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**Research Article**

# PERFORMANCE EVALUATION OF AQUACROP MODEL FOR CUCUMBER (*Cucumis sativus* L.) CROP UNDER NATURALLY VENTILATED POLYHOUSE

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**Abstract:** AquaCrop, an essential simulation model developed by the FAO, plays a pivotal role in achieving sustainable management of agricultural water resources by precisely forecasting crop yield in conditions of water scarcity. This study focused on adapting AquaCrop for cucumber cultivation within a naturally ventilated polyhouse, using a gravity-based drip irrigation system in Udaipur, Rajasthan, India. The calibration of the model was executed using data encompassing canopy cover, biomass, and cucumber yield from 2018 to 2020. The calibration phase showcased a strong coefficient of determination ($R^2NS$) of 0.996 for canopy cover. Nonetheless, the model exhibited a tendency to overestimate both biomass and yield during the cultivation phase, displaying $R^2NS$ values of 0.85 and 0.915, respectively. The validation stage yield results that displayed a close alignment between actual and simulated values for both biomass and yield, demonstrating $R^2NS$ values of 0.89 and 0.93, respectively. Despite this close alignment, the model still leaned towards an overestimation, as indicated by negative CRM values of -0.226 and -0.210 for biomass and yield, respectively. Even though this overestimation aspect was present, the AquaCrop model stood as a dependable tool for projecting crop growth patterns and fine-tuning water management tactics. This research not only sheds light on the appropriateness of AquaCrop for cucumber cultivation within a specific agro-climatic setting but also contributes to the optimization of agricultural methodologies and water resource management within the region. The meticulously calibrated model parameters establish a valuable reference point for future simulations of cucumber crops in Udaipur. The universal applicability and robustness of AquaCrop elevate its significance as a potent instrument for elevating agricultural productivity and global water resource management.

**Keywords:** *AquaCrop, Biomass, Calibration, Canopy, Cucumber, Validation, Yield*

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## Introduction

In modern agriculture, the primary challenge revolves around boosting production revenue while minimizing harm to the ecosystem. Enhancing energy and nutrient efficiency has become paramount, and achieving a precise equilibrium between water and nutrients has emerged as a key factor in obtaining better yields and top-quality harvests. The practice of fertigation, which entails the timely and uniform administration of water and nutrients, proves highly advantageous in meeting the nutritional requirements of crops, cutting down on fertilizer usage, and curbing losses due to leaching.

In the pursuit of sustainable water management in agriculture, the significance of prediction and simulation models like AquaCrop cannot be overstated. Developed by the FAO, AquaCrop stands as a dependable approach for anticipating crop output in regions with water scarcity. Its accurate forecasts of yield growth through water-related factors render it invaluable for diverse agricultural applications. By utilizing environmental conditions as input, AquaCrop generates predictions for biomass, crop yield, and water efficiency. This aids in comprehending how crops react to shifts in climate and in fine-tuning water consumption.

AquaCrop's broad versatility and its ability to evaluate crop responses within the plant-soil ecosystem make it an accessible asset for users across various contexts. It simplifies irrigation scheduling, computes water requirements, and furnishes valuable insights for policymakers to shape the trajectory of agriculture amidst the challenges of climate change. In sum, AquaCrop significantly contributes to the overarching objective of achieving sustainable and effective water management in the realm of agriculture [1-4].

## Materials and Methods

### Site Description

Between 2018 and 2020, a field experiment took place at the Technology Park, College of Technology and Engineering, MPUAT Udaipur. Geographically located at 24° 35'31.5" to 24° 35'38.5" N latitude and 75° 42'18.2" E longitude, Udaipur stands at an elevation of 582.17 meters above sea level in southern Rajasthan.

The study zone belongs to agro-climatic sub-humid zone (iv a) and receives an annual average rainfall of 654.3 mm, predominantly during July to September. Udaipur experiences peak temperatures of 46°C in May and a low of 5°C in December, while high atmospheric humidity prevails from June to October.

Daily meteorological data, encompassing parameters like maximum and minimum temperatures ($T_{max}$ and $T_{min}$), maximum and minimum relative humidity ($RH_{max}$ and $RH_{min}$), wind speed at 3m height, sunshine hours, and rainfall, were collected from the meteorological observatory of the Department of Soil and Water Engineering, CTAE, Udaipur. Data spanning the past five years (2013-2018) were utilized for analysis.

This study specifically investigated soil infiltration characteristics using the double-cylinder process. The soil physio-chemical attributes were also assessed using standardized techniques. For experimentation, an established naturally ventilated polyhouse covered by a 50 percent shading net was employed. Spanning 28 m x 10 m, the polyhouse had a southern-side opening gate. Outfitted with manually operated curtains, insect screens, transparent plastic film curtains, and nylon insect-resistant nets on all sides, the site was strategically chosen to circumvent contamination and drainage concerns [5-8].

The irrigation system adopted was a gravity-based drip irrigation mechanism, with gravitational force governing the process. The supply tank was positioned 1.5m above ground level, and the system included twenty-seven laterals, each spaced at 1 m intervals and 8 m in length. Drippers were set at 30 cm intervals on a raised bed featuring two rows of cucumbers, with one lateral line dedicated to irrigation.
The primary goal of this study was to explore soil infiltration traits and comprehend the local agro-climatic conditions. Utilizing a well-designed polyhouse and a gravity-based drip irrigation system, the study aimed to support cucumber cultivation. The outcomes of this research hold potential ramifications for enhancing agricultural methodologies and water management in the area.

**Experimental Setup**

A randomized block design was employed in a naturally ventilated polyhouse, with three replications ($R_1$, $R_2$, and $R_3$). The experiment area was divided into 8 m × 0.7 m beds, where nine treatments were randomly assigned. Each treatment comprised 30 cucumber plants, with five earmarked for plant parameter observations. The experimental specifics are as follows:
Design: Randomized Block Design (RBD)
Replications: 03
Treatments: 09
Bed size: 8 m × 0.70 m
Experimental field size: 24.3 m × 8 m
Gross field size: 28 m × 10 m
Plant Spacing: 0.50 m × 0.50 m
Crop and Variety: Cucumber cv. mini angel F1 Hybrid
No. of plants per row: 15
No. of rows in each bed: 02
Total no. of plants in each bed: 3

**Treatment Details**

The experiment was conducted in a naturally ventilated polyhouse under nine treatment combinations, encompassing three irrigation levels and three fertigation levels. The details of these treatments are as follows:

**Irrigation Levels:**

$I_1$: Drip irrigation with 100% ETC
$I_2$: Drip irrigation with 80% ETC
$I_3$: Drip irrigation with 60% ETC
Fertigation Levels (NPK kg/ha):
$F_1$: 120% RDF
$F_2$: 100% RDF
$F_3$: 80% RDF

**Treatment Combinations:**

$T_1$: Drip irrigation with 100% ETC and 120% RDF
$T_2$: Drip irrigation with 100% ETC and 100% RDF
$T_3$: Drip irrigation with 100% ETC and 80% RDF
$T_4$: Drip irrigation with 80% ETC and 120% RDF
$T_5$: Drip irrigation with 80% ETC and 100% RDF
$T_6$: Drip irrigation with 80% ETC and 80% RDF
$T_7$: Drip irrigation with 60% ETC and 120% RDF
$T_8$: Drip irrigation with 60% ETC and 100% RDF
$T_9$: Drip irrigation with 60% ETC and 80% RDF
All treatments were randomly arranged with three replications ($R_1$, $R_2$, and $R_3$) for each treatment as blocks.

**Description of AquaCrop model**

The AquaCrop model is rooted in a distinct crop growth mechanism driven by the principle of water-induced development. In this context, the quantity of water consumed by crops assumes a pivotal role in shaping their growth and output. Given the intricate ways in which crops react to water scarcity, the need for practical approaches to assess the impact of water availability on crop yields becomes imperative. To tackle this challenge, empirical production functions have been applied. One standout reference in ascertaining crop yield response to water, particularly in the realm of field, vegetable, and tree crops, is the FAO Irrigation and Drainage Paper No. 33 [9]. This noteworthy publication furnishes valuable insights and methodologies for gauging crop yield response across varying water conditions. The AquaCrop model employs a specific equation drawn from the findings of this paper, enabling researchers and agricultural practitioners to meticulously gauge the repercussions of diverse water regimes on crop productivity. By integrating this empirical approach into the AquaCrop model, users gain the ability to make well-informed choices regarding water management strategies, thus optimizing crop production while accounting for water availability. This contributes to the fostering of more sustainable and efficient agricultural practices. The AquaCrop model's capacity to amalgamate water-driven crop growth principles with the empirical yield response function positions it as a precious instrument for elevating global agricultural productivity and managing water resources.

$$\left(1-\frac{Y_a}{Y_X}\right)=k_y\left(1-\frac{ET_a}{ET_X}\right) \qquad [1]$$

Where,
$Y_X$ and $Y_a$ = Maximum and Actual yield,
$ET_X$ and $ET_a$ = Maximum and Actual evapotranspiration, and
$K_y$ = Crop yield factor.
The AquaCrop growth engine stands out as a distinctive model within the existing landscape due to its well-balanced accuracy, simplicity, and robustness, attributes achieved through ongoing refinements and enhancements by FAO experts. Steduto *et al.* (2009) [10] have comprehensively explained the conceptual framework, underlying principles, distinct components, and features of AquaCrop, while Raes *et al.* (2009) [11] have delved into its structural intricacies and algorithms.
AquaCrop's foundation originates from the approach proposed by Doorenbos and Kassam (1979), yet it incorporates two pivotal differentiations to augment its performance. Firstly, AquaCrop intelligently segregates evapotranspiration (ET) into soil evaporation (E) and crop transpiration (Tr). This separation adeptly accommodates nonproductive consumptive water usage (E) during periods of incomplete ground cover-a significant factor influencing water consumption in different growth stages. This enhancement empowers AquaCrop to provide more precise assessments of water requisites and usage.
Secondly, AquaCrop partitions the ultimate yield (Y) into biomass (B) and harvest index (HI). This division fosters a clear differentiation between the fundamental relationships of the environment with biomass (B) and those with harvest index (HI). Consequently, AquaCrop avoids the confounding ramifications of water stress on both biomass (B) and harvest index (HI), culminating in a more accurate and comprehensive growth model for crop simulations. With these advancements seamlessly integrated, AquaCrop has solidified its status as a trustworthy tool for agricultural practitioners and researchers alike. Its capacity to independently segregate and evaluate evapotranspiration components and yield factors significantly bolsters its precision and resilience in simulating crop growth across diverse water availability scenarios. This positions AquaCrop as a valuable resource for refining water management strategies, predicting crop productivity, and advocating sustainable agricultural practices on a global scale.

$$B=WP\sum T_r \qquad [2]$$

Where,
B = Biomass
Tr = Crop transpiration, mm and
WP = Water productivity parameter, kg $m^{-3}$
The canopy represents the source for actual transpiration that gets translated in a proportional amount of biomass produced through the water productivity parameter (WP) [Eq-2]. The harvestable portion of such biomass (yield) is then determined through harvest index (HI) as below [Eq-3].

$$Y=HI\times B \qquad [3]$$

Where,
Y = Yield
HI = Harvesting Index
B = Biomass
Even though AquaCrop uses HI parameter, it does not calculate the separation of biomass into various organs (e.g., leaves, roots, etc.), i.e., biomass production is decoupled from canopy expansion and root deepening.

## Results and Discussion

### Calibration of AquaCrop Model

The calibration of the AquaCrop model was conducted during the time frame spanning 2018 to 2020. The calibration process involved parameter adjustments, including the crop duration and field days after sowing for the full irrigation treatment $T_1$ (where irrigation was scheduled at 100% ETC under non-mulch conditions). This calibration phase aimed to fine-tune the model's accuracy.

To evaluate the model's performance, observed values of critical model parameters such as canopy cover (CC), cucumber biomass, and yield were compared against the simulated results. The subsequent sections delve into a discussion of the model's performance. A visual representation of the canopy cover curve, transpiration curve, and the simulated yield can be found in [Fig-1].

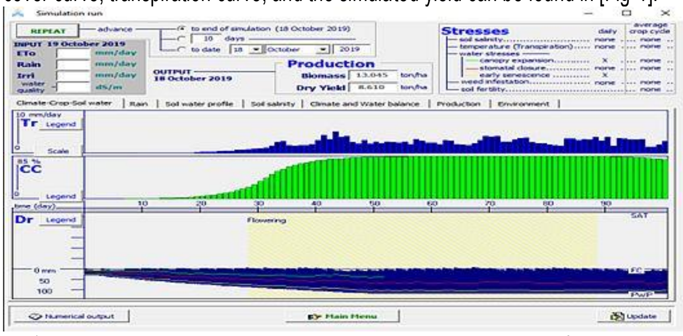

Fig-1 Model generated transpiration, canopy cover and soil moisture in the root zone for treatments $T_2$

### Canopy Cover (CC)

During the calibration procedure, a range of canopy parameters were subject to manual adjustments. These included initial canopy cover (CC), the count of days for recovery, maximum canopy cover (CC), and the decay of canopy cover. Canopy cover measurements were taken at specific intervals corresponding to different growth stages of the cucumber crop. The complete duration of the crop's growth cycle and the period leading to senescence were assessed to meticulously refine the model.

Temporal changes in both observed and simulated canopy cover were compared, and the findings are presented in [Table-1]. Cucumber-specific crop parameters were fine-tuned based on observations from field trials conducted under optimal water supply conditions. The initial parameter examined was canopy cover, which signifies the expansion of leaf canopy under conditions without limitations. This involved assessing both the maximum value of canopy cover (CC) and the duration required to attain specific canopy cover levels (CC).

This iterative calibration process endeavors to heighten the precision of the model in predicting the growth dynamics of cucumber crops and in optimizing strategies for water management.

*Table-1 Observed and Simulated Canopy Cover During Calibration of AquaCrop Model*

| Date | DAS | Canopy cover (%) | |
|---|---|---|---|
| | | Observed | Simulated |
| 29-Jul | 20 | 6.9 | 4.8 |
| 21-Aug | 43 | 83.5 | 78.6 |
| 26-Aug | 48 | 85.7 | 82.2 |
| 30-Aug | 52 | 87.2 | 83.4 |
| 02-Sep | 55 | 87.2 | 85 |
| 09-Sep | 62 | 80.4 | 85 |
| 17-Sep | 70 | 78.3 | 85 |
| 24-Sep | 77 | 77.3 | 85 |
| 30-Sep | 83 | 77.8 | 85 |
| 10-Oct | 93 | 76.6 | 83.8 |
| 14-Oct | 97 | 70.3 | 81.6 |
| 18-Oct | 101 | 67.6 | 78.4 |
| $R^2_{NS}$ | 0.996 | | |
| CRM | -0.0434 | | |

As depicted in [Fig-2], there is a consistent incremental rise in the percentage of canopy cover, both in observed and simulated data, as the days after sowing (DAS) advance. This upward trend culminates in a peak at around 55 days after sowing. This observation is in line with the anticipated mid-season phase of cucumber cultivation, which typically spans from 50 DAS to 90 DAS, as highlighted in FAO Paper No. 56 [12]. The graph essentially illustrates that the development of canopy cover adheres to the anticipated growth trajectory for cucumber crops throughout their cultivation cycle.

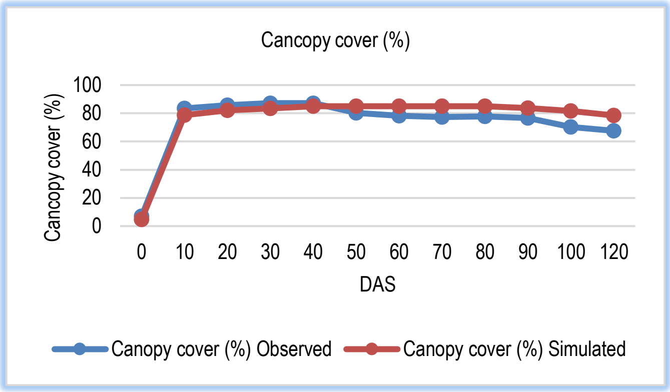


Fig-2 Observed and Simulated Canopy Cover for Calibration Period

The findings of the study indicate that at 50 days after sowing (DAS), the observed maximum canopy cover reached 87.2 percent, while the simulated maximum canopy cover was 85 percent at 55 DAS. The model's performance is highlighted by a high R²NS value of 0.996, along with a negative CRM value of -0.0434, signifying a tendency for overestimation in canopy cover. The R²NS value being within an appropriate range suggests that the model fits well and possesses robust predictive capabilities. The scatter plot depicted in [Fig-3] showcases a noteworthy alignment between the observed and simulated canopy cover throughout the crop's growth period, substantiating the high R²NS value. Nonetheless, the model tends to overestimate the canopy cover, particularly during the developmental phase spanning from 60 to 110 DAS. On the whole, the scatter plot for canopy cover closely tracks the 1:1 line, indicating a well-balanced model that offers estimations of canopy cover without consistent overestimation or underestimation.

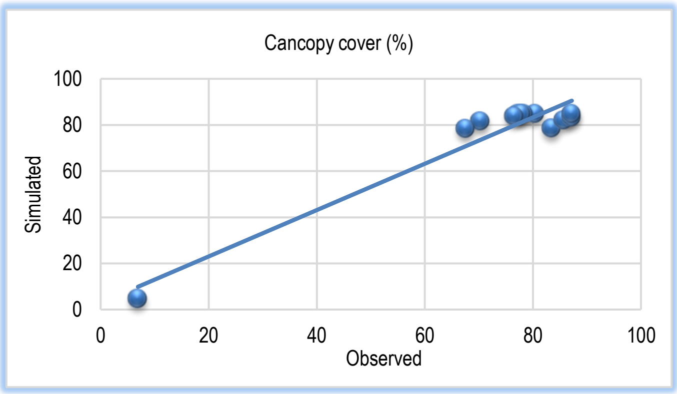


Fig-3 Scatter Plot of Observed and Simulated Canopy Cover for Calibration Period

*Table-2 Cumulative Observed and Simulated Biomass during Calibration of AquaCrop Model*

| Date | DAS | Cumulative Biomass (t/ha) | |
|---|---|---|---|
| | | Observed | Simulated |
| 10-Jul | 1 | 0.00 | 0.00 |
| 29-Jul | 20 | 0.09 | 0.09 |
| 21-Aug | 43 | 2.24 | 2.54 |
| 26-Aug | 48 | 3.12 | 3.46 |
| 30-Aug | 52 | 3.69 | 4.19 |
| 02-Sep | 55 | 4.25 | 4.94 |
| 09-Sep | 62 | 5.23 | 6.06 |
| 17-Sep | 70 | 6.36 | 7.54 |
| 24-Sep | 77 | 7.25 | 8.83 |
| 30-Sep | 83 | 8.24 | 9.92 |
| 10-Oct | 93 | 9.79 | 11.72 |
| 14-Oct | 97 | 10.25 | 12.40 |
| 18-Oct | 101 | 10.51 | 13.05 |
| $R^2_{NS}$ | 0.854 | | |
| CRM | -0.193 | | |

### Biomass

After adjusting the canopy for matching biomass, harvesting index and water productivity. The cumulative and simulated observed biomass is presented in [Table-2].

As shown in [Table-2], the coefficient of determination ($R^2NS$) for the AquaCrop model stands at 0.854, aligning well with an acceptable range for model fitting. This notable $R^2NS$ value underlines the model's effectiveness in simulating the overall biomass yield. Moreover, the model exhibited strong predictive capabilities concerning biomass values at harvest, substantiated by the computed statistical indices.

The temporal evolution of observed and simulated biomass is visually displayed in [Fig-4], further reinforcing the model's precision in capturing the evolving dynamics of biomass growth over time. These encouraging outcomes underscore the AquaCrop model's reliability in both predicting and evaluating the total biomass yield. This reliability positions the model as a valuable tool for assessing crop productivity and refining water management strategies.

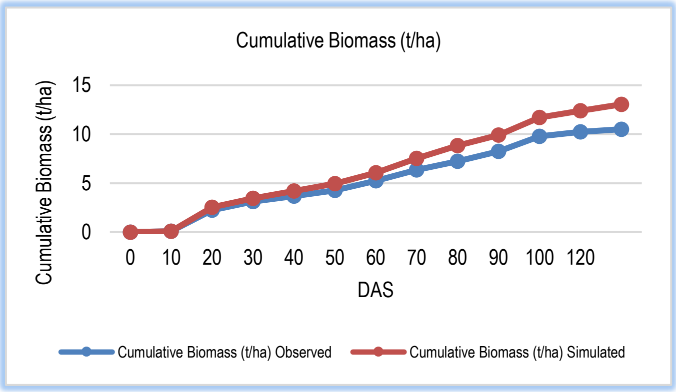


Fig-4 Observed and Simulated Biomass for Calibration Period

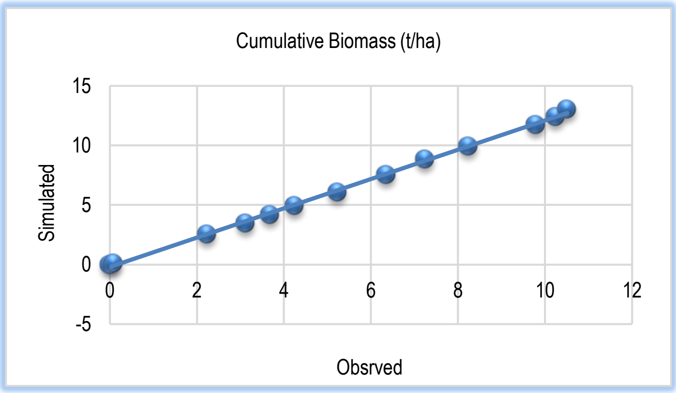


Fig-5 Scatter plot of observed and simulated biomass for calibration period

Based on the data extracted from [Fig-4] and [Fig-5], the cumulative observed biomass during the calibration phase amounted to 10.51 t/ha, while the AquaCrop model predicted a cumulative biomass of 13.05 t/ha. The Nash Sutcliffe coefficient ($R^2NS$) of 0.85 signifies that both the observed and simulated biomass adhered to a similar pattern. However, the coefficient of residual mass (CRM) at -0.193 indicates a propensity for the model to overestimate biomass. Over the growth stages, the model consistently exhibited this overestimation, particularly from 40 to 105 days after sowing.

Notwithstanding the relatively high $R^2NS$ value of 0.85, which meets the criterion for model fitting, the conspicuous biomass overestimation is substantiated by the negative CRM value. This overestimation aligns with findings documented by Zhang *et al.* (2013) [13] concerning above-ground biomass and by Tayade *et al.* (2018) [14] regarding potato crops. The combined assessment of $R^2NS$ and CRM establishes statistical benchmarks for evaluating model performance. While $R^2NS$ is notably high, the consistent biomass overestimation should be acknowledged when interpreting the outcomes.

### Yield of cucumber

The primary objective of this study was to ascertain the water productivity characteristic value (WP) under the specific environmental and technical conditions of Udaipur. This was achieved by calculating the final yield of a cucumber crop cultivar under various irrigation rates. AquaCrop facilitated the linkage between observed and projected final dry fruit yields across different irrigation scenarios. The cucumber fruit yield was manually adjusted based on the harvest index estimated by Kaur *et al.* (2019) [15] and the cumulative observed and simulated yields are detailed in [Table-3].

According to the data presented in [Table-3], the observed cucumber fruit yield during the calibration period amounted to 6.941 t/ha. The model's prediction yielded a figure of 8.61 t/ha, factoring in a harvest index of 65.49%. The Nash Sutcliffe coefficient ($R^2NS$) stands at 0.915, indicating a favorable alignment between the observed and simulated yields up to 60 DAS. However, the AquaCrop model consistently exhibited an overestimation of simulated yield in comparison to the observed yield across the entire crop growth duration. This trend is corroborated by the negative coefficient of residual mass (CRM) recorded at -0.240.

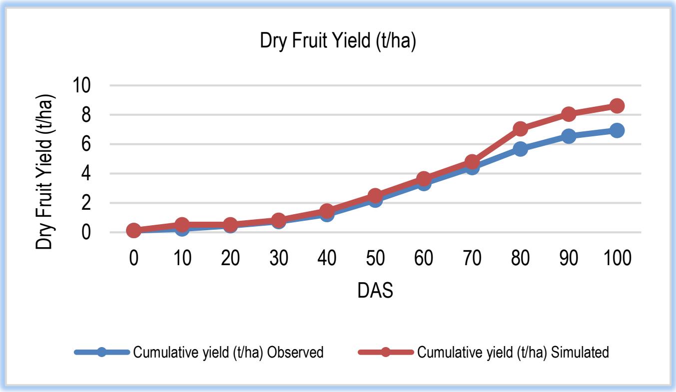


Fig-6 Observed and simulated yield for calibration period

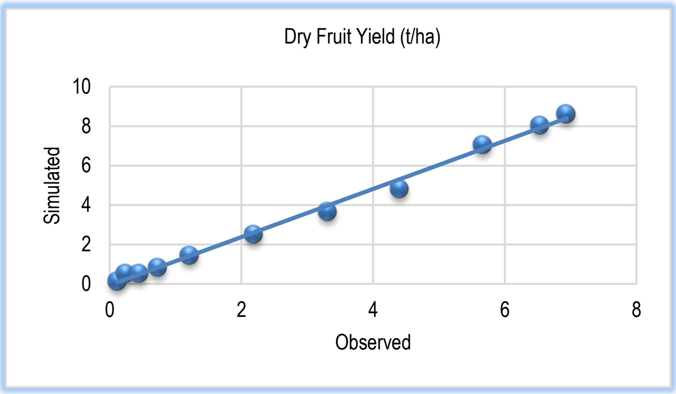


Fig-7 Scatter plot of observed and simulated yield for calibration period

*Table-3 Cumulative Observed and Simulated Yield During Calibration of AquaCrop Model*

| Date | DAS | Cumulative yield (t/ha) | |
|---|---|---|---|
| | | Observed | Simulated |
| 21-Aug | 43 | 0.118 | 0.123 |
| 26-Aug | 48 | 0.243 | 0.514 |
| 30-Aug | 52 | 0.448 | 0.512 |
| 02-Sep | 55 | 0.737 | 0.834 |
| 09-Sep | 62 | 1.215 | 1.448 |
| 17-Sep | 70 | 2.195 | 2.508 |
| 24-Sep | 77 | 3.318 | 3.659 |
| 30-Sep | 83 | 4.411 | 4.808 |
| 10-Oct | 93 | 5.671 | 7.051 |
| 14-Oct | 97 | 6.541 | 8.041 |
| 18-Oct | 101 | 6.941 | 8.61 |
| $R^2_{NS}$ | | 0.915 | |
| CRM | | -0.240 | |

[Fig-6] visually illustrates the temporal fluctuations of both observed and simulated yield, while [Fig-7] presents a scatter plot specific to the calibration period. When compared, the R²NS and CRM values reported by Tayade *et al.* (2018) for potato crop yield - 0.82 and -0.142, respectively - exhibit a similarity with the AquaCrop model's general performance in simulating yield for the cucumber crop in the current study. The data illustrated in [Fig-6] clearly highlights that the observed yield stood at 6.941 t/ha, whereas the simulated yield amounted to 8.61 t/ha. This discrepancy indicates an overestimation by the model over the course of the crop's growth phase.

[Fig-7], presenting a scatter plot, portrays the observed and simulated yields during the calibration period. The calibration of the model was validated by the close alignment between the observed and simulated values for canopy cover, biomass, and cucumber yield. Additionally, the evaluation of statistical measures, namely R²NS and CRM, fell within the acceptable range, thus affirming the successful calibration of the AquaCrop model. This conclusion mirrors a similar study conducted by Bitri and Grazhdani (2015) [16], which demonstrated the model's proficient simulation of potato tuber yield, supported by favorable performance assessment metrics like RMSE and R².

The calibrated parameters of the model, outlined in [Table-3], stand as a dependable point of reference for forthcoming simulations of cucumber crops under Udaipur's unique environmental and technical conditions.

## Model Validation

Model validation was conducted as an extension of the calibration process, without any additional adjustments to the calibrated model parameters. The validation period ranged from 2018 to 2020 for all treatments, except the control treatment ($T_2$). The cumulative yield and biomass for each treatment during the validation period were simulated using the model and presented in [Table-4], along with the results of statistical tests for the validation period

*Table-4 Statistical Analysis of Validated Results for Biomass and Yield*

| SN | Treatments | Yield (t/ha) | | Biomass (t/ha) | |
|---|---|---|---|---|---|
| | | Observed | Simulated | Observed | Simulated |
| 1 | $T_5$ | 7.91 | 8.61 | 11.99 | 13.05 |
| 2 | $T_8$ | 5.63 | 8.41 | 8.53 | 12.74 |
| $R^2_{NS}$ | | 0.93 | | 0.89 | |
| CRM | | -0.210 | | -0.226 | |

Observed biomass exhibited a range spanning from 8.53 to 11.99 t/ha, while the observed cucumber yields displayed variations ranging from 5.63 to 7.91 t/ha. In contrast, the simulated biomass oscillated between 12.74 and 13.05 t/ha, with the simulated cucumber yield varying from 8.41 to 8.61 t/ha.

Regarding model performance, the Nash Sutcliffe coefficient (R²NS) values stood at 0.89 for biomass and 0.93 for cucumber yield, indicating a remarkable agreement between observed and simulated data for both biomass and yield metrics. However, the coefficients of residual mass (CRM) reported values of -0.226 for biomass and -0.210 for yield, signifying a tendency of the model to consistently overestimate both biomass and yield.

## Conclusion

From the above study it can be concluded that the AquaCrop model is suitable to simulate fruit yield, biomass and canopy cover for cucumber crop for Udaipur region. Both the statistical performance evaluation parameter was found in acceptable range while validating the model.

**Application of research:** Study of performance check of aquacrop model on cucumber

**Research Category:** Irrigation and fertigation

**Abbreviations:** DAS- Days after sowing

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Research project name or number: MTech thesis

**Author Contributions:** All authors equally contributed

**Author statement:** All authors read, reviewed, agreed and approved the final manuscript. Note-All authors agreed that- Written informed consent was obtained from all participants prior to publish / enrolment

**Study area / Sample Collection:** College of Technology and Engineering, Udaipur, 313001, Rajasthan, India

**Cultivar / Variety / Breed name:** Cucumber cv. Mini angel F1 Hybrid

**Conflict of Interest:** None declared

**Ethical approval:** This article does not contain any studies with human participants or animals performed by any of the authors.
Ethical Committee Approval Number: Nil

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