each evaporation control treatment at Agricultural Research Station (ARS), Ananthapuramu.

Treatment	β_0	β_1 95% CI (High, Low)	β_2 95% CI (High, Low)	β_3 95% CI (High, Low)	β_4 95% CI (High, Low)	R^2	RMSE (mm day ⁻¹)	MAE (mm day ⁻¹)
Control	7.73	2.505 *** (0.737, 0.6)	−0.347 * (0.03, 0.0045)	0.901 *** (0.295, 0.172)	0.398 ** (0.01, −0.172)	0.805	1.046	0.862
Bamboo sheet	0.835	0.283 *** (0.088, 0.072)	−0.01 * (0.0035, 0.0005)	0.051 *** (0.035, 0.02)	0.043 *** (0.0012, −0.02)	0.789	0.127	0.099
Groundnut shell	4.869	1.567 *** (0.39, 0.319)	−0.21 ** (0.0155, 0.0024)	0.441 *** (0.156, 0.091)	0.231 *** (0.0054, −0.09)	0.802	0.628	0.455
Saw dust	4.887	1.542 *** (0.435, 0.355)	−0.223 ** (0.0173, 0.0026)	0.428 *** (0.174, 0.102)	0.218 *** (0.006, −0.103)	0.803	0.62	0.474
Paddy husk	5.375	1.776 *** (0.46, 0.376)	−0.212 ** (0.018, 0.0028)	0.499 *** (0.184, 0.108)	0.261 *** (0.0064, −0.11)	0.8	0.653	0.502
Cetyl alcohol	6.551	2.144 *** (0.53, 0.433)	−0.279 * (0.211, 0.0032)	0.645 *** (0.212, 0.124)	0.334 *** (0.0074, −0.125)	0.808	0.754	0.579
Stearyl alcohol	6.301	2.072 *** (0.556, 0.454)	−0.26 * (0.221, 0.003)	0.618 *** (0.222, 0.13)	0.32 *** (0.008, −0.132)	0.806	0.791	0.607
Cetyl + Stearyl alcohol	6.136	1.993 *** (0.486, 0.397)	−0.258 * (0.02, 0.003)	0.589 *** (0.194, 0.114)	0.304 *** (0.007, −0.115)	0.807	0.693	0.53
Silicone oil	6.208	2.071 *** (0.427, 0.349)	−0.262 * (0.017, 0.0026)	0.613 *** (0.171, 0.1)	0.318 *** (0.006, −0.101)	0.806	0.765	0.585
Neem oil	6.837	2.257 *** (0.58, 0.472)	−0.3 * (0.023, 0.0036)	0.697 *** (0.23, 0.135)	0.36 *** (0.008, −0.137)	0.807	0.727	0.611
Silicone + Neem oil	6.208	2.071 *** (0.538, 0.44)	−0.261 ** (0.021, 0.0033)	0.613 *** (0.215, 0.126)	0.318 *** (0.007, −0.128)	0.806	0.765	0.568
<i>Azolla</i> cover	3.596	1.144 (0.28, 0.228)	−0.169 (0.011, 0.001)	0.297 (0.112, 0.065)	0.16 (0.004, −0.066)	0.796	0.504	0.396

Significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, CI is confidence interval, β_0 is intercept, β_1 is coefficient of $T_{\max}$ (mm day⁻¹ °C⁻¹), β_2 is coefficient of RH (mm day⁻¹ %⁻¹), β_3 is coefficient of wind speed (mm day⁻¹ km⁻¹ h), and β_4 is coefficient of sunshine hours (mm day⁻¹ h⁻¹).

Wind speed significantly influenced evaporation through turbulent exchanges, as shown in Figure 8. In the control scenario, daily evaporation rates increased from 4–5 mm day⁻¹ at very low wind speeds (< 1 km h⁻¹) to 10–11 mm day⁻¹ at 9–10 km h⁻¹, indicating a sensitivity of 0.6–0.7 mm day⁻¹ km⁻¹ h. The treatments exhibited lower responses; for instance, bamboo increased from 0.3–0.4 to 1.2–1.3 mm day⁻¹, *Azolla* from 1.0–1.5 to 4.0–4.5 mm day⁻¹, residues from 2–3 to 6–7 mm day⁻¹, and chemical treatments from 3–4 to 7–9 mm day⁻¹. The most pronounced wind responses were observed for the control and chemical films, underscoring the sensitivity of bare water surfaces and the susceptibility of monolayers to wind-induced mixing. This is consistent with the β_3 coefficients (0.297–0.901 mm day⁻¹ km⁻¹ h) presented in Table 1, which were highest for the control and intermediate for the mulches and chemical films. As daily sunshine increased from overcast conditions (<2 h) to sunny conditions (~10–11 h), control evaporation increased from 3–4 to 10–12 mm day⁻¹, as depicted in Figure 9. Bamboo exhibited minimal response (0.2–0.3 to 1.3–1.4 mm day⁻¹), whereas *Azolla* increased from 0.5–1.0 to 4–5 mm day⁻¹, residues from 1–2 to 6–7 mm day⁻¹, and chemical treatments from 2–3 to 7–9 mm day⁻¹. These responses reflect the effects of radiation and surface heating. Sunshine coefficients (β_4) were positive (0.160–0.398 mm day⁻¹ h⁻¹), with the highest values in the control and the lowest in bamboo and *Azolla*. The model performance demonstrated strong relationships across treatments, with R^2 values ranging from 0.789 for bamboo to 0.808 for cetyl alcohol. The control exhibited RMSE and MAE values of 1.046 and 0.862 mm day⁻¹, respectively (Table 1). Bamboo had the lowest errors (RMSE 0.127, MAE 0.099 mm day⁻¹), followed by *Azolla* (RMSE 0.504, MAE 0.396 mm day⁻¹), while mulches and chemical films showed intermediate errors.

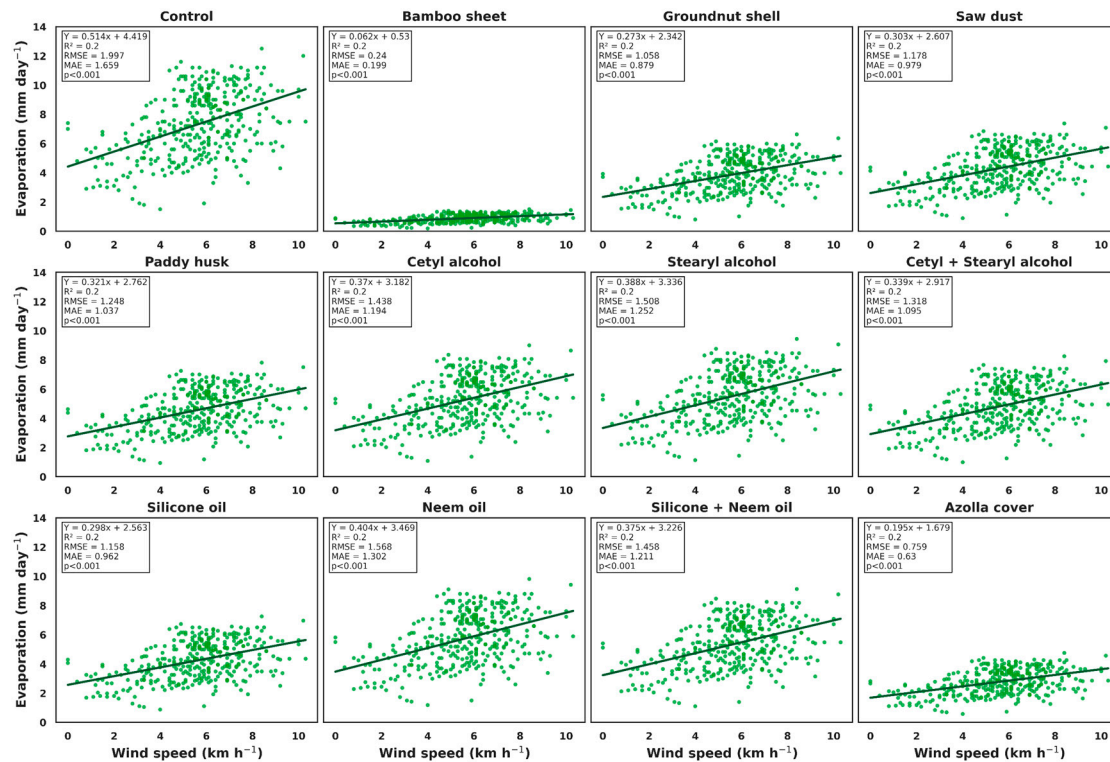


Figure 8. Relationship between wind speed (km h⁻¹) and daily evaporation (mm).

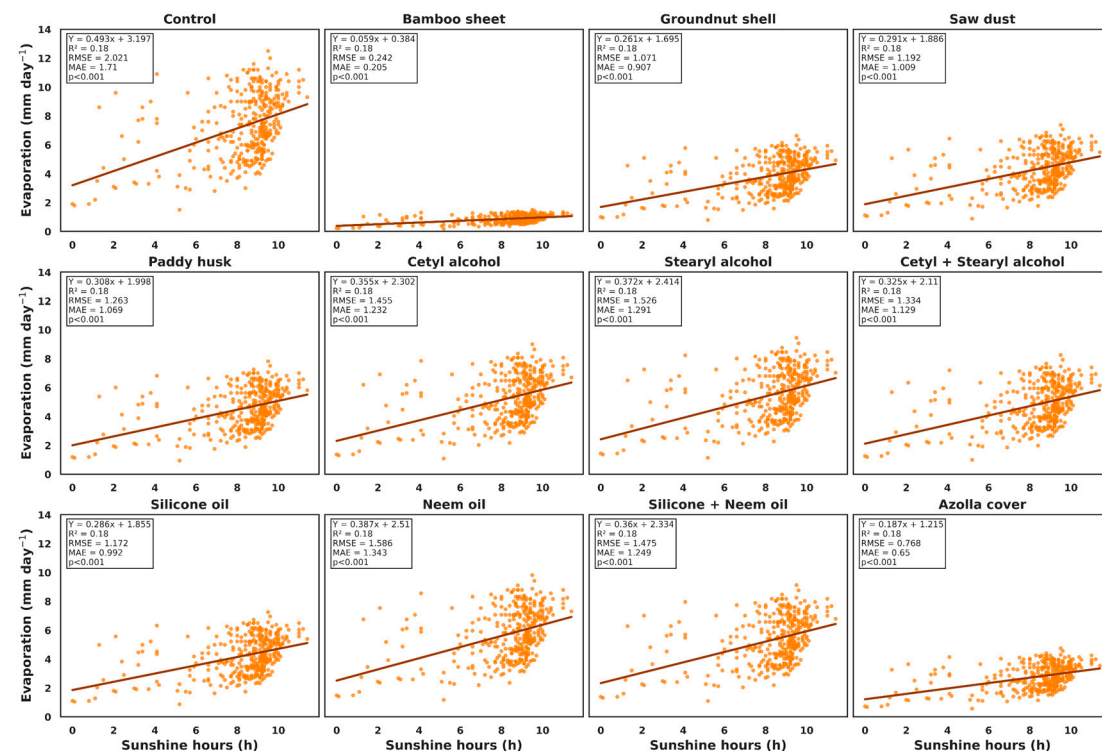


Figure 9. Relationship between sunshine hours and daily evaporation (mm). Treatment Effects and Weather Interactions on Evaporation.

The bamboo sheet covers exhibited the lowest evaporation rates at 0.8 mm day⁻¹, whereas *Azolla* covers showed median values of 2.8 mm day⁻¹. In contrast, control and chemical films recorded higher rates, ranging from 4.5 to 5.8 mm day⁻¹. Sawdust, groundnut shell, and paddy husk showed evaporation rates between 3.0 and 4.5 mm day⁻¹.

respectively. The bamboo sheets achieved the highest evaporation reduction efficiency (ERE) at $88.0 \pm 1.0\%$, followed by *Azolla* at $61.7 \pm 1.5\%$, groundnut shells at $47 \pm 1.0\%$, sawdust at $41 \pm 1.0\%$, and paddy husks at $37.5 \pm 1.0\%$ (Figure 10). Chemical and oil-based treatments exhibited lower EREs, ranging from $42 \pm 1.0\%$ to $21.5 \pm 1.0\%$, and altered water quality by reducing surface tension and oxygen transfer, potentially decreasing dissolved oxygen levels in farm ponds. These long-chain fatty alcohols, despite being biodegradable and having low acute aquatic toxicity, impede oxygen transfer into water bodies, particularly in stagnant farm ponds with limited application. Oil-based treatments, such as silicone oil (sediment-persistent) and neem oil (aquatic-toxic at high doses), may infiltrate soil profiles, affecting the crop root zone and potentially causing phytotoxicity, reduced nutrient uptake, or bioaccumulation in edible portions, especially for sensitive crops such as vegetables or legumes prevalent in semi-arid regions. Based on the results, the treatments were ranked as follows: bamboo sheet > *Azolla* > groundnut shell > silicone oil > sawdust > paddy husk > cetyl + stearyl alcohol > cetyl alcohol > silicone + neem oil > stearyl alcohol > neem oil. As the temperature increased, the evaporation rates increased across all treatments. Below 30°C , evaporation rate ranged from 0.8 to 3.1 mm day^{-1} , whereas above 35°C , evaporation rate ranged from 1.2 to 7.5 mm day^{-1} . Higher relative humidity (RH) levels decreased the evaporation. Wind speed influenced treatment effectiveness, with evaporation rate from 0.9 to 4.2 mm day^{-1} at low speeds and $1.3\text{--}6.8 \text{ mm day}^{-1}$ at high speeds. Floating covers exhibited less variation owing to wind, whereas thin films were ineffective during intense winds.

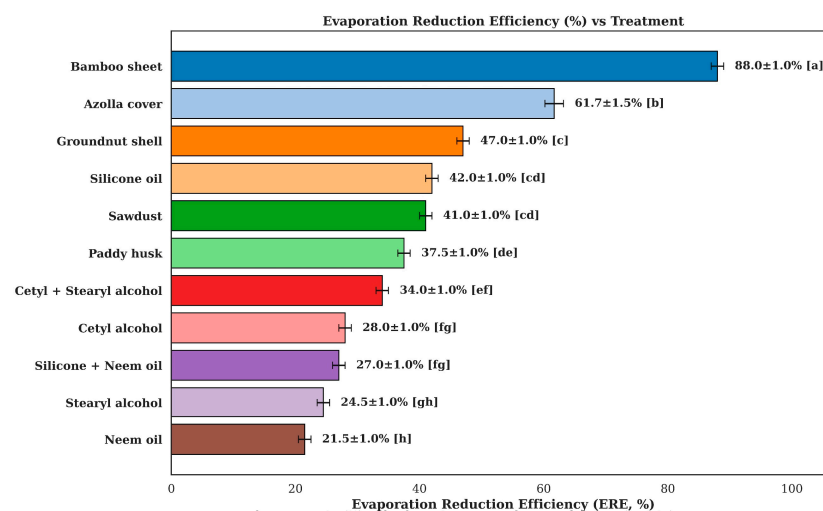


Figure 10. Evaporation reduction efficiency (%) of various physical, organic, and chemical treatments under controlled water tank experiments. Bars represent mean $\pm$ standard deviation. Different lowercase letters indicate significant differences among treatments based on Tukey's HSD test ($p \leq 0.05$).

3.3. Economic Performance and Uncertainty of Evaporation Control Treatments

The economic analysis indicated that all methods for reducing evaporation were financially viable, with water savings surpassing the annualized costs associated with each treatment (Figure 11). The efficiency of evaporation reduction varied, ranging from over 20% for the least effective method to 88% for the bamboo sheets. This resulted in annual water savings of $2300\text{--}2500 \text{ m}^3 \text{ ha}^{-1}$ for the less effective treatments and $4700\text{--}4800 \text{ m}^3 \text{ ha}^{-1}$ for the bamboo sheets. At the baseline water price, these savings translated into annual benefits of $230\text{--}250 \text{ US\$ ha}^{-1} \text{ yr}^{-1}$ for the least effective treatments and $950 \text{ US\$ ha}^{-1} \text{ yr}^{-1}$ for bamboo sheets. Intermediate options, such as *Azolla*, groundnut shells, sawdust, paddy husks, and surfactant mixtures, yielded benefits of $400\text{--}700 \text{ US\$ ha}^{-1} \text{ yr}^{-1}$ (Table 2).

With low annualized costs (30–220 US\$ ha⁻¹ yr⁻¹), the annual net benefits ranged from 250 to 900 US\$ ha⁻¹ yr⁻¹, with bamboo sheets and *Azolla* showing the best performance. Over the duration of the project, these benefits generated substantial net present values (NPVs) across various water-price scenarios (Figure 12). At a water price of 2 US\$ m⁻³, the lower-performing treatments achieved NPVs of 7000–10,000 US\$ ha⁻¹, while bamboo sheets exceeded 30,000 US\$ ha⁻¹ and *Azolla* surpassed 20,000 US\$ ha⁻¹. At 5 US\$ m⁻³, NPVs increased to 25,000–60,000 US\$ ha⁻¹, with bamboo sheets and *Azolla* reaching 80,000 and 50,000 US\$ ha⁻¹, respectively. At 10 US\$ m⁻³, NPVs exceeded 60,000–90,000 US\$ ha⁻¹ for residues and surfactants, reaching 160,000 and 110,000 US\$ ha⁻¹ for bamboo sheets and *Azolla*, respectively. The benefit–cost ratios exhibited similar trends, with most treatments exceeding 50 at 2 US\$ m⁻³, 250–900 at 5 US\$ m⁻³, and 900–1900 at 10 US\$ m⁻³, with bamboo sheets consistently achieving the highest values (Figure 13). The NPV exceedance curves remained positive for all treatments, with a probability of NPV > 0 effectively at 1.0 for the best options, whereas the return on investment (ROI) and benefit–cost ratio (BCR) curves demonstrated values well above 100% and 1.0 in most Monte Carlo simulations (Figure 14).

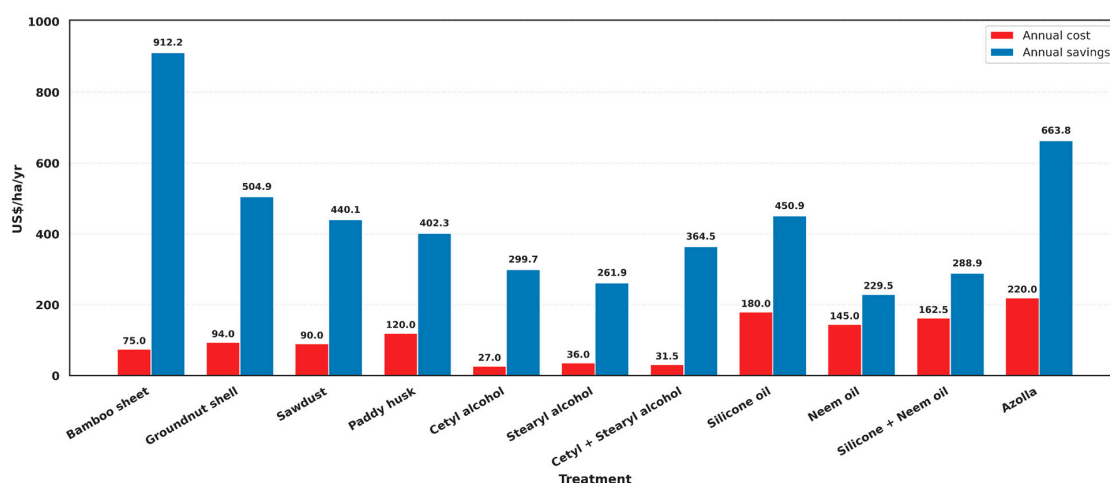


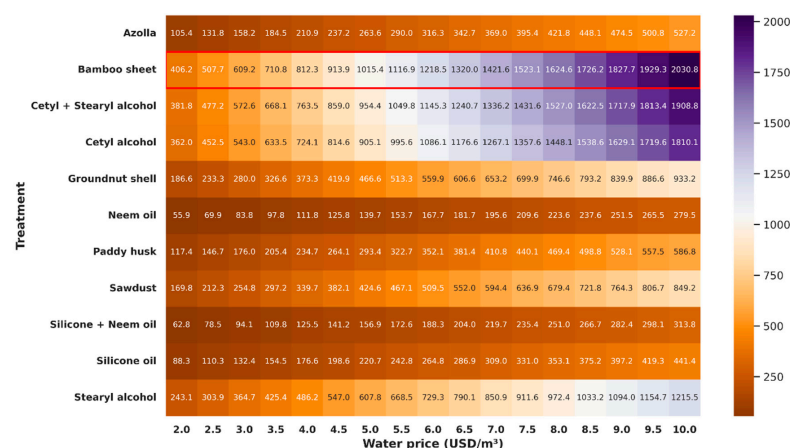
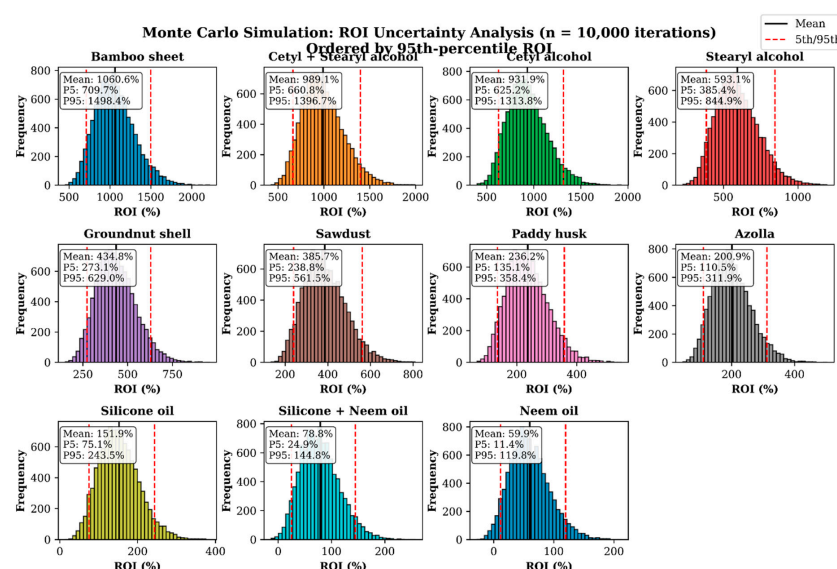
Figure 11. Annual cost and annual savings per treatment (US\$ ha⁻¹ yr⁻¹).



Figure 12. Net present value (NPV, US\$ ha⁻¹) of different water surface treatments as a function of irrigation water price.

Table 2. Fixed and variable costs, evaporation reduction efficiency (ERE), water savings and corresponding water value for different evaporation control treatments.

Treatment	Fixed Cost (US\$ ha ⁻¹)	Variable Cost (US\$ ha ⁻¹)	Evaporation Reduction Efficiency (ERE) (%)	Volume of Water Saved (m ³ m ⁻² of Pan)	Water Saved (m ³ ha ⁻¹)	Water Price (US\$ m ⁻³)	Water Savings Price (US\$ m ⁻³)
Bamboo sheet	75.0	83.2	88.0	0.4752	4752.0	0.2	950.4
Groundnut shell	94.0	96.7	47.0	0.2538	2538.0	0.2	507.6
Saw dust	90.0	92.7	41.0	0.2214	2214.0	0.2	442.8
Paddy husk	120.0	122.7	37.5	0.2025	2025.0	0.2	405.0
Cetyl alcohol	27.0	29.7	28.0	0.1512	1512.0	0.2	302.4
Stearyl alcohol	36.0	38.7	24.5	0.1323	1323.0	0.2	264.6
Cetyl + Stearyl alcohol	31.5	34.2	34.0	0.1836	1836.0	0.2	367.2
Silicone oil	180.0	182.7	42.0	0.2268	2268.0	0.2	453.6
Neem oil	145.0	147.7	21.5	0.1161	1161.0	0.2	232.2
Silicone + Neem oil	162.5	165.2	27.0	0.1458	1458.0	0.2	291.6
Azolla cover	220.0	225.8	62.0	0.3348	3348.0	0.2	669.6

**Figure 13.** Benefit–Cost Ratio (BCR) of all evaporation-control treatments across water prices (2–10 USD m⁻³). Values represent averages over discount rates. Bamboo sheets and Azolla show the highest economic returns, while all treatments maintain BCR > 1. The red mark indicates the best treatment.**Figure 14.** Return on Investment (ROI) uncertainty distributions generated from 10,000-iteration Monte Carlo simulations for all evaporation-control treatments. Histograms illustrate treatment-wise ROI variability, with mean, 5th, and 95th percentiles indicated. Physical covers and long-chain fatty alcohol films yield the highest ROI and tightest uncertainty bounds, while oil-based treatments display lower central tendencies and broader dispersion.

4. Discussion

4.1. Evaporation Dynamics, Climatic Sensitivity, and Treatment Performance

The observed trend in the control evaporation from January to March corresponds to the atmospheric demand during the late *rabi* and pre-monsoon seasons, which are characterized by increasing temperatures, net radiation, and vapor pressure deficit [12,15]. During this period, control evaporation ranged from 3–5 mm day⁻¹ in January to 8–11 mm day⁻¹ by March, aligning with observations in the semi-arid regions of India and drylands [57,58]. Although interannual variations were aligned with seasonal temperature and wind conditions, the seasonal pattern and treatment ranking remained stable. All treatments responded to meteorological factors with different sensitivities. Bamboo sheets exhibited the lowest evaporation rates, rarely exceeding 2–2.5 mm day⁻¹ even under extreme conditions, preventing 80–90% of potential water loss. Bamboo sheets act as a rigid physical barrier that intercepts solar radiation, suppresses surface turbulence, and increases aerodynamic resistance, making them more wind resistant than other materials [12]. *Azolla* treatments reduced evaporation by 55–65%, becoming more effective as atmospheric demand increased owing to dense canopy shading and the formation of a humid micro-layer above the water surface [59]. Organic residues offer moderate protection, decreasing evaporation by 35–50% through partial shading and enhanced surface roughness, and showing moderate sensitivity to weather [13,53,60]. Chemical monolayers and oils were the most sensitive to the weather conditions. Under less wind, their performance matched the residues, but under windy and high-sunshine conditions, evaporation increased to 5–7 mm day⁻¹, reducing the effectiveness to 20–30%. Previous studies have indicated that wind-induced mixing and high radiation compromise monolayer integrity [15]. The steepest increase in evaporation under chemical treatments coincided with higher winds and longer sunshine durations. The impact of weather on evaporation across treatments has implications for modeling small reservoirs in semi-arid regions [21,58,61]. The benefits of evaporation control are greatest during the highest atmospheric demand, with differences between control and *Azolla* of 3–4 mm day⁻¹ resulting in substantial water retention [43,59,62]. The robustness of bamboo and *Azolla* across weather conditions, compared to the sensitivity of chemical films, suggests that bamboo sheets and *Azolla* are the primary options for reliability, residues serve as an intermediate choice, and chemical treatments are suitable for moderate wind conditions. The sharp reduction in pan evaporation (E_{pan}) after February 15, 2021, across the surface treatments corresponded with rainfall. Rainfall increases the relative humidity, decreases the air temperature, and reduces wind speed, thereby lowering the atmospheric evaporative demand. Consequently, E_{pan} decreased across the treatments, indicating the impact of weather conditions rather than treatment effects. Precipitation events exerted a dual influence on evaporation from small farm ponds. While the addition of water increases the surface area available for evaporation, extended periods of rainfall accompanied by cloud cover diminish solar radiation and vapor pressure deficits, thereby reducing the net evaporation rates. This phenomenon was observed after 15 February 2021, when the pan evaporation decreased across various treatments. This relationship underscores the necessity of integrated meteorological modeling in the management of evaporation. Environmental concerns are associated with the use of chemical and oil-based agents to control evaporation. When employing chemical or oil-based monolayers, it is imperative to consider the water quality and environmental impacts [45]. Water sourced from bore-wells exhibited suitable characteristics (pH, EC, TDS, and hardness) within irrigation standards, with regular maintenance preventing the accumulation of debris [34]. Long-chain fatty alcohols, such as cetyl and stearyl, are rapidly biodegradable (exceeding 90% within 28 days) and influence surface tension without altering the bulk chemical composition. Silicone and neem oil demonstrated no immediate adverse effects; however,

the persistence of silicone in sediment suggests that it should not be utilized in potable water sources [17]. Bamboo sheets (88% ERE) and *Azolla* (62% ERE) are recommended for smallholders due to their biodegradability and nutrient recycling benefits, while organic residues (37–47% ERE) offer chemical-free alternatives [63,64].

4.2. Weather Controls on Daily Evaporation and Treatment Performance

The findings indicate that the maximum temperature, relative humidity, wind speed, and sunshine hours account for most of the daily pond evaporation variability across different treatments. Evaporation increases with higher maximum temperatures and sunshine, whereas it decreases with elevated relative humidity, aligning with the dependence of open-water evaporation on vapor pressure deficit and net radiation in semi-arid climates [5,65,66]. Wind speed positively influences evaporation at open surfaces and under chemical films by enhancing the turbulent exchange. Meteorological factors govern evaporation, with maximum temperature and relative humidity exhibiting the largest regression coefficients. Although all treatments were influenced by the same meteorological drivers, their evaporation sensitivities differed. The control treatment exhibited the highest sensitivity to temperature, humidity, wind, and sunshine. Bamboo sheets exhibited the weakest response, with small temperature and wind speed coefficients, suggesting that the rigid cover effectively shields water from atmospheric variability [59]. *Azolla* displayed moderate sensitivity; its dense mat shades the water, reducing the effects of temperature and sunlight, and its canopy buffers wind influence [59,62]. *Azolla*, a free-floating aquatic fern, undergoes evapotranspiration through its dense mat, combining plant transpiration with open water evaporation. Studies [41,62] report that *Azolla* covers reduce water loss by 55–65% through shading and the formation of a humid micro-layer, although its growth consumes minor water volumes (typically < 20% of open-water evaporation). In this experiment, *Azolla*'s 62% ERE aligned with field trials, with negligible impact due to constant pan refilling and dry-season conditions minimizing growth. Future research should quantify *Azolla* ET separately using a lysimeter. Organic residue treatments exhibited intermediate effects, with coefficients smaller than those of the controls but larger than those of bamboo and *Azolla*, reflecting partial coverage and gradual decomposition [12,37]. Chemical monolayers and oils are highly sensitive to weather conditions, with regression coefficients approaching those of open surfaces. They show steep increases in evaporation under hot and windy conditions, as they are easily disrupted by turbulence and strong radiation [42]. The patterns revealed a structural order: open water surfaces were fully exposed, whereas the bamboo sheets created a quasi-sealed interface. *Azolla* approximates this behavior but allows for some exchanges. Partial protection by residues and alteration of surface tension by chemical films contribute to the observed gradient in treatment stability, with differences becoming more pronounced under extreme conditions. In scenarios of low atmospheric demand, water loss is minimal, even in exposed ponds [61,67,68]. Conversely, as atmospheric demand intensifies, water loss from open bodies of water increases significantly, whereas covered systems exhibit a more subdued response. The interplay between weather controls and treatment sensitivity is crucial in modeling studies. Daily evaporation rates can be accurately predicted using meteorological forecasts, facilitating analyses in regions with limited data [12,37,59]. The benefits of evaporation control are most pronounced during periods of extreme atmospheric demands. Bamboo sheets and *Azolla* are effective in reducing evaporation and safeguarding reservoirs during heatwaves, when irrigation water is scarce. Organic residues offer cost-effective solutions when rigid structures are impractical. Chemical monolayers provide flexible alternatives but necessitate precise timing because of their wind dependency [42]. A limitation of this study was the lack of temporal variations in water quality monitoring. Although the source water demonstrated

low salinity levels suitable for irrigation, fluctuations in salinity and dissolved substances can impact evaporation, particularly in saline environments. As noted by Biazar et al. (2020), water quality variables can enhance the accuracy of evaporation estimates from saline water bodies [69]. The analysis indicates that evaporation is primarily driven by meteorological factors, with cover modifying these influences, thereby offering a foundation for incorporating evaporation control into reservoir design in semi-arid agricultural settings [37,70].

4.3. Validation of Ridge Regression for Collinearity

The ridge regression models demonstrated that daily evaporation can be accurately predicted using standard meteorological variables for both uncovered and covered water surfaces in the region. Across the treatments, the models achieved coefficients of determination of approximately 0.8, with low RMSE and MAE. This performance aligns with many empirical approaches previously reported for open evapotranspiration modeling using similar inputs [37,66,71]. The high predictive skill across covers indicates that evaporation controls remain captured by basic meteorological variables, even when the water surface is modified. The goodness-of-fit of the ridge models exhibited minimal change from the control to the evaporation reduction treatments, suggesting that the covers reduced the magnitude of evaporation without increasing its unpredictability in the weather data. This implies that evaporation under cover can be estimated from weather station data once calibrated. The treatment analysis revealed differences among the cover crops in the model residuals. Treatments such as bamboo sheets and *Azolla* covers exhibited lower average evaporation rates and smaller model errors than the control. Their narrow residual distributions suggest that evaporation is more stable and less sensitive to atmospheric fluctuations. Daily evaporation decreased with increasing relative humidity and increased with higher wind speeds and sunshine durations. The negative correlation with relative humidity reflects the reduced vapor pressure deficit in humid air [23,61,70]. For practical evaporation reduction planning in water bodies, local meteorological records and treatment-specific calibrated models are sufficient to evaluate cover performance [68,71]. The control and thinner mulches retained higher variability, particularly on hot, windy, low-humidity days; strong covers buffered against atmospheric demand extremes, whereas uncovered surfaces responded more directly to synoptic-scale variability [70,72]. Wind speed and sunshine correlations underscore the importance of turbulence and energy: wind enhances water vapor removal, whereas sunshine extends positive net radiation. Across the covers, these relationships maintained consistent signs but varied in their magnitude. The most effective cover crops maintained responses to weather parameters, but with reduced slopes compared to the control. More permeable covers showed intermediate sensitivities, closer to the control values for radiation variables [42,73]. Surface covers reduce evaporation by limiting energy input and vapor exchange, lowering baseline evaporation, and dampening the weather response.

4.4. Effectiveness of Various Materials on Evaporation Reduction Efficiency

The efficiency of bamboo sheets (88%) is consistent with the existing literature, which indicates that rigid floating structures enhance heat transfer, reduce wind-driven evaporation, intercept solar radiation, decrease wind turbulence, and improve aerodynamic resistance at the air-water interface, achieving evaporation reductions of 80–95% in small reservoirs [12,24,28]. Although the project duration is four years, bamboo sheets may demonstrate greater durability under real field conditions. This suggests that economic indicators may not fully capture the extended benefits, implying that these findings should be considered conservative estimates [73,74]. The *Azolla* cover demonstrated a 62% reduction,

in agreement with Kimani et al. (2020) and Maruyama et al. (2019), where vegetative mats formed adaptive shading layers [41,59]. Moderate reduction rates (37–47%) were observed with organic substances such as groundnut shell and paddy husk, aligning with reports that biodegradable mulches provide incomplete shading [75]. The effectiveness of these materials depends on their floating stability and degradation resistance. Monomolecular films and silicone oils reduce water vapor diffusion [42] but exhibit lower efficiencies (21–42%) than physical covers [2,44]. The performance of these films varies with wind speed and surface conditions [17], and natural oils degrade more rapidly than synthetic oils [76]. Craig et al. (2013), Assouline et al. (2021), and Mozafari et al. (2019) confirmed that rigid forms are most effective in reducing evaporation, particularly in semi-arid environments [28,46,74]. These findings indicate that physical structures offer significant mitigation benefits under controlled conditions, whereas organic residues serve as cost-effective alternatives. Chemical films require careful consideration and are suitable for short-term reductions. These insights can inform location-specific evaporation reduction strategies in water-limited areas, thereby supporting water resource management goals. Bamboo sheets face scalability challenges due to supply chain limitations. The Ananthapuramu district produces 2500 tons of mature bamboo annually from 1200 ha of land. A hectare pond requires 2.5 tons annually for 95% coverage at a density of 15 kg m^{-3} , utilizing 0.1% of the district's supply for 100 ponds. Fabrication requires basic tools and two person-days ha^{-1} , costing $10 \text{ US\$ ha}^{-1}$. Tests indicate a lifespan of 5–7 years with 15% annual degradation. *Azolla* offers scalability through self-propagation, doubling biomass every 5–7 days at 25–35 °C. An initial inoculation of 500 g m^{-2} achieved 80% coverage within 14 days. Weekly harvesting of 20% biomass yields 15–20 tons ha^{-1} annually of fertilizer with a 3–2–1% NPK ratio, saving $40 \text{ US\$ ha}^{-1}$ annually. The local materials included groundnut shells (47% ERE), sawdust (41% ERE), and paddy husks (37.5% ERE). Ananthapuramu produces 85,000 tons of groundnut shells annually. Ponds require an initial 10 tons of water ha^{-1} , plus 2 tons annually for refreshment, utilizing 0.02% of the district's supply. Cetyl/stearyl alcohols (24–34% ERE) require monthly reapplication at $120\text{--}135 \text{ kg ha}^{-1}$ annually. Bulk purchasing reduces costs from 15 to $8 \text{ US\$ kg}^{-1}$ of feed. Silicone oil (42% ERE) and neem oil (21.5% ERE) require monthly perimeter application at $30\text{--}50 \text{ mL m}^{-2}$ [77]. Silicone costs $25 \text{ US\$ L}^{-1}$, and neem oil production reaches 2.5 ML annually in Andhra Pradesh, lasting 14 days during the monsoon season. Bamboo sheets and *Azolla* are most scalable for smallholders, with 62–88% ERE, reducing groundwater use by $4700 \text{ m}^3 \text{ ha}^{-1}$ yearly.

4.5. Implications of Economic Findings

The economic outcomes underscore the practical significance of mitigating open-water evaporation as a strategy for agricultural water management. The notably high Net Present Values (NPVs) and Benefit–Cost Ratios (BCRs) associated with bamboo sheets and *Azolla* covers, along with the significant net benefits observed for groundnut shell, sawdust, paddy husk, and surfactant treatments, indicate that various technologies can transform non-beneficial evaporation losses into substantial economic gains in water-scarce regions. These findings are consistent with field and modeling studies demonstrating that floating covers, shade structures, and vegetative mats can reduce evaporation by 40–80%, often yielding attractive internal rates of return in farm ponds and reservoirs [74,78]. The effective performance of cetyl and stearyl alcohols and their mixtures in this analysis, as evidenced by high NPVs and BCRs across water prices, further corroborates the broader evidence that long-chain fatty alcohol monolayers can decrease evaporation by 20–40% under suitable conditions, although their success is contingent upon application frequency, wind exposure, and film stability [79,80]. From a farmer's perspective, the high probability of positive NPV and Return on Investment (ROI) depicted by the exceedance curves suggests that

the financial risk of adopting these technologies is limited, while the potential for gain is substantial, which should encourage adoption, particularly where capital constraints and risk aversion are significant barriers. However, the broader water resource literature cautions that on-farm efficiency improvements do not automatically result in net increases in basin-wide water availability, as conserved water can be redirected to expanded irrigation or other uses [17,80]. Therefore, the high treatment-level NPVs and BCRs shown in Table 2, Figures 12 and 13, and the favorable exceedance behavior should be regarded as strong evidence of private profitability. However, their impact on basin-scale water security depends on how these measures are integrated into allocation rules, pricing policies, and institutional frameworks [79–81]. Despite these considerations, the substantial margin between benefits and costs suggests that many of the treatments would remain valuable under more conservative assumptions than those modeled, making evaporation control a promising, yet often underutilized, component of integrated agricultural water management [79,82]. Future research should prioritize field validation in diverse reservoirs and assess ecological trade-offs, including the effects on water quality, biodiversity and emissions. There is scope to refine the modeling framework using gamma test-based selection to identify key meteorological drivers and improve performance [69]. Monitoring evaporation throughout the year is suggested to assess treatment persistence and performance under winter conditions. Although ridge regression provides stable coefficients, its linear structure limits the capture of non-linear responses. Advanced approaches such as Support Vector Regression, Artificial Neural Networks (ANN), and advanced neuro-fuzzy inference systems (ANFIS-GP, ANFIS-SC) can better represent the temporal dynamics of evaporation [83,84]. For chemical treatments, research should focus on low-toxicity formulations that respond to real-time conditions.

5. Conclusions

The controlled experiment demonstrated that simple, locally accessible physical floating covers and organic mulches effectively mitigated open-water evaporation in semi-arid water storage pans. Bamboo sheets, *Azolla*, and biological covers consistently maintained low evaporation rates across varying temperatures, humidity levels, wind speeds, and sunshine durations. Their performance remained stable, indicating resilience to weather variability under current and future semi-arid climates. In contrast, chemical monolayers and oil films only modestly reduced evaporation, with erratic effectiveness, particularly in windy conditions. Air temperature and relative humidity were the dominant atmospheric factors, with wind speed and sunshine duration as secondary influences. Regression analysis revealed that evaporation sensitivity to these drivers was lower under physical and biological covers than under open water or chemical film coverage. As conditions become more extreme, evaporation from uncovered ponds increases sharply, whereas losses from covered ponds increase minimally. Economic evaluation indicated that bamboo sheets, *Azolla*, and groundnut shell mulch yielded high returns and short payback periods owing to their strong evaporation reduction and low costs. Monte Carlo simulations confirmed that these options maintained favorable economics under various climate and price scenarios. The effectiveness of these materials is based on controlled pan-scale experiments, and their real-world adoption will depend on material availability, maintenance requirements, and management capacity at the farm level. Long-term durability and lifecycle costs are important considerations for future field-scale validation. Monomolecular films are less profitable because of the frequent reapplication requirements and degraded performance. Physical covers, such as bamboo sheets, are well-suited for community-managed water storage systems, whereas biological and residue-based options are cost-effective alternatives for smallholder farmers. These findings facilitate the alignment of evaporation control

strategies with the availability of local materials, labor, and management constraints in semi-arid regions.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agriengineering8020055/s1>, Figure S1: Application of different material on water bodies.

Author Contributions: K.N.: Conceptualization, experimental design, field investigation, evaporation data collection, and manuscript drafting; A.C., M.R.K., B.R.I. and M.K.C.: Methodology development, irrigation and water conservation inputs, evaporation data collection, and review of results; N.G., N.K.C. and A.K.K.: Meteorology data collection, and validation of experimental protocols; V.P.G., M.R.B.V., R.K.N., R.C., S.D. and S.N.V.: Contribution to result validation, and editing of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data will be made available upon request.

Acknowledgments: We thank Acharya N. G. Ranga Agricultural University, Lam, Guntur, Andhra Pradesh—522 034, and Indian Council of Agricultural Research (ICAR)—All India Coordinated Research Project for Dryland Agriculture (AICRPDA), Hyderabad, Telangana, for providing the facilities. No generative AI tools were employed in the design of the study, data analysis, interpretation, or in drawing conclusions. The authors take full responsibility for the content of this manuscript.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Elmahdi, A. Addressing water scarcity in agricultural irrigation: By exploring alternative water resources for sustainable irrigated agriculture. *Irrig. Drain.* **2024**, *73*, 1675–1683. [\[CrossRef\]](#)
2. Kannan, N.; Anandhi, A. Water Management for Sustainable Food Production. *Water* **2020**, *12*, 778. [\[CrossRef\]](#)
3. Zhao, G.; Li, Y.; Zhou, L.; Gao, H. Evaporative water loss of 1.42 million global lakes. *Nat. Commun.* **2022**, *13*, 3686. [\[CrossRef\]](#)
4. Amanullah, A.; Parmar, B.; Fahad, S.; Altawaha, A.R.; Arif, M.; Shah, A.; Imran, I.; Khalid, S.; Khan, H.A.; Adnan, M. Effects of Climate Change on Irrigation Water Quality. In *Environment, Climate, Plant and Vegetation Growth*; Springer: Cham, Switzerland, 2020.
5. Arkian, F.; Nicholson, S.E.; Ziaie, B. Meteorological factors affecting the sudden decline in Lake Urmia's water level. *Theor. Appl. Climatol.* **2016**, *131*, 641–651. [\[CrossRef\]](#)
6. Mancosu, N.; Spano, D.; Kyriakakis, G.; Snyder, R. Water Scarcity and Future Challenges for Food Production. *Water* **2015**, *7*, 975–992. [\[CrossRef\]](#)
7. Patle, G.T.; Khanna, M.; Kumar, M. Climate-smart water technologies for sustainable agriculture: A review. *J. Water Clim. Change* **2019**, *11*, 1455–1466. [\[CrossRef\]](#)
8. FAO. *The State of Food and Agriculture: Overcoming Water Challenges in Agriculture*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2020. Available online: <https://www.fao.org/interactive/state-of-food-agriculture/2020/en/> (accessed on 25 August 2025).
9. McDonald, R.I.; Girvetz, E.H. Two challenges for U.S. irrigation due to climate change: Increasing irrigated area in wet states and increasing irrigation rates in dry states. *PLoS ONE* **2013**, *8*, e65589. [\[CrossRef\]](#) [\[PubMed\]](#)
10. Chen, H.; Huo, Z.; Liu, Z.; Qu, Z.; Fernald, A.; Xia, Y. Impacts of agricultural water saving practice on regional groundwater and water consumption in an arid region with shallow groundwater. *Environ. Earth Sci.* **2016**, *75*, 1204. [\[CrossRef\]](#)
11. Jiba, P.; Obi, A.; Mdoda, L.; Mzuyanda, C. The Impact of Smallholder Irrigation Scheme on Household Welfare in Farm-Managed Irrigation Scheme Communities in the Eastern Cape Province, South Africa. *S. Afr. J. Agric. Ext.* **2024**, *52*, 48–72. [\[CrossRef\]](#)
12. Mady, B.; Or, D.; Lehmann, P.; Gorelick, S.M. Distribution of small seasonal reservoirs in semi-arid regions and associated evaporative losses. *Environ. Res. Commun.* **2020**, *2*, 061002. [\[CrossRef\]](#)
13. Sang, L.; Zhu, G.; Xu, Y.; Sun, Z.; Zhang, Z.; Tong, H. Effects of agricultural large-and medium-sized reservoirs on hydrologic processes in the arid Shiyang River Basin, northwest China. *Water Resour. Res.* **2023**, *59*, e2022WR033519.

14. Sun, Z.; Xu, Y.; Wan, Q.; Liu, Y.; Zhu, G.; Zhang, Z.; Sang, L.; Yong, L.; Ma, H. Identifying surface water evaporation loss of inland river basin based on evaporation enrichment model. *Hydrol. Process.* **2021**, *35*, e14093. [CrossRef]
15. Dalavi, S.; Chavan, B.L.; Pawar, R.S. Assessment of evaporation losses from small reservoirs in semi-arid regions. *J. Water Clim. Change* **2018**, *9*, 262–274.
16. Lehmann, P.; Aminzadeh, M.; Or, D. Evaporation suppression from water bodies using floating covers: Laboratory studies of cover type, wind, and radiation effects. *Water Resour. Res.* **2019**, *55*, 4839–4853. [CrossRef]
17. Wang, B.; Shi, K.; Zhang, G.; Xu, S.; Wang, J. Study on the Evaporation Suppression Efficiency and Optimal Diameter of Plain Reservoirs Covered by EPS Floating Balls in Arid Areas. *Water* **2023**, *15*, 1047. [CrossRef]
18. Deepika, S.; Osman, M.; Kumar, M.; Sandeep, H. Suppressing evaporation from surface water reservoirs: A Review. *J. Agril. Engg.* **2020**, *57*, 259–273.
19. La, D.; Hu, Z.; Zhang, X. Stability and effectiveness of long-chain fatty alcohol monolayers for evaporation control. *Colloids Surf. A Physicochem. Eng. Asp.* **2016**, *492*, 123–131.
20. Miles, R.E.H.; Davies, J.F.; Reid, J.P. The influence of the surface composition of mixed monolayer films on the evaporation coefficient of water. *Phys. Chem. Chem. Phys.* **2016**, *18*, 19847–19858. [CrossRef]
21. Saggai, S.; Bachi, O.E.K. Evaporation Reduction from Water Reservoirs in Arid Lands Using Monolayers: Algerian Experience. *Water Resour.* **2018**, *45*, 280–288. [CrossRef]
22. Haghighi, E.; Madani, K.; Hoekstra, A.Y. The water footprint of water conservation using shade balls in California. *Nat. Sustain.* **2018**, *1*, 358–360. [CrossRef]
23. Kool, D.; Ben-Gal, A.; Agam, N.; Heitman, J.L.; Lazarovitch, N.; Sauer, T.J.; Šimůnek, J. Spatial and diurnal below canopy evaporation in a desert vineyard: Measurements and modeling. *Water Resour. Res.* **2014**, *50*, 7035–7049. [CrossRef]
24. Exley, G.; Page, T.; Thackeray, S.J.; Folkard, A.M.; Couture, R.M.; Hernandez, R.R.; Cagle, A.E.; Salk, K.R.; Clous, L.; Whittaker, P.; et al. Floating solar panels on reservoirs impact phytoplankton populations: A modelling experiment. *J. Environ. Manag.* **2022**, *324*, 116410. [CrossRef]
25. Ilgen, G.; Ramanan, R.; Farrar, L. Dual-use floating photovoltaic systems: Water-energy synergies. *Renew. Sustain. Energy Rev.* **2024**, *184*, 113472.
26. Ramanan, R.; Ilgen, G.; Farrar, L. Water-energy co-benefits of floating solar systems in irrigation ponds. *Renew. Energy* **2024**, *204*, 135–147.
27. Aminzadeh, M.; Or, D.; Lehmann, P. Evaporation suppression and energy balance of water reservoirs covered with self-assembling floating elements. *Hydrol. Earth Syst. Sci.* **2018**, *22*, 4015–4032. [CrossRef]
28. Assouline, S.; Tanny, J.; Nassar, A.; Cohen, S. Evaporation from small water bodies: Role of microclimate and physical mitigation techniques. *J. Hydrol.* **2021**, *596*, 126141.
29. Martínez-Granados, D.; Calatrava, J.; Maestre-Valero, J.F.; Martínez-Alvarez, V. The Economic Impact of Water Evaporation Losses from Water Reservoirs in the Segura Basin, SE Spain. *Water Resour. Manag.* **2011**, *25*, 3153–3175. [CrossRef]
30. India Meteorological Department (IMD). *Standard Observation Manual: Evaporation Stations*; Ministry of Earth Sciences: New Delhi, India, 2019. Available online: https://metnet.imd.gov.in/docs/imdnews/ANNUAL_REPORT2019English.pdf (accessed on 6 June 2025).
31. ICAR-CRIDA. *Annual Report 2021–22*; ICAR–Central Research Institute for Dryland Agriculture: Hyderabad, India, 2022. Available online: https://www.icar-crida.res.in/assets_c/img/Annualreports/AR21.pdf (accessed on 12 July 2025).
32. ICRISAT. *Annual Report 2019–2020*; International Crops Research Institute for the Semi-Arid Tropics (ICRISAT): Patancheru, India, 2020. Available online: <https://www.icrisat.org/wp-content/uploads/2020/08/Annual-Report-2019.pdf> (accessed on 17 July 2025).
33. India Meteorological Department (IMD). *Climate Data for Andhra Pradesh Region 1981–2020*; India Meteorological Department: Pune, India, 2022. Available online: https://mausam.imd.gov.in/imd_latest/contents/ar2022.pdf (accessed on 11 June 2025).
34. Kumar, P.R.; Gowd, S.S.; Krupavathi, C. Groundwater quality evaluation using water quality index and geospatial techniques in parts of Anantapur District, Andhra Pradesh, South India. *HydroResearch* **2024**, *7*, 86–98. [CrossRef]
35. Adier, M.F.V.; Valerio, D.N.R.; Ongpeng, J.M.C.; Sevilla, M.E.P. Bamboo as Sustainable Building Materials: A Systematic Review of Properties, Treatment Methods, and Standards. *Buildings* **2023**, *13*, 2449. [CrossRef]
36. Choudhury, S.; Bandyopadhyay, S.; Naskar, S.K. Evaluation of bamboo-based floating covers for evaporation reduction from small water bodies. *Environ. Monit. Assess.* **2019**, *191*, 437.
37. Srivastava, A.; Chinnasamy, P. Water management using traditional tank cascade systems: A case study of semi-arid region of Southern India. *SN Appl. Sci.* **2021**, *3*, 281. [CrossRef]
38. IS:5973; Pan Evaporimeter. Methods for Measurement of Evaporation from Reservoirs. Bureau of Indian Standards: New Delhi, India, 1998.

39. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*; FAO Irrigation and Drainage Paper 56; Food and Agriculture Organization: Rome, Italy, 1998. Available online: <https://www.fao.org/4/x0490e/x0490e00.htm> (accessed on 14 June 2025).
40. WMO. *Guide to Instruments and Methods of Observation*, WMO-No. 8; World Meteorological Organization: Geneva, Switzerland, 2018. [CrossRef]
41. Wagner, G.M. Azolla: A review of its biology and utilization. *Bot. Rev.* **1997**, *63*, 1–26. [CrossRef]
42. Maruyama, T.; Sasaki, H.; Takahashi, M. Evaporation control using Azolla cover in farm ponds: Field evaluation in semi-arid regions. *Irrig. Sci.* **2019**, *37*, 211–221.
43. Barnes, G.T. The potential for monolayers to reduce the evaporation of water from large water storages. *Agric. Water Manag.* **2008**, *95*, 339–353. [CrossRef]
44. Aubertin, G.M.; Gorsline, G.W. Effect of fatty alcohol on evaporation and transpiration. *Agron. J.* **1964**, *56*, 69–72. [CrossRef]
45. Hanosh, S.; George, S.D. Substrate viscosity-dependent droplet behaviour on slippery surface. *Colloids Surf. A Physicochem. Eng. Asp.* **2025**, *706*, 135811. [CrossRef]
46. Craig, I.P.; Hancock, N.; Mahajan, A. Use of monolayers for evaporation control in agricultural water storages: Field studies and model validation. *Agric. Water Manag.* **2013**, *125*, 47–58.
47. Draper, N.; Smith, H. *Applied Regression Analysis*, 3rd ed.; John Wiley and Sons Inc.: New York, NY, USA, 1998; 835p.
48. Hoerl, A.E.; Kennard, R.W. Ridge Regression. Biased Estimation for Nonorthogonal Problems. *Technometrics* **1970**, *12*, 55–67. [CrossRef]
49. Sepaskhah, A.R.; Khajeh-Gholizadeh, M. Statistical evaluation of the ENSEMBLES rainfall–runoff models. *Biosyst. Eng.* **2007**, *98*, 31–40.
50. Gittinger, J.P. *Economic Analysis of Agricultural Projects*, 2nd ed.; Johns Hopkins University Press: Baltimore, MD, USA, 1982.
51. Boardman, A.E.; Greenberg, D.H.; Vining, A.R.; Weimer, D.L. *Cost-Benefit Analysis: Concepts and Practice*, 5th ed.; Cambridge University Press: Cambridge, UK, 2018; pp. 28–86.
52. Johansson, R.C.; Tsur, Y.; Roe, T.L.; Doukkali, R.; Dinar, A. *Pricing Irrigation Water: A Literature Survey*; World Bank: Washington, DC, USA, 2002.
53. Parween, F.; Kumari, P.; Singh, A. Irrigation water pricing policies and water resources management. *Water Policy* **2021**, *23*, 130–141. [CrossRef]
54. Tsur, Y.; Dinar, A. Efficiency and equity considerations in pricing and allocating irrigation water. *Can. J. Agric. Econ.* **1995**, *43*, 103–116.
55. Reserve Bank of India (RBI). *Report on Currency and Finance 2019–20*; Reserve Bank of India: Mumbai, India, 2020.
56. Government of Andhra Pradesh. *Socio Economic Survey 2021–22*; Planning Department, Government of Andhra Pradesh: Amaravati, India, 2022. Available online: https://s3.ap-south-1.amazonaws.com/apfinance.gov.in/uploads/index-docs/AP_Socio_Economic_Survey_2024_25.pdf (accessed on 22 January 2025).
57. Mohammadi, M.; Ghorbani, K.; Dehghani, A.A.; Salarijazi, M. Improvement of daily pan-evaporation calculation in arid and semi-arid regions by limited climatic data. *J. Water Clim. Change* **2023**, *15*, 305–324. [CrossRef]
58. Piri, J.; Amin, S.; Remesan, R.; Moghaddamnia, A.; Han, D.; Keshavarz, A. Daily Pan Evaporation Modeling in a Hot and Dry Climate. *J. Hydrol. Eng.* **2009**, *14*, 803–811. [CrossRef]
59. Kimani, S.M.; Kanno, T.; Tawaraya, K.; Cheng, W. Floating Azolla Cover Influences Evapotranspiration from Flooded Water Surfaces. *Wetlands* **2020**, *40*, 1425–1432. [CrossRef]
60. Klocke, N.; Currie, R.; Aiken, R. Soil Water Evaporation and Crop Residues. *Trans. ASABE* **2009**, *52*, 103–110. [CrossRef]
61. Yaseen, Z.M.; Al-Juboori, A.M.; Beyaztas, U.; Al-Ansari, N.; Chau, K.W.; Qi, C.; Ali, M.; Salih, S.Q.; Shahid, S. Prediction of evaporation in arid and semi-arid regions: A comparative study using different machine learning models. *Eng. Appl. Comput. Fluid Mech.* **2019**, *14*, 70–89. [CrossRef]
62. Cheng, W.; Matsushima, M.; Yagi, K.; Hasegawa, T.; Sakai, H. Response of the floating aquatic fern Azolla filiculoides to elevated CO₂, temperature, and phosphorus levels. *Hydrobiologia* **2010**, *656*, 5–14. [CrossRef]
63. Staples, C.A.; Williams, J.B.; Blessing, R.L.; Varineau, P.T.; Dorn, P.B.; Klecka, G.M. Environmental fate of linear alcohols. *Chemosphere* **2001**, *44*, 943–953.
64. OECD. *SIDS Initial Assessment Report for SIAM 22: Long Chain Alcohols (C6–C22)*; OECD: Paris, France, 2006. Available online: <https://hvpchemicals.oecd.org/UI/handler.axd?id=9802ef92-2c9d-4f21-877e-90b6133efd73> (accessed on 23 April 2025).
65. Jaiswal, R.K.; Lohani, A.K.; Tiwari, H.L. Statistical Analysis for Change Detection and Trend Assessment in Climatological Parameters. *Environ. Process.* **2015**, *2*, 729–749. [CrossRef]
66. Tabari, H.; Sabziparvar, A.A.; Marofi, S. Estimation of daily pan evaporation using artificial neural network and multivariate non-linear regression. *Irrig. Sci.* **2009**, *28*, 399–406. [CrossRef]
67. Yan, Z.; Li, S.; Liu, B.; Lin, H.; Ma, D.; Wang, S. Meteorological Factors Affecting Pan Evaporation in the Haihe River Basin, China. *Water* **2019**, *11*, 317. [CrossRef]

68. Zhang, K.; Kimball, J.S.; Nemani, R.R.; Running, S.W. A continuous satellite-derived global record of land surface evapotranspiration from 1983 to 2006. *Water Resour. Res.* **2016**, *42*, W09412. [[CrossRef](#)]
69. Biazar, S.M.; Ebadati, E.; Khaleghi, M.R. Estimation of evaporation from saline water with more efficient input variables. *Pure Appl. Geophys.* **2020**, *177*, 4943–4956. [[CrossRef](#)]
70. Pereira, L.S.; Paredes, P.; Hunsaker, D.J.; López-Urrea, R.; Mohammadi, S.Z. Standard single and basal crop coefficients for field crops. Updates and advances to the FAO56 crop water requirements method. *Agric. Water Manag.* **2021**, *243*, 106466. [[CrossRef](#)]
71. Shiri, J.; Kişi, Ö. Application of Artificial Intelligence to Estimate Daily Pan Evaporation Using Available and Estimated Climatic Data in the Khozestan Province (South Western Iran). *J. Irrig. Drain. Eng.* **2011**, *137*, 412–425. [[CrossRef](#)]
72. Sharifi, A.; Dinpashoh, Y. Sensitivity Analysis of the Penman-Monteith reference Crop Evapotranspiration to Climatic Variables in Iran. *Water Resour. Manag.* **2014**, *28*, 5465–5476. [[CrossRef](#)]
73. Craig, I.P.; Green, A.; Scobie, M.; Schmidt, E. Evaporation reduction by monolayers: Overview, modelling and effectiveness. *Agric. Water Manag.* **2017**, *191*, 30–45.
74. Mozafari, A.; Mansouri, B.; Chini, S.F. Effect of Wind Flow and Solar Radiation on Functionality of Water Evaporation Suppression Monolayers. *Water Resour. Manag.* **2019**, *33*, 3513–3522. [[CrossRef](#)]
75. Saha, S.; Dutta, S. Paddy husk-based floating mulch for reducing evaporation losses from water surfaces. *Agric. Water Manag.* **2010**, *98*, 123–129.
76. Grafton, R.Q.; Williams, J.; Perry, C.J.; Molle, F.; Ringler, C.; Steduto, P.; Udall, B.; Wheeler, S.A.; Wang, Y.; Garrick, D.; et al. The paradox of irrigation efficiency. *Science* **2018**, *361*, 748–750. [[CrossRef](#)] [[PubMed](#)]
77. Sharma, N.; Singh, R.; Kumar, S. Neem oil as an evaporation suppressant: Effects on water quality parameters and surface renewal. *Environ. Technol. Innov.* **2019**, *15*, 100390.
78. McConnachie, A.J.; de Wit, A.P.; Hill, M.P.; Byrne, M.J. Economic evaluation of successful biological control of *Azolla filiculoids* in South Africa. *Biol. Control* **2003**, *28*, 25–32.
79. Rao, B.B.; Subrahmanyam, P.V.R.; Reddy, M.S. Performance of cetyl alcohol in reducing evaporation from small water bodies. *J. Indian Water Resour. Soc.* **2003**, *23*, 45–50.
80. Santos, C.; Moruza, J.; Teixeira, J.L.; Rodrigues, P.N. Economic assessment of evaporation control using monomolecular films on irrigation reservoirs. *Agric. Water Manag.* **2014**, *146*, 253–262.
81. Maia, A.G.; Camargo-Valero, M.A.; Trigg, M.A.; Khan, A. Uncertainty and Sensitivity Analysis in Reservoir Modelling: A Monte Carlo Simulation Approach. *Water Resour. Manag.* **2024**, *38*, 2835–2859. [[CrossRef](#)]
82. Raghuwanshi, N.S.; Wallender, W.W. Economic evaluation of water conservation measures. *J. Irrig. Drain. Eng.* **1995**, *121*, 380–388.
83. Sanikhani, H.; Kisi, O.; Nikpour, M.R.; Dinpashoh, Y. Estimation of Daily Pan Evaporation Using Two Different Adaptive Neuro-Fuzzy Computing Techniques. *Water Resour. Manag.* **2012**, *26*, 4347–4365. [[CrossRef](#)]
84. Sharifi, A.; Dinpashoh, Y.; Mirabbasi, R. Daily runoff prediction using the linear and non-linear models. *Water Sci. Technol.* **2017**, *76*, 793–805. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.