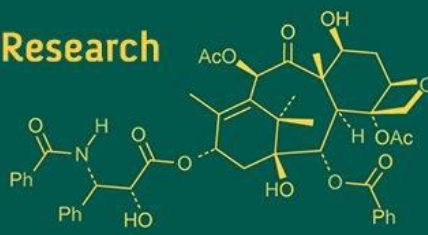


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Performance evaluation of AquaCrop model for simulation of onion crop under mulch and non-mulch conditions

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Abstract

This study evaluated the FAO-AquaCrop model's performance in simulating onion crop growth and yield under varying irrigation levels and mulching conditions at the Precision Farming Development Centre, Dr. RPCAU, Pusa, Bihar, India. The experiment employed a randomized block design with six treatments combining three irrigation levels (100%, 80%, and 60% water requirement) with and without plastic mulch. The soil at the experimental site was characterized as calcareous sandy loam with 52% sand, 18% silt, and 30% clay, and a mean bulk density of 1.56 g/cc. The AquaCrop model was calibrated using crop-specific parameters including canopy growth coefficient (15.3%/day), canopy decline coefficient (8.0%/day), and growth stages for onion cultivation. Model performance was assessed using statistical indicators including prediction error (Pe), coefficient of determination (R^2), mean absolute error (MAE), root mean square error (RMSE), and model efficiency (E). Results demonstrated strong correlations between simulated and observed values for both onion bulb yield ($R^2 = 0.992$, $E = 0.96$, $RMSE = 0.33$) and biomass ($R^2 = 0.994$, $E = 0.99$, $RMSE = 0.28$), with low prediction errors ranging from 1.46% to 9.71% for yield and 0.71% to 5.26% for biomass. The model performed consistently across all irrigation levels and mulching conditions, confirming Aqua Crop's reliability as a decision support tool for optimizing onion production under various water management strategies in the sub-humid climate of Bihar, India.

Keywords: Yield, biomass, onion, AquaCrop model

Introduction

Water productivity in agriculture, defined as "the ratio of the net benefits from crop, forestry, livestock, and mixed agricultural systems to the amount of water required to produce these benefits" (Molden *et al.*, 2007) [12], has become increasingly critical in modern agricultural management. The central goal of improving water productivity is to generate food, income, livelihood, and ecological benefits while minimizing environmental and social costs per unit of water utilized.

In the present scenario of growing water scarcity, there is an urgent need to manage irrigation water efficiently to achieve optimum agricultural yields with limited water resources. Enhancing current crop water production levels through improved irrigation practices represents one of the most promising strategies for water conservation and optimal production. While irrigation has been practiced since the dawn of civilization, drip irrigation has emerged as one of the most efficient methods, delivering water precisely to the plant root zone. This approach is particularly valuable for horticultural and vegetable crops.

Over the past five decades, drip irrigation combined with synthetic plastic mulching techniques has been extensively implemented worldwide to maximize water use efficiency and improve agricultural productivity, especially in water-scarce regions. Singh *et al.* (2023) [18] demonstrated that employing drip irrigation at 80% of crop evapotranspiration (ETC) with polyethylene mulch led to significant improvements in onion cultivation, including taller plants, increased leaf counts, larger bulb diameters, 47% water savings, and a 48% increase in yield compared to conventional surface irrigation methods.

Onions occupy a significant place in human diets due to their nutritional value and medicinal properties. They contain various pharmacologically active compounds, particularly S-alkenyl cysteine sulfoxides (ACSOs), which contribute to their distinctive flavor and pungency.

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These compounds confer antimicrobial, antibacterial, hypoglycemic, hypocholesterolemic, antiatherosclerotic, and antithrombotic properties (Ortola *et al.*, 2015) ^[14]. For optimal yield, onion crops typically require between 350 and 550 millimeters of water. Consistent watering is essential to prevent bulb cracking and the formation of 'doubles,' while also ensuring high crop quality. Within India, Maharashtra leads onion production, followed by Madhya Pradesh, with Bihar ranking sixth after Rajasthan.

As global population continues to rise, agricultural systems face mounting pressure to increase yields. Given the limited potential for expanding arable land, production increases must come primarily through enhanced productivity per unit of land. This necessitates more efficient water management strategies.

Understanding crop water requirements is fundamental to the effective design and management of drip irrigation systems. This knowledge can be obtained either through field experiments or through modeling approaches. Various models are available for simulating agricultural water requirements, irrigation scheduling, yield, biomass, and water productivity.

Among these, FAO's AquaCrop model has gained prominence in agricultural research and practice. Developed through collaboration between FAO and renowned experts from major research centers, international governmental organizations, and academic institutions, the model has undergone continuous refinement, with FAO-AquaCrop version 6.1 released in May 2018. As a dynamic crop simulation tool, AquaCrop offers various alternatives for predicting crop responses to different field management practices. Given its focus on yield response to water, the latest AquaCrop version 7.1 presents an excellent

opportunity for testing and developing water management strategies specifically for onion cultivation.

Materials and Methods

The experiment took place at the Precision Farming Development Centre (PFDC) in the department of Soil and Water Conservation Engineering, CEAT, Dr. RPCAU, Pusa, Bihar. The field is located at 25.98°N latitude, 85.67°E longitude, and approximately 52.00 meters above the sea level. The region experiences a sub humid climate influenced by the southwest monsoon. This location was chosen due to its relevance for studying the performance of the Aqua Crop model under the local climatic conditions. The soil was formed by sediment transported down by the Burhi Gandak river, and it was relatively fresh. Because there was 26.6% calcium carbonate present, the soil was calcareous. The soil type at the experiment site is sandy loam, comprising 52% sand, 18% silt, and 30% clay. The experiment site's average bulk density was ascertained through applying the core technique. The mean bulk density has been found at 1.56 g/cc. The field technique was used to determine the soil's field capacity and saturation soil moisture content. The onion plants were transplant with a spacing of 15×10 cm on February 3, 2024, on the prepared bed. The experiment was laid out in a randomized block design with six treatment, three replication. The treatment details of experiments are presented in Table 1. The data on the weather condition during the crop growing season of present investigation concerning maximum and minimum temperature, rainfall, wind speed, relative humidity, evaporation and bright sunshine hours were obtained from Agro-meteorology observatory, Dr., RPCAU, Pusa. It has presented in Fig. 1.

Table 1: Details of treatments

Sr. No.	Treatments	Treatments details
1.	T ₁	Application of 100% water requirement without plastic mulch (control)
2.	T ₂	Application of 100% water requirement with plastic mulch
3.	T ₃	Application of 80% water requirement without plastic mulch
4.	T ₄	Application of 80% water requirement with plastic mulch
5.	T ₅	Application of 60% water requirement without plastic mulch
6.	T ₆	Application of 60% water requirement with plastic mulch.

FAO-AquaCrop model

The FAO-AquaCrop model, developed by Steduto *et al.* (2009) ^[15] and Raes *et al.* (2009) ^[15], is a crop growth simulation tool that integrates four key components. These include: (1) a soil water balance model that tracks moisture levels; (2) a crop growth and yield component that simulates plant development; (3) an atmospheric model that accounts for factors such as rainfall, reference evapotranspiration (ET₀), and CO₂ concentration; and (4) a management model that incorporates irrigation and fertilization practices (Raes *et al.*, 2011) ^[15].

Soil water balance

The soil water balance in AquaCrop tracks water storage in

the root zone by considering water inflows and outflows. Root zone depletion influences water stress factors (K_s), which affect canopy expansion, transpiration, canopy aging, harvest index, and root growth rate.

Climatic data

The AquaCrop model requires daily weather data, including minimum and maximum air temperatures, reference crop evapotranspiration (ET₀), rainfall, and the mean annual carbon dioxide (CO₂) concentration. ET₀ is calculated using the ET₀ calculator, which considers daily maximum and minimum temperatures, wind speed measured at 2 meters above the ground, solar radiation, and daily relative humidity (RH).

Metrological Condition

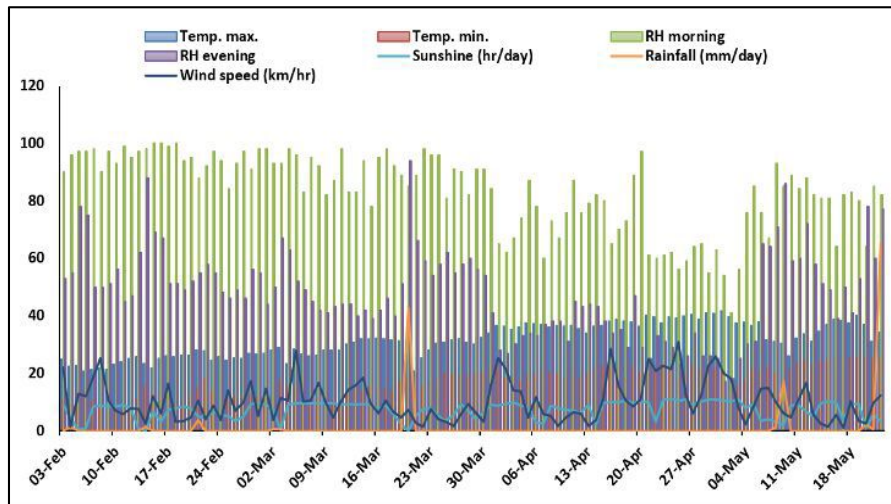


Fig 1: Metrological conditions at Pusa during the crop growing seasons February 2024 to May 2024

Crop data

The AquaCrop model requires a limited set of crop parameters that describe crop characteristics. The FAO has calibrated these parameters for major agricultural crops and provides them as default values within the model. When a crop is selected, its corresponding parameters are automatically loaded.

The model's crop data inputs include: (i) Key growth stages such as emergence, maximum canopy cover, maximum root depth, the onset of canopy senescence, maturity, and the start and end of flowering. (ii) The maximum transpiration crop coefficient ($K_{cTr,x}$). (iii) Minimum and maximum root depths (Z_r) along with the root expansion shape factor. (iv) Initial and maximum canopy cover (CC_0 , CC_x), the canopy growth coefficient (CGC), and the canopy decline coefficient (CDC). (v) The biomass (water) productivity adjustment factor (BWP^*). (vi) The reference harvest index (H_{Io}). (vii) Water stress coefficients related to canopy expansion, stomatal closure, early canopy senescence, and aeration stress caused by waterlogging.

Soil parameters

The soil data required for the AquaCrop model at the experimental site includes the number of soil horizons, soil texture, field capacity (FC), permanent wilting point (PWP), saturated hydraulic conductivity (K_{sat}), and volumetric water content at saturation (sat). The experimental site had no impervious or restrictive soil layers that could hinder root growth. Surface runoff from rainfall during the experiment was estimated using the site's curve number (CN).

Management practices

Field and irrigation management practices were evaluated. Field management included soil fertility levels and methods to conserve soil water, such as plastic mulching. Fertility levels influenced canopy development, senescence, and water productivity.

For irrigation management, we choose irrigated conditions, with drip irrigation methods. Irrigation scheduling varied based on depth, timing, and seasonal needs. Full irrigation (100% via drip) and deficit irrigation (80% and 60%) were applied on the same days as full irrigation plots. Fertility levels were consistent across all treatments.

Parameter Adjustment

The initial onion model parameters were obtained from the AquaCrop database. Key factors such as canopy cover development, rooting depth, and water productivity were adjusted to match observed growth patterns and yield outcomes. These refinements enhanced the model's accuracy, improving its reliability in simulating onion growth and optimizing irrigation and crop management practices.

Model evaluation criteria

The AquaCrop model's onion yield and biomass predictions were compared with observed data from a February 3 to May 22, 2024 experiment. Prediction error (Pe), R^2 , mean absolute error (MAE), root mean square error (RMSE), and model efficiency (E) were used to assess accuracy. R^2 and E evaluated predictive capability, while Pe, MAE, RMSE, and NRMSE indicated prediction errors. Biomass at harvest and onion bulb yield were key evaluation parameters, with Pe and E calculated using the Nash and Sutcliffe method (1970) [13].

$$P_e = \frac{(S_i - O_i)}{O_i} \times 100 \quad \dots (i)$$

$$E = 1 - \frac{\sum_{i=1}^N (O_i - S_i)^2}{\sum_{i=1}^N (O_i - \bar{O}_i)^2} \quad \dots (ii)$$

Where (S_i) and (O_i) represent the predicted and actual (observed) values, ($\bar{O}_i$) is the mean of the observed values, and N denotes the number of observations.

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (S_i - O_i)^2}{N}} \quad \dots (iii)$$

$$NRMSE = \frac{1}{O} \sqrt{\frac{\sum_{i=1}^N (S_i - O_i)^2}{N}} \times 100 \quad \dots (iv)$$

$$MAE = \frac{\sum_{i=1}^N |y_i - x_i|}{n} \quad \dots (v)$$

Where,

y_i = Actual value

x_i = Predicted value

Model efficiency (E) and R^2 values close to one, along with prediction error (Pe), mean absolute error (MAE), and root mean square error (RMSE) near zero, indicate better model performance.

Results and Discussion

FAO-AquaCrop Model Evaluation for Onion Crop

The AquaCrop model was analyzed using 2024 experimental data to forecast onion yield under varying irrigation and mulch conditions. The evaluation focused on onion biomass and yield, comparing simulated and observed

data. Three irrigation levels and mulch/non-mulch conditions were assessed. Prediction error, R^2 , MAE, RMSE, and model efficiency were used to evaluate performance. Table 2 outlines crop parameters, including a canopy growth coefficient of 15.3%/day, a canopy decline coefficient of 8.0%/day (0.52% GDD⁻¹), and growth stages of 7, 85, and 109 days for recuperation, senescence, and maturity. The maximum root depth was 0.2 m, with base and cut-off temperatures set at 10 °C and 30 °C. The harvestable yield was calculated by multiplying biomass by the harvest index.

Table 2: Input data for adopted crop parameter of onion crop used in AquaCrop.

S. No.	Crop Parameter	Value	Unit
1.	Base temperature	10	°C
2.	Cut-off temperature	30	°C
3.	Initial canopy cover	9.90	%
4.	Maximum canopy cover	85	%
5.	Canopy growth coefficient (CGC)	15.3	% day ⁻¹
6.	Canopy decline coefficient (CDC)	8.0	% day ⁻¹
7.	Reference harvesting index (HI ₀)	49	%
8.	Time from transplanting to recovered transplant	7	days
9.	Time from transplanting to maximum rooting depth time	50	days
10.	Time from transplanting to maximum canopy cover	56	days
11.	Time from transplanting to start yield formation	62	days
12.	Length building up HI	42	days
13.	Time from transplanting to start of canopy senescence	85	days
14.	Time from transplanting to maturity	109	days
15.	Maximum effective rooting depth	0.20	m

Simulation of bulb yield

The model's performance in predicting onion bulb yield with and without mulch is shown in Table 3 and Fig. 2 (a) & (b). Strong correlations were observed between simulated and observed yields, with R^2 values of 0.7-0.9 for mulch and non-mulch conditions and 0.99 for combined treatments.

The model showed good accuracy with RMSE (0.33), MAE (0.53), and prediction errors ranging from 1.46% to 9.71% (Table 5, & Fig. 4 (a)). It performed reliably across all irrigation levels (100%, 80%, 60%), demonstrating robustness under varying water stress conditions.

Table 3: Evaluated results of onion bulb yield

Bulb yield (t/ha)			
Treatment	Observed (O _i)	Simulated (S _i)	Prediction error, (±%) P _e
T ₁ (210.17 mm, NM)	5.15	5.65	9.71
T ₂ (118.55 mm, WM)	8.07	8.65	7.19
T ₃ (168.13 mm, NM)	3.61	3.80	5.26
T ₄ (94.84 mm, WM)	7.56	7.67	1.46
T ₅ (126.10 mm, NM)	3.24	3.42	5.56
T ₆ (71.13 mm, WM)	4.34	4.49	3.46

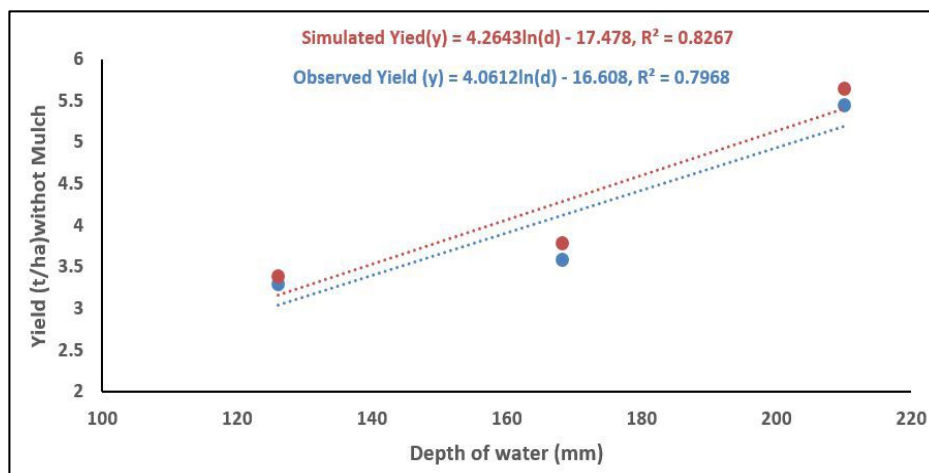


Fig 2(a): Relationship between observed and simulated yield (t/ha) for treatments T₁, T₃, and T₅ respectively without plastic mulch conditions regarding depth of water (mm)

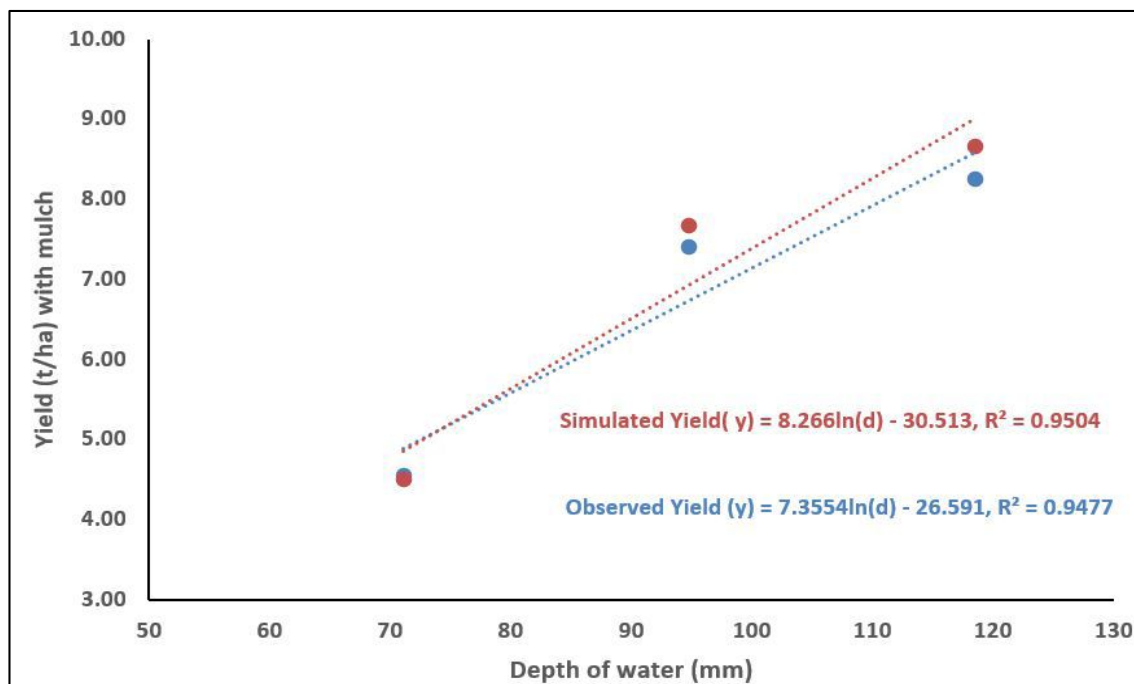


Fig 2(b): Relationship between observed and simulated yield (t/ha) for treatments T₂, T₄ and T₆ respectively with plastic mulch conditions regarding depth of water (mm).

Simulation of Biomass

The AquaCrop model accurately simulated onion biomass with R^2 values of 0.6-0.9 for individual treatments and 0.99 for combined data. Prediction errors were low (RMSE: 0.28, MAE: 0.44) with errors ranging from 0.71% to 5.26% (Table 4, Fig. 3 (a) & (b)). Model efficiency was high (0.99 for biomass), confirming strong performance (Table 5, & Fig. 4(b)). Similar accuracy trends were reported by Mohammadi *et al.* (2019) ^[11], Bello and Walker (2017) ^[7], reinforcing AquaCrop's reliability in simulating onion growth under varying conditions.

Table 4: Evaluated results of onion biomass

Treatment	Biomass (t/ha)		Prediction error, ($\pm\%$) P_e
	Observed (O_i)	Simulated (S_i)	
T ₁	8.84	8.54	0.71
T ₂	11.10	11.63	4.77
T ₃	5.07	5.13	1.18
T ₄	10.65	10.78	1.22
T ₅	5.02	5.23	4.18
T ₆	6.66	7.01	5.26

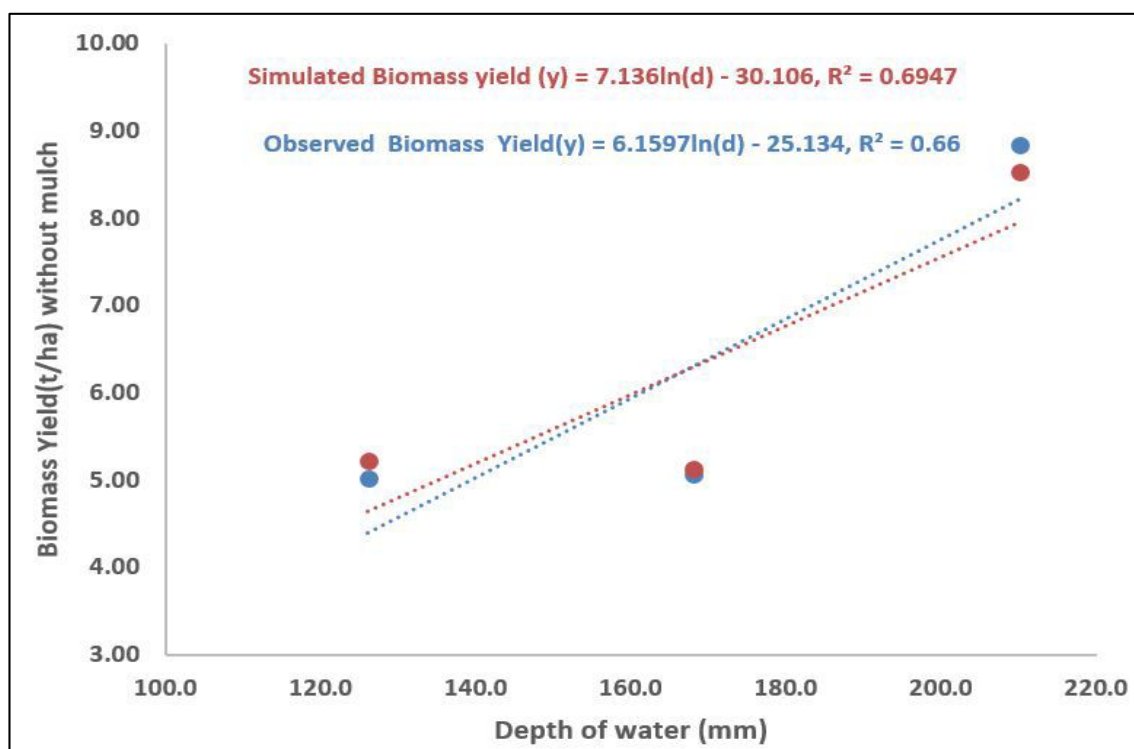


Fig 3 (a): Relationship between observed and simulated biomass yield (t/ha), treatments T₁, T₃, and T₅ respectively without plastic mulch regarding depth of water (mm).

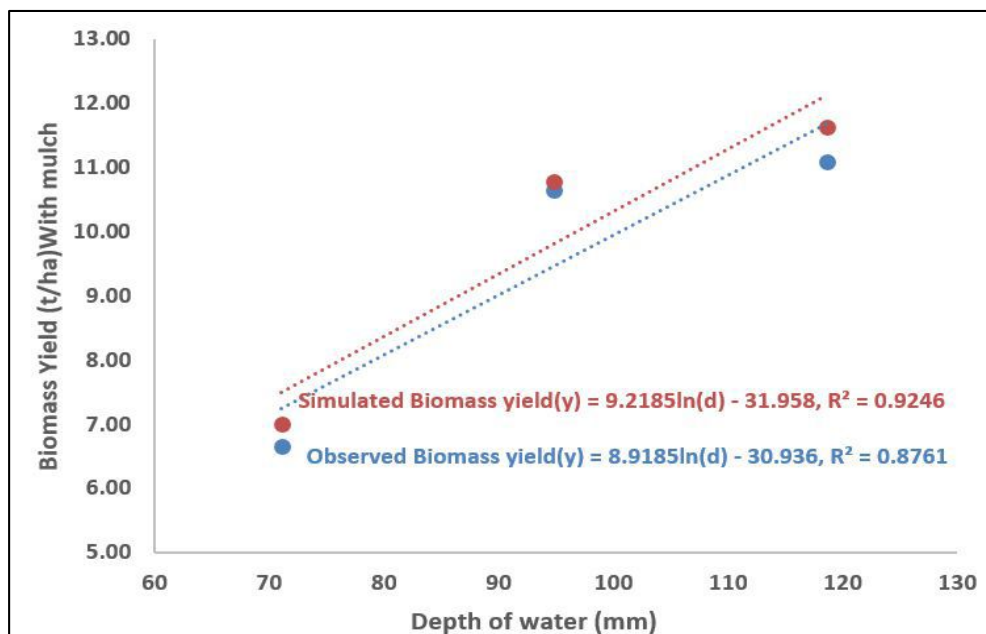


Fig 3 (b): Relationship between observed and simulated biomass yield (t/ha) for treatments T₂, T₄ and T₆ respectively with plastic mulch regarding depth of water (mm).

AquaCrop model evaluation results

Table 5: Prediction error statistics of the evaluation of AquaCrop model

Model output parameter	Mean		Model efficiency (E)	RMSE	MAE	R ²
	Observed (O _i)	Simulated (S _i)				
Bulb yield (t/ha)	5.32	5.61	0.96	0.33	0.53	0.992
Biomass (t/ha)	7.83	8.05	0.99	0.28	0.44	0.994

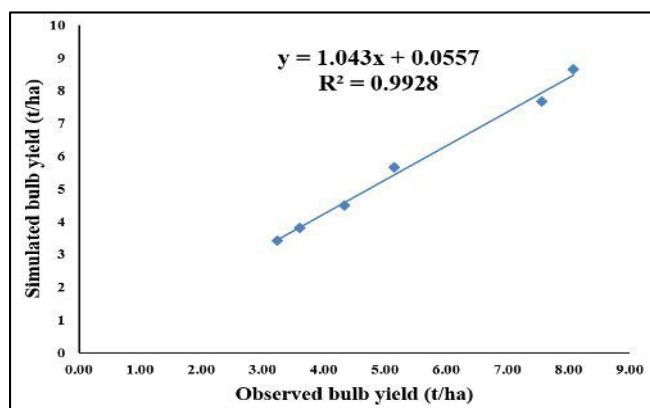


Fig 4 (a): Model tested results for bulb yield under different treatments.

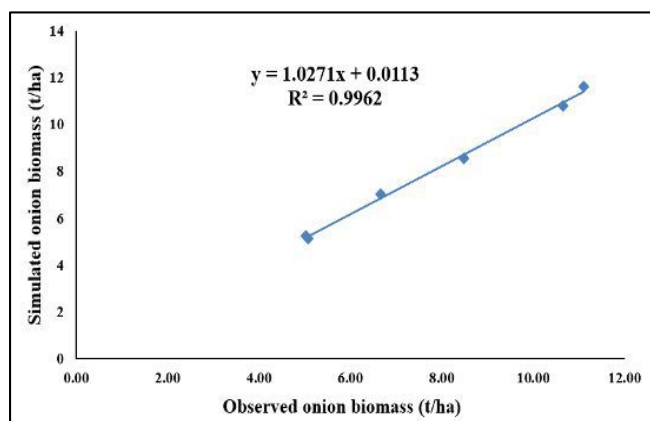


Fig 4 (b): Results of model testing for biomass under different level of irrigation and mulch or non-mulch condition

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