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Modelling of Cowpea Response to Varying Irrigation and SAP Levels Under Greenhouse Conditions Using AquaCrop

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ABSTRACT

Irrigation water management is key to promoting resilient crop production amidst the increasing effects of climate change. Super absorbent polymer (SAP) is an innovative technology for conserving irrigation water within arid and semi-arid lands (ASALs). AquaCrop, a water productivity model, has been used for irrigation water management. This study aimed to model the response of cowpea to various irrigation and SAP levels under greenhouse conditions via AquaCrop. The experiments included five SAP application rates [0% (control), 0.05%, 0.1%, 0.15% and 0.2% to weight of the soil substrate] and five irrigation levels [full irrigation (FI), and 80%, 70%, 60% and 30% FI]. The AquaCrop model simulations matched the observed values with a normalized root mean square error of less than 16%. The simulated yield and biomass for full irrigation and 0% SAP were 5.1 and 11.0 t/ha, respectively, whereas the observed values were 5.3 and 10.8 t/ha, respectively. Treatments with SAP showed increased yield, biomass, water productivity (WP_{ET}) and harvest index (HI) with increased water stress up to 137%, 17%, 10% and 117%, respectively. Thus, SAP can improve crop production, and the AquaCrop model is suitable for improving irrigation water productivity within ASALs where water is scarce.

Résumé

La gestion de l'eau d'irrigation est essentielle pour promouvoir une production agricole résistante aux effets croissants du changement climatique. Le polymère super absorbant (SAP) est une technologie innovatrice utilisée pour conserver l'eau d'irrigation dans les terres arides et semi-arides (ASAL). AquaCrop, un modèle de productivité de l'eau, a été utilisé pour la gestion de l'eau d'irrigation. Cette étude visait à modéliser la réponse du niébé à différents niveaux d'irrigation et de SAP dans des conditions de serre via AquaCrop. Les expériences comprenaient cinq taux d'application de SAP (0% (réglage), 0,05%, 0,1%, 0,15% et 0,2% par rapport au poids du substrat du sol) et cinq niveaux d'irrigation (irrigation complète (FI) et (80%, 70%, 60% et 30%) FI)). Les simulations du modèle AquaCrop ont correspondu aux valeurs observées avec une erreur moyenne quadratique normalisée inférieure à 16%. Le rendement et la biomasse simulés pour une irrigation complète et 0% de SAP étaient de 5,1 t/ha et 11,0 t/ha respectivement, tandis que les valeurs observées étaient de 5,3 t/ha et 10,8 t/ha respectivement. Les traitements avec SAP ont montré une augmentation du rendement, de la biomasse, de la productivité de l'eau (WPET) et de l'indice de récolte (HI) avec

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une augmentation du stress hydrique jusqu'à 137%, 17%, 10% et 117%, respectivement. Ainsi, le SAP peut améliorer la production agricole, et le modèle AquaCrop est adapté à l'amélioration de la productivité de l'eau d'irrigation dans les terres arides et semi-arides (ASAL) où l'eau est rare.

1 | Introduction

Drought is the greatest threat to food security and livelihoods in arid and semi-arid lands (ASALs) in drought-prone developing countries. The effects of climate change and increasing water demand have escalated water scarcity (Gitz et al. 2016). An increasing human population is estimated to lead to a 50% increase in demand for food and agricultural products between 2013 and 2050 (Vos and Bellù 2018). Irrigation is practiced to increase agricultural food production amidst the changing climate using limited water resources. Therefore, climate change and the growing demand for food require innovative technologies to improve irrigation water-use efficiency. The use of super absorbent polymers (SAPs) in irrigation is an innovative technology for conserving limited water resources within the ASALs (Ashraf, Ragavan, and Begam 2021). Super absorbent polymers are cross-linked hydrophilic networks that can absorb and retain 1000 times more water than their original size and weight and release water slowly around the root zone on demand (Bai, Song, and Zhang 2013). SAPs act as supplemental water reservoirs in the soil that help retain water and make it available to plants as needed (Saha, Sekharan, and Manna 2020; AbdAllah, Mashaheet, and Burkey 2021). They work by absorbing water and swelling to many times their original volume. This water is then slowly released into the soil as the plant needs it, reducing the need for frequent irrigation. SAPs are particularly useful in areas with low rainfall or high evaporation rates, as they can help conserve water and reduce the risk of crop failure (Ashraf, Ragavan, and Begam 2021).

SAPs are known to improve plant growth parameters and yield (Ostrand et al. 2020). SAPs absorb and retain water during supply and provide constant access to water by plants when needed, hence increasing crop yield. Research has also shown that SAPs increase the irrigation interval and irrigation water use efficiency (Chang et al. 2021). According to Cerasola et al. (2022), SAPs reduce crop irrigation requirements by up to 25% and increase irrigation water use efficiency by up to 37%. Furthermore, Zheng et al. (2023) reported that SAP increased crop yield by 13% and water productivity by 17%. SAP conserves irrigation water by reducing the amount of irrigation water while maintaining production (Satriani, Catalano, and Scalcione 2018). This can help reduce the frequency of irrigation and improve water efficiency.

Cowpea (*Vigna unguiculata*) is one of the most popular leafy vegetables (in terms of production and consumption) in developing countries, including Kenya. It is a leguminous plant that can be consumed at different stages of growth development: fresh green leaves, dry leaves, immature green pods, immature and mature green beans, or dry grains. It plays an important socioeconomic role and provides food and nutrition security in sub-Saharan Africa (Nunes et al. 2021). However, drought has been one of the greatest challenges to its limited production (Omomowo and Babalola 2021). To promote cowpea production within ASALs, innovative technologies, including SAP, can be used. However, determining irrigation water productivity (WP) is key to promoting irrigation system performance. WP is a measure of the amount of crop produced per unit of irrigation water applied. It is measured through the response of crops to irrigation (Cerasola et al. 2022). Crop WP is critical for enhancing irrigation water management when SAP is used in irrigation, particularly in ASALs where water is scarce.

The AquaCrop model has been widely used to simulate daily crop growth and production accurately in response to water. Thus, it is an important tool for optimizing irrigation water productivity, particularly in ASALs where water resources are limited (Steduto et al. 2009; FAO 2022; Alvar-Beltrán et al. 2023). The AquaCrop model has been used to successfully simulate cowpea biomass production, yield and water productivity under full and deficit irrigation (Kanda, Senzanje, and Mabhaudhi 2021a); yield under water stress (Ferrreira and da Silva 2023); water use (Kanda, Senzanje, and Mabhaudhi 2021b); and the impact of sowing date on yield (Nunes et al. 2021). However, AquaCrop model simulations of cowpea in soil treated with SAP have not yet been performed.

Therefore, the purpose of this study was to evaluate the performance of the AquaCrop model in the simulation of the response of cowpea to varying irrigation and SAP levels under greenhouse conditions.

2 | Materials and Methods

2.1 | Area of Study

The experiments were conducted in a greenhouse located at latitude 1°21′29.1″ S and longitude 38°01′16.7″ E in Kitui County, Kenya, between 2020 and 2021. The climate in Kitui County is classified as semi-arid and characterized by a low mean annual rainfall of 600 mm, high average annual maximum and minimum temperatures; and annual mean temperatures of approximately 31°C, 15°C and 21°C (Mutunga et al. 2022). Climate data for AquaCrop parameterization were acquired from the nearest weather station (TA00480 SEKU Main Campus) for 2020 and 2021. The daily weather data used included the minimum and maximum air temperatures (°C), solar radiation (W/m^2), wind speed (m/s) and relative humidity (%). During the plant growth period, the average minimum and maximum daily temperatures were 12°C and 31°C, respectively, as presented in Figure 1. The experiments were conducted in a greenhouse with controlled conditions; hence, precipitation and wind speed were not considered.

2.2 | Experimental Design and Crop Management

The experiment was performed in a randomized complete block design comprising 25 treatments. On the basis of the literature

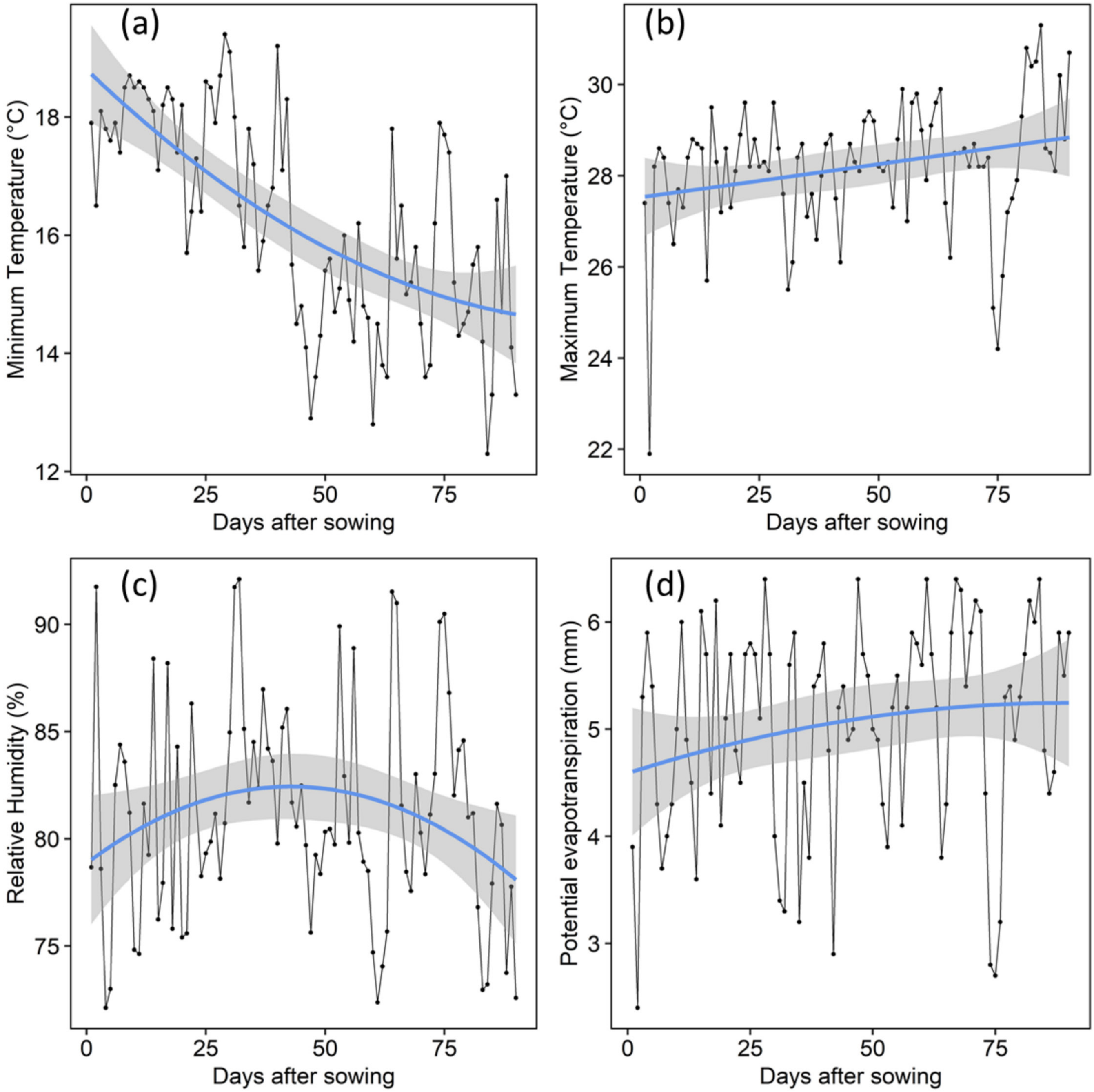

FIGURE 1 | (a) Daily minimum temperature (T_{min}), (b) maximum temperature (T_{max}), (c) relative humidity and (d) potential evapotranspiration (ETo) for the experimental site during the cowpea growing season.

(Malik et al. 2023), five SAP application rates and five irrigation levels were selected. The treatments included a factorial combination of five SAP application rates [0% (control), 0.05%, 0.1%, 0.15% and 0.2% relative to the weight of the soil substrate] and five irrigation levels [full irrigation (FI), 80% FI, 70% FI, 60% FI and 30% FI], with three replications. The pot size was 0.04 m^3, and each pot contained 3 kg of soil substrate. The SAP granules were applied to each pot accordingly and mixed with the soil substrate properly, and the pots were arranged in the greenhouse according to the experimental layout presented in Table 1. The leafy vegetable studied was cowpea (*V. unguiculata*).

The soil samples were collected from the greenhouse and its environments and analysed for their physiochemical properties (Table 2). The soil was classified as sandy clay loam with neutral pH values ranging from 6.70 to 6.86, which is recommended for irrigation since it is considered to have maximum availability of most macronutrients essential for plant growth and yield. Chicken manure was added to the soil to increase the levels of nitrogen, nutrients and organic matter. To increase the growth of the crops, foliar fertilizer comprising 14% nitrogen, 12% phosphorous, and 8% potassium was applied 30 days after sowing at a rate of 2.4 L/ha.

Furthermore, the collected soil data were used to determine the soil moisture content at the saturation point, field capacity, permanent wilting point, available water, saturated hydraulic conductivity and matric bulk density via the SPAW (Soil – Plant – Air – Water) model (Nassiri-Mahallati and Jahan 2020). The soil particle size distribution included 69% sand, 5% silt and 26% clay, resulting in sandy clay loam soil texture classification Table 3.

Harvesting was performed when 90% of the plants were at the maturity stage (90 days from sowing) by cutting the whole plant above the soil. The fresh weights of the entire plant, leaves and pods were measured after harvesting. Both the biomass and yield were oven-dried at a temperature of 50°C, and the dry weight was determined.

2.3 | Model Description

The AquaCrop model developed by the Food and Agriculture Organization (FAO) division for Land and Water, is a water productivity model that simulates daily biomass production and final crop yield in relation to water supply and consumption as well as agronomic management (Raes et al. 2009; Steduto et al. 2009). Thus, this method is a valuable tool for optimizing irrigation water use, particularly in ASALs where water resources are limited. AquaCrop simulates the crop yield response to water in five phases that integrate soil, crop and climate dynamics: (i) simulation of crop canopy cover development (*CC*) based on the green canopy cover and canopy water expansion and senescence (Equation 1); (ii) estimation of crop transpiration (T_r) as a function of canopy cover, potential evapotranspiration (*ETo*) and water stress (Equation 2); (iii) calculation of biomass production (*B*) based on cumulative transpiration and biomass water productivity (*WP*) (Equation 3); (iv) calculation of crop yield (*Y*) from crop biomass and harvest index (*HI*) (Equation 4); and (v) computation of yield water productivity (WP_{ET}) as in (Equation 5) (Raes et al. 2009, 2022; Steduto et al. 2009; Lu et al. 2021):

$$CC = CC_x \left(1 - e^{-K_c(t-to)}\right) \quad (1)$$

$$T_r = \left(CC^* \times K_{C\,T_r,\ \ x}\right) ET_o \quad (2)$$

$$B = WP \times \sum T_r \quad (3)$$

$$Y = HI \times B \quad (4)$$

$$WP_{ET} = \frac{Y}{ET} \quad (5)$$

where *CC* represents crop canopy cover (%), CC_x represents maximum canopy cover (%), K_c represents the canopy cover expansion rate at an elapsed time (unitless), T_r represents crop transpiration (mm), CC^* represents adjusted canopy cover (%), $K_{C\,T_r,\ \ x}$ represents the maximum crop transpiration

TABLE 1 | Study experimental layout.

SAP application rate (% of SAP in soil substrate)	Irrigation level				
	I_1 (FI)	I_2 (80% of FI)	I_3 (70% of FI)	I_4 (60% of FI)	I_5 (30% of FI)
S_1 (0%) - control	S_1I_1	S_1I_2	S_1I_3	S_1I_4	S_1I_5
S_2 (0.05%)	S_2I_1	S_2I_2	S_2I_3	S_2I_4	S_2I_5
S_3 (0.1%)	S_3I_1	S_3I_2	S_3I_3	S_3I_4	S_3I_5
S_4 (0.15%)	S_4I_1	S_4I_2	S_4I_3	S_4I_4	S_4I_5
S_5 (0.2%)	S_5I_1	S_5I_2	S_5I_3	S_5I_4	S_5I_5

Note: S_1, S_2, S_3, S_4 and S_5 are SAP application rates, FI is full irrigation, and I_1, I_2, I_3, I_4 and I_5 are irrigation levels.

TABLE 3 | Soil characteristics.

Parameter	Value	Metric units
Texture class	Sandy clay loam	
Permanent wilting point (PWP)	17.2	%
Field capacity (FC)	25.8	%
Saturation	42.2	%
Available water	0.09	cm/cm
Saturated hydraulic conductivity	10.33	mm/h
Matric bulk density	1.53	g/cm^3
Hydraulic conductivity K_{sat}	249.9	mm/day
TAW	86	mm/m
tau	0.6	

TABLE 2 | Physiochemical properties of soil.

Site	pH (H_2O)	N (mg/kg)	% O. C.	K (mg/kg)	P (mg/kg)	EC (ds/m)	Bulk density (g/cm^3)	Porosity (%)	K_{Sat} (cm/h)
1	6.86	90	1.31	148.2	75.2	0.14	1.40	47.3	3.82
2	6.70	160	1.50	78.0	80.5	0.18	1.43	46.1	3.47
3	6.78	120	1.40	101.4	82.8	0.14	1.46	45.0	3.15

coefficient (unitless), ET_o represents potential crop evapotranspiration (mm), B represents biomass (t/ha), WP represents water productivity (g/m^2), $\sum T_r$ represents cumulative crop evapotranspiration (mm), Y represents yield (t/ha), HI represents the harvest index (unitless), ET represents evapotranspiration water loss (mm), and WP_{ET} represents water productivity (kg/m^3).

AquaCrop uses several input files to run the simulations, including climate, crop, soil, management (field management and irrigation management), soil profile and initial soil water conditions files (Raes et al. 2009; Steduto et al. 2009; Iqbal et al. 2014; Nunes et al. 2021). The model input data for this study included the following:

I. Climatic data from the TA00480 SEKU Main Campus weather station. Potential evapotranspiration (ET_o) was determined via the FAO ET_o calculator embedded in AquaCrop. MaunaLoa carbon dioxide (CO_2) concentration data for 1902 to 2099 from AquaCrop were adopted (Figure 1).

II. The cowpea crop data included base and upper temperature limits for growth, the planting density and planting method used, the initial canopy cover, the growth stage calendar and the harvest index.

III. The management data consisted of field management practices and irrigation management practices. Field management refers to agricultural practices to manage the soil and crop environment, with a focus on maintaining soil health, optimizing water use and promoting sustainable crop production. These include weed management, mulching, soil fertility management, field surface practices to improve water distribution and multiple harvests. Irrigation management refers to the irrigation method, net irrigation water requirement and irrigation scheduling, including the timing and depth of each irrigation event. Cowpea net irrigation water requirements and irrigation scheduling were performed via CROPWAT software. Drip irrigation method was used as the irrigation water application method for the study. Mulching was not performed, and multiple harvests were not considered in this study.

IV. Soil data profiling the soil characteristics data obtained from the field experiments and SPAW (Soil – Plant – Air – Water) model analysis.

V. The initial soil water conditions were set at field capacity.

2.3.1 | Calibration and validation

The data from the treatments under full irrigation and without SAP (S_1I_1), as shown in Table 1, were chosen to calibrate the model for cowpea, and the simulated results were compared with the measured data. Canopy cover, final biomass and yield data were collected and used for model calibration. After calibration, the model was validated via treatments with SAPs and varying irrigation levels. All the simulations were run with a common set of parameterized crop parameters. SAP enhances soil properties, increasing its water holding capacity (Tian et al. 2023). The effects of varying SAP application proportions were simulated in the AquaCrop model by adjusting the calibrated treatment's soil water retention characteristics for soil moisture at field capacity.

2.3.2 | Simulation Results Evaluation

To evaluate the performance of the AquaCrop model in comparison with the observed values, different statistical indicators were used. These include the coefficient of determination (R^2) (Equation 6), the root mean square error (RMSE) (Equation 7), the normalized root mean square error (NRMSE) (Equation 8), Willmott's index of agreement (d) (Equation 9), and the Nash–Sutcliffe model efficiency coefficient (NSE) ((10).

$$R^2 = \left[\frac{\sum \left(O_i - \hat{O}\right)\left(S_i - \hat{S}\right)}{\sqrt{\sum \left(O_i - \hat{O}\right)^2 \sum \left(S_i - \hat{S}\right)^2}} \right]^2 \quad (6)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=n}^{n} \left(O_i - S_i\right)^2} \quad (7)$$

$$NRMSE = \sqrt{\frac{1}{n} \sum_{i=n}^{n} \left(O_i - S_i\right)^2} \times \frac{100}{\hat{O}} \quad (8)$$

$$d = 1 - \frac{\sum_{i=n}^{n} \left(S_i - O_i\right)^2}{\sum_{i=n}^{n} \left(\left|O_i - \hat{O}\right| + + \left|S_i - \hat{S}\right|\right)^2} \quad (9)$$

$$NSE = 1 - \frac{\sum_{i=n}^{n} \left(O_i - S_i\right)^2}{\sum_{i=n}^{n} \left(O_i - \hat{O}\right)^2} \quad (10)$$

where O_i, S_i, $\hat{O}$, $\hat{S}$ and n are the observed, simulated, observed mean, simulated mean values and number of treatments, respectively.

R^2 indicates the proportion of variance between the observed and simulated values, with values closer to 1 indicating good agreement. The RMSE provides the magnitude of the error in the same units as the simulated variable (t/ha). The closer the value is to zero, the higher the model performance. d measures the degree of model prediction error with values ranging from 0 to 1, with values closer to 1 indicating perfect agreement. For the NRMSE, values closer to zero indicate good model performance (Alvar-Beltrán et al. 2023). The AquaCrop model is considered good, with NRMSE values between zero and 15%, with values less than 5% being high performing, 16% to 25% indicating satisfactory agreement, and any value greater than 25% indicating a poor model. The NSE measures how perfectly the model simulations match the observed values, with values closer to 1 indicating a perfect model. A good model has NSE values ranging from 0.6 to 1, with values greater than 0.8 indicating a very good model (Raes et al., 2023).

TABLE 4 | AquaCrop model parameterization for cowpea.

Crop parameter	Value	Determination
Cowpea variety	Katumani 80 variety (K80)	
Method of planting	Direct sowing	
Conservative parameters		
Base temperature (°C)	10	L
Upper temperature (°C)	36	L
Parameters affected by planting/management		
Plant density (plants/ha)	611,465	F
Time to 90% emergence (calendar days)	7	F
Size of canopy cover per seedling at 90% emergence (m^2)	2.3395×10^{-3}	F
Canopy size per seedling at 90% emergence (cm^2)	7.80	C
Initial canopy cover, % (CC_o)	4.77	F
Reference harvest index (HI_o)	0.50	F
Cultivar specific crop parameters [phenological development (calendar days)]		
Time to reach maximum canopy cover (CC_x)	37	F
Time to beginning of canopy senescence	64	F
Time to physiological maturity (Calendar days)	90	F
Time to start flowering	49	F
Duration of 50% flowering (Degree of determinacy)	8	F
Length building up HI	37	C
Crop parameters affected by conditions in the soil profile		
Maximum effective rooting depth ((Z_x) cm)	60	L
Time to reach maximum rooting depth (Calendar days)	53	C

Note: L is adopted from the literature, F is the field experiment observation, and C is estimated from the model calibration.

3 | Results

3.1 | Experimental Results

Under optimal conditions (S_1 treatments with zero SAP), cowpea yield and biomass decreased with increasing water stress. The recorded yield ranged between 5.36 and 1.74 t/ha. However, with SAP application, a different trend was observed, where cowpea yield and biomass increased with increasing water stress up to a certain threshold. The highest yield and biomass were recorded at 5.23 and 10.57 t/ha, respectively, at the 0.1% SAP application rate and 20% water stress. The evapotranspiration water productivity (WP_{ET}) followed a similar trend, with an optimum recorded at the 0.1% SAP application rate and 70% water stress.

TABLE 5 | Model simulation of SAP effect on field capacity moisture.

SAP application rate (% of SAP in soil substrate)	Moisture adjustment at field capacity (FC)
S_1 (0%) - control	FC vol %
S_2 (0.05%)	FC ± 12.2 vol %
S_3 (0.1%)	FC ± 12.9 vol %
S_4 (0.15%)	FC ± 14.2 vol %
S_5 (0.2%)	FC ± 14.4 vol %

Note: S_1, S_2, S_3, S_4 and S_5 are SAP application rates and FC is the moisture at field capacity.

3.2 | Model Parameterization

The values of cowpea conservative parameters, including the base and upper temperatures, were 10°C and 36°C, respectively (Kanda, Senzanje, and Mabhaudhi 2021a). Parameters affected by planting/management, cultivar-specific crop parameters related to cowpea phenological development, and parameters affected by conditions in the soil profile were determined through field experimental observations and measurements, a literature review from similar studies, and estimation via the AquaCrop model, as presented in Table 4.

The AquaCrop model does not have built features for modelling SAP. The effects of the varying SAP application proportions were simulated in the AquaCrop model by adjusting the calibrated treatment's soil water retention characteristics for soil moisture at field capacity (Nassiri-Mahallati and Jahan 2020), as presented in Table 5.

3.3 | Model Performance

The observed values for cowpea's final aboveground biomass (B) and yield (Y) were satisfactorily predicted by the AquaCrop simulations (Figure 2 and Figure 3). Overall, the calibration and validation of cowpea yield and biomass yielded 0.2 t/ha ≤ RMSE ≤ 0.5 t/ha, 3% ≤ NRMSE ≤ 16%, 0.93 ≤ d ≤ 0.99, 0.84 ≤ R^2 ≤ 0.97, and 0.68 ≤ NSE ≤ 0.97, indicating a very high performance. For both the observed and simulated values, treatments with SAP showed increased yield, biomass, water productivity (WP_{ET}) and harvest index (HI) with increased water stress up to 137%, 17%, 10% and 117%, respectively. The S_1 yield RMSE, NRMSE, d, R^2 and NSE were 0.5 t/ha, 16%, 0.93, 0.97 and 0.82, respectively, indicating good model performance (Table 6). During calibration, the yield simulations showed an underestimation trend compared with the observed yield. This did not affect the model performance since the model efficiency coefficient was 0.82. The model simulated biomass more accurately, with RMSE, NRMSE, d, R^2 and NSE values of 0.41 t/ha, 5%, 0.99, 0.98 and 0.95, respectively (Table 6), indicating a very high performance. The high estimation of simulation errors and low efficiency coefficient for yield were due to yield underestimation. However, the model's statistical indices are within the satisfactory values for a good model. During validation, the AquaCrop model simulations were also similar to the observed results (Table 6).

3.4 | Model Simulations

3.4.1 | Yield

A slight difference between the measured yield and the simulated yield was noted across all the treatments. S_1 (without SAP) tended to yield underestimation, with a mean difference of 40%. The yield underestimation could be attributed to possible errors in canopy cover and canopy senescence estimation (Kanda, Senzanje, and Mabhaudhi 2021a; Nunes et al. 2021). The results obtained in this

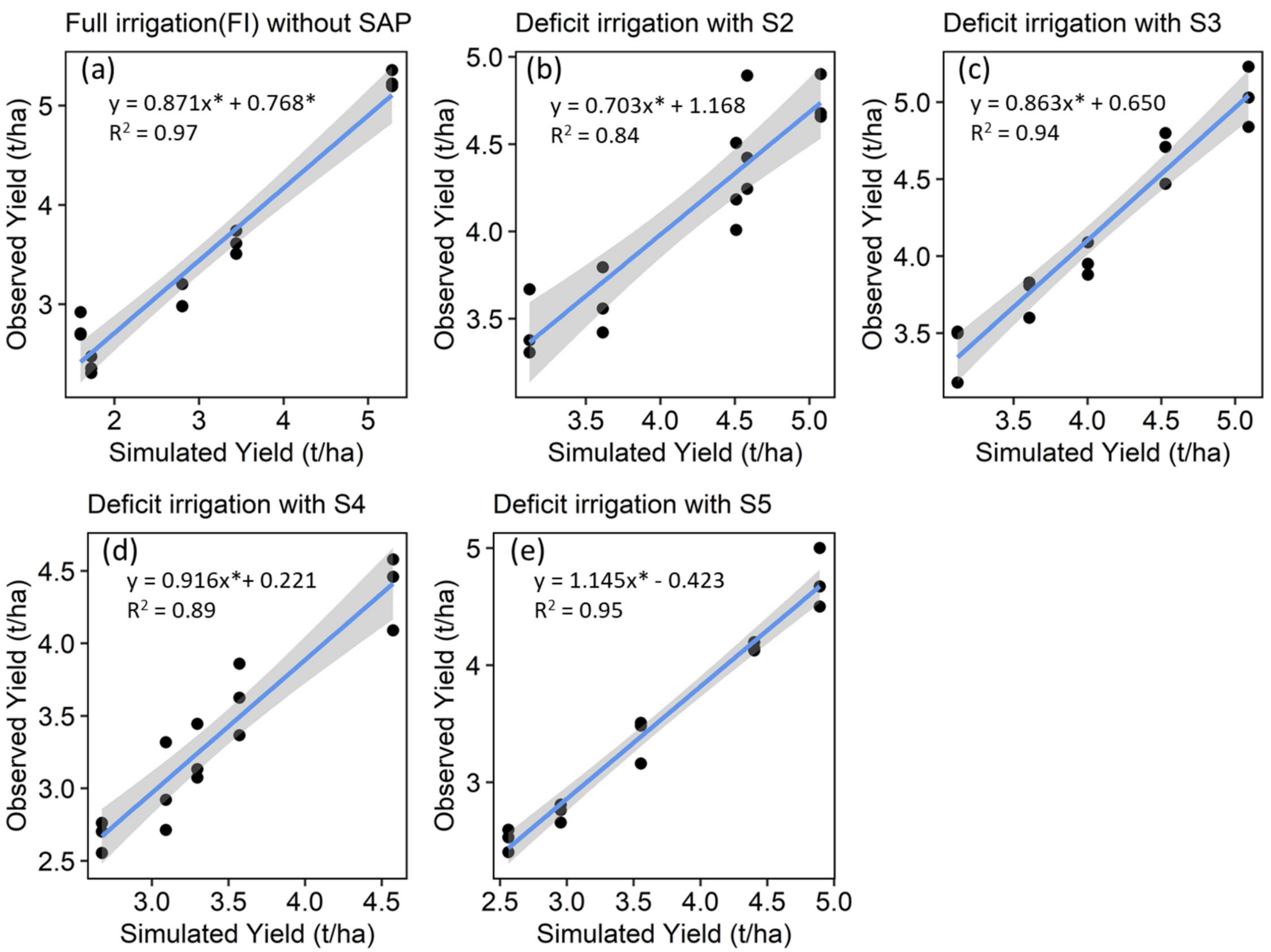

FIGURE 2 | Observed vs simulated dry cowpea yield for calibration (a) full irrigation without SAP (S_1); and validation (b) deficit irrigation with 0.05% SAP (S_2), (c) deficit irrigation with 0.1% SAP (S_3), (d) deficit irrigation with 0.15% SAP (S_4) and (e) deficit irrigation with 0.2% SAP (S_5).

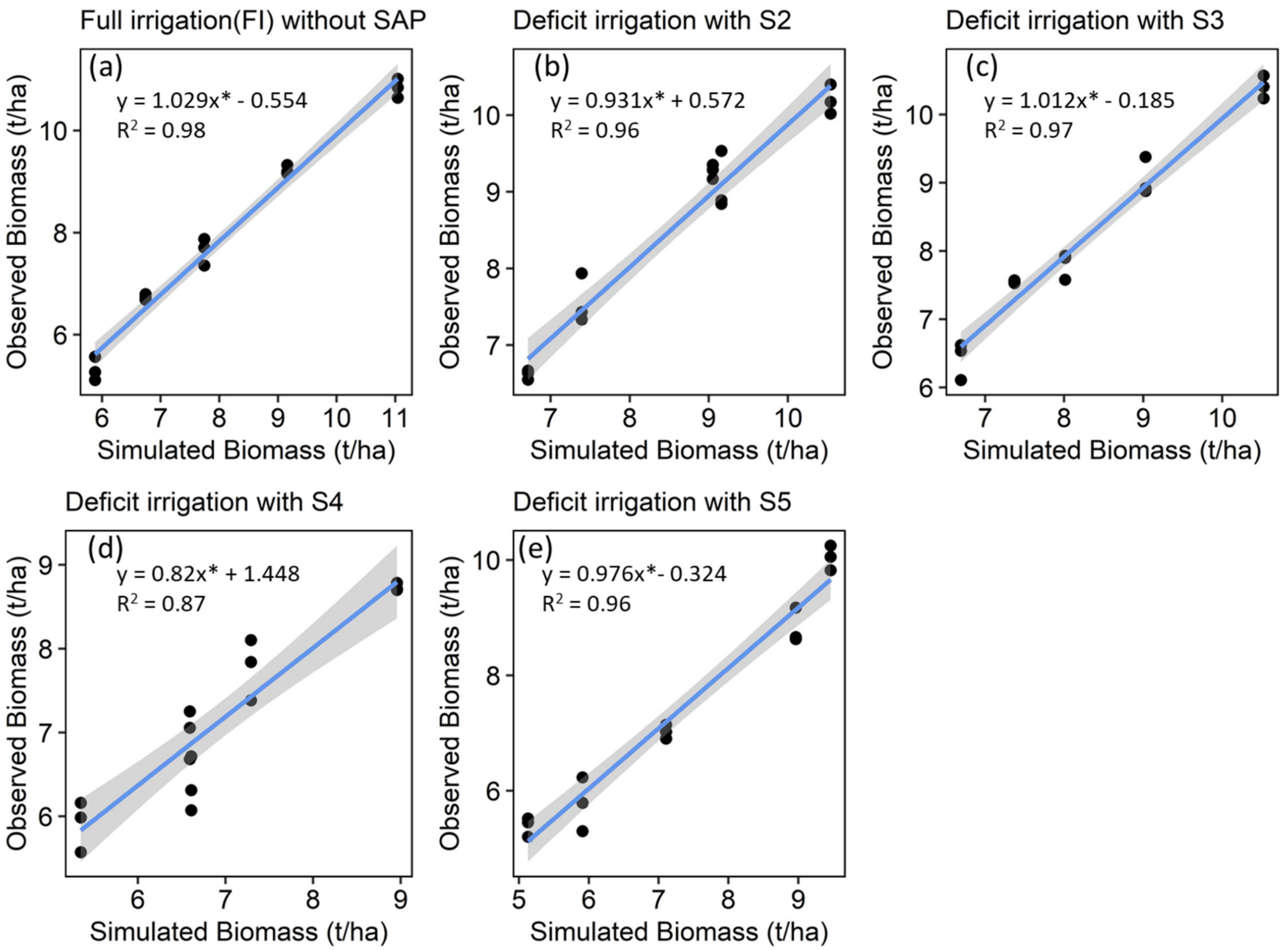

FIGURE 3 | Observed vs simulated dry cowpea biomass for calibration (a) full irrigation without SAP (S_1); and validation (b) deficit irrigation with 0.05% SAP (S_2), (c) deficit irrigation with 0.1% SAP (S_3) and (d) deficit irrigation with 0.15% SAP (S_4), and (e) deficit irrigation with 0.2% SAP (S_5).

TABLE 6 | Model statistical evaluation.

Statistical indicator	$S1_Y$	$S1_B$	$S2_Y$	$S2_B$	$S3_Y$	$S3_B$	$S4_Y$	$S4_B$	$S5_Y$	$S5_B$
RMSE	0.50	0.41	0.31	0.29	0.20	0.25	0.22	0.47	0.21	0.30
NRMSE	16%	5%	7%	3%	5%	3%	6%	7%	6%	4%
d	0.93	0.99	0.94	0.99	0.98	0.99	0.97	0.95	0.98	0.99
R^2	0.97	0.98	0.84	0.96	0.94	0.97	0.89	0.87	0.95	0.96
NSE	0.81	0.95	0.68	0.95	0.89	0.97	0.87	0.80	0.93	0.95

Note: S_1, S_2, S_3, S_4 and S_5 are SAP application rates and $_Y$ and $_B$ are yield and biomass, respectively, at a particular SAP application proportion.

study were comparable to reports by other researchers. Kanda, Senzanje, and Mabhaudhi (2021b) reported the underestimation and overestimation of cowpea yield under optimum and water deficit conditions, respectively. Nunes et al. (2021) reported a slight underestimation of cowpea yield during calibration and better performance of AquaCrop simulations during validation. Paredes et al. (2015) also reported a tendency of the AquaCrop model to underestimate soybean biomass and yield. However, during validation, the model was more accurate.

Treatments with SAP showed an increase in yield with increase in water stress similar to the study by Nassiri-Mahallati and Jahan (2020). The increase was observed to reach a maximum and started to decrease, similar to the findings of a previous study on cowpea growth (Ndunge Benard, Obiero, and Mbuge 2022). The optimum levels were different for each of the SAP treatments (Figure 4). The increase in simulated yield between the treatment without SAP (S_1) and the treatment with SAP reached 137%. Compared with those in the S1 treatment and the S2, S3, S4 and S5

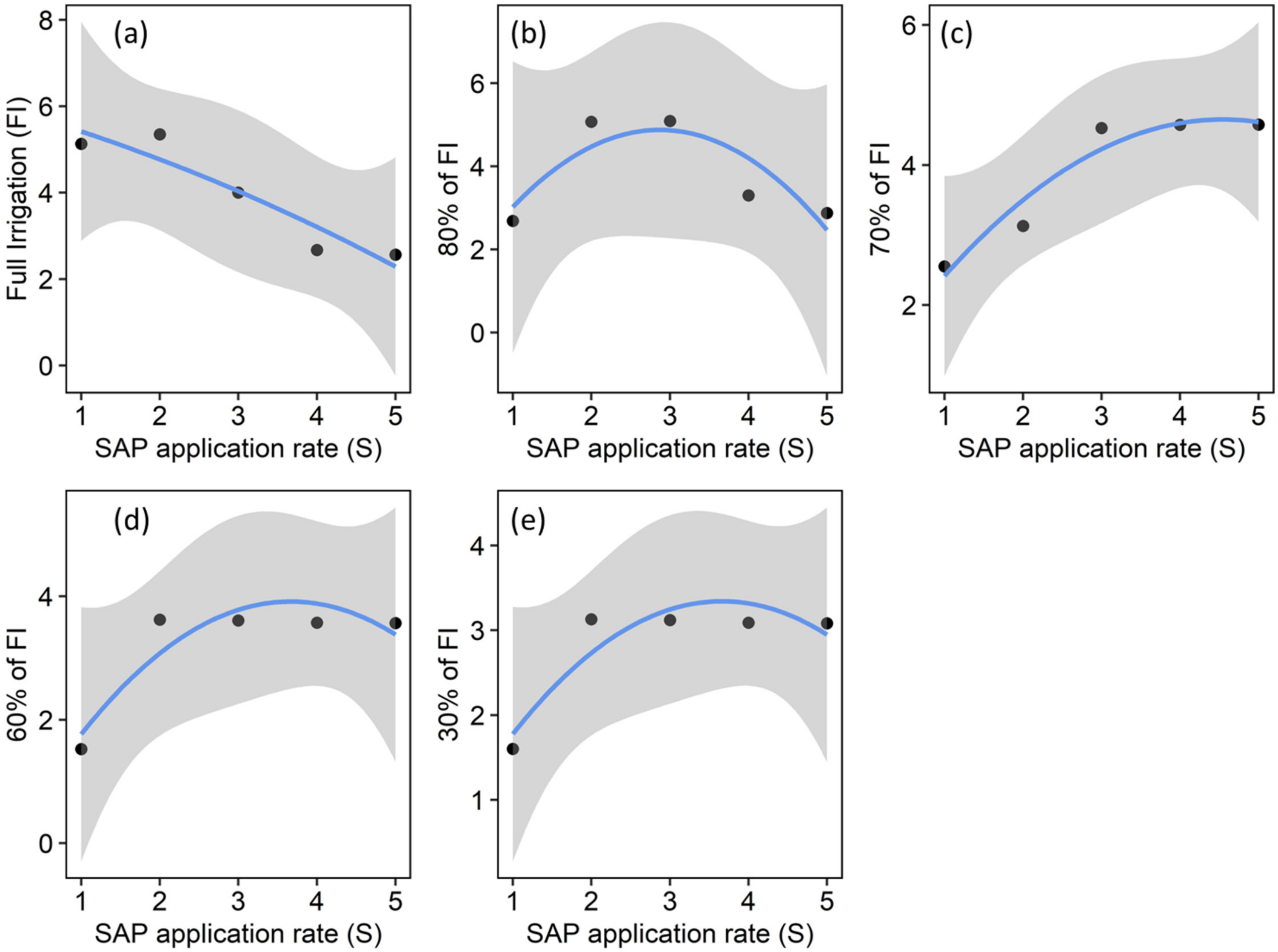

FIGURE 4 | The trend of simulated cowpea yield (t/ha) over varying SAP application rate and water deficit (a) full irrigation (FI) vs SAP application rate [S1 (no SAP), S2 (0.05% SAP), S3 (0.1% SAP), S4 (0.15% SAP), and S5 (0.2% SAP)]; (b) 80% FI vs SAP application rate; (c) 70% FI vs SAP application rate; (d) 60% FI vs SAP application rate; and (e) 30% FI vs SAP application rate.

treatments, the simulated yields in the S_2, S_3, S_4 and S_5 treatments were 137%, 137%, 134% and 134%, respectively, at 60% FI.

3.4.2 | Biomass

The model simulated the biomass more accurately than the yield did for all the treatments. Both the simulated and observed biomass trends were similar to those of the yield (Figure 5). The increase in the simulated biomass between the S_1 treatment and the SAP treatment reached 17%. The greatest increases in the simulated biomass in comparison with those in the S1 treatment and the S_2, S_3, S_4 and S_5 treatments were 17%, 17%, 16% and 15%, respectively, at 70% FI. Previous studies also reported good performance of AquaCrop in simulating biomass production (Bello and Walker 2017; Kanda, Senzanje, and Mabhaudhi 2021a).

3.4.3 | Water Productivity

The highest simulated yield water productivity (WP_{ET}) for the treatments without SAP was recorded at full irrigation (FI) at 1.55 kg/m^3 and decreased with increasing water stress. However, with the use of SAP, WP_{ET} had a similar trend as the yield and biomass increased with increasing water stress up to a certain optimum and then started to decrease (Figure 6). The highest WP_{ET} for S_2 treatments was 1.71 kg/m^3 at FI as compared to 1.55 kg/m^3. Whereas for S_3, S_4 and S_5, the highest WP_{ET} were 1.68, 1.7 and 1.71 kg/m^3, respectively, at 70% FI.

3.4.4 | Harvest Index

There was no significant change in the harvest index (HI) for all the treatments with SAP (S_2, S_3, S_4 and S_5) with increasing water stress (Figure 7). However, it was noted that SAP increased HI up to 117% with increase in water stress.

4 | Discussion

The AquaCrop model was parameterized, calibrated and validated for cowpea under different irrigation schedules and SAP application rates. The average dry cowpea yield and biomass

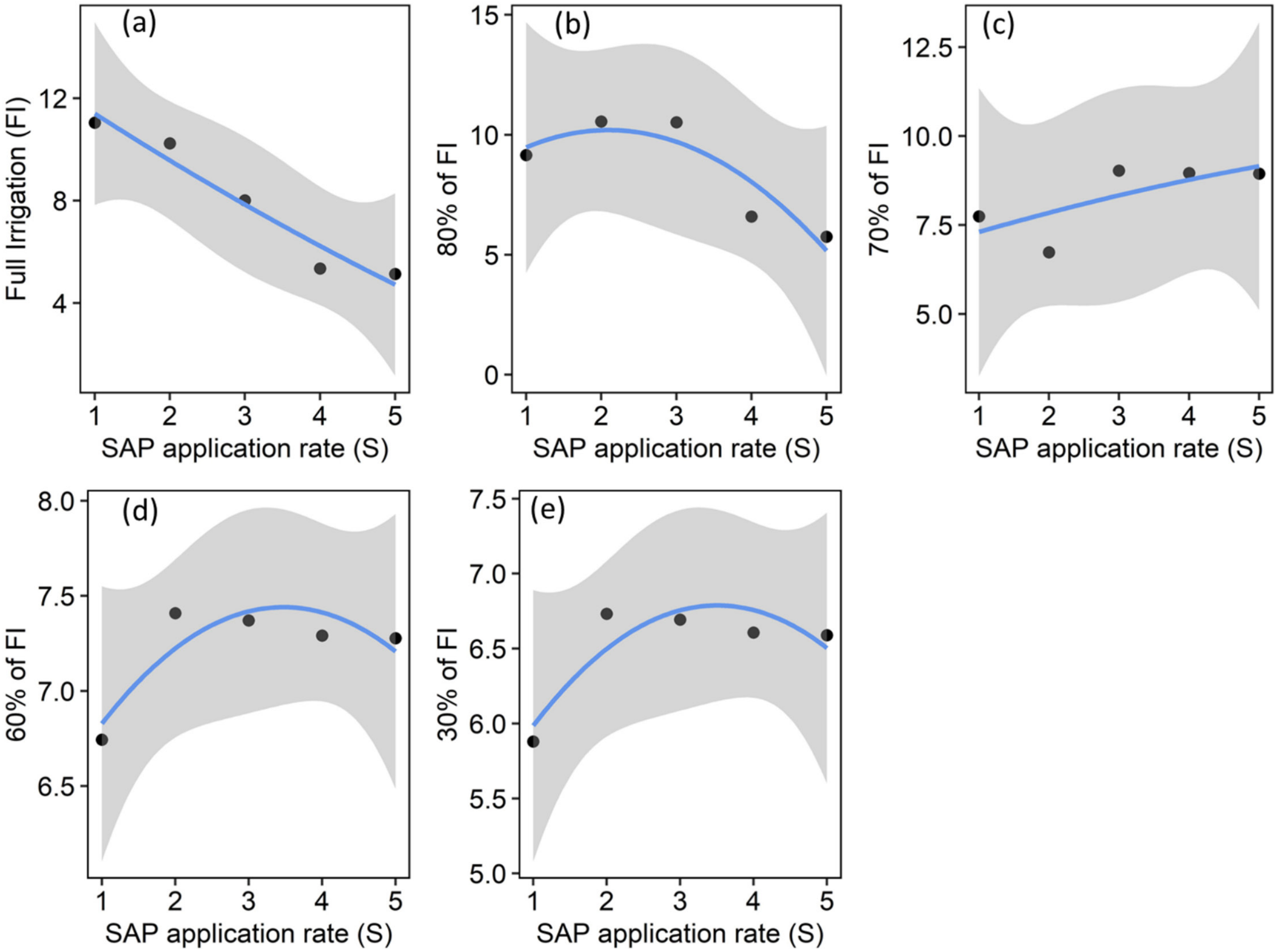

FIGURE 5 | Simulated cowpea biomass (t/ha) over varying SAP application rate and water deficit (a) full irrigation (FI) vs SAP application rate [S1 (no SAP), S2 (0.05% SAP), S3 (0.1% SAP), S4 (0.15% SAP), and S5 (0.2% SAP)]; (b) 80% FI vs SAP application rate; (c) 70% FI vs SAP application rate; (d) 60% FI vs SAP application rate; and (e) 30% FI vs SAP application rate.

recorded under full irrigation without SAP (S_1I_1) were 5.3 and 10.8 t/ha, respectively. These values were similar to the simulated values of 5.13 t/ha yield and 11.0 t/ha biomass. The R^2, NSE, d and NRMSE values were consistent with those reported by Ferrreira and da Silva (2023), who reported good performance of the AquaCrop model in simulating cowpea grain yield, with R^2 values of 0.99, NSE values of 0.92, d values of 0.98, NRMSE values of 16%, and d values of 0.98. The biomass R^2, NSE, d and NRMSE values were also similar to the findings of the study by Kanda, Senzanje, and Mabhaudhi (2021a), which reported a cowpea biomass simulation R^2 of 0.98, an NSE of 0.90, a d of 0.98, and an NRMSE of 18.7%. The S_1I_1 treatment resulted in a decrease in yield and aboveground biomass with increasing water stress for both the measured and simulated values. When water stress increases during yield formation, which affects stomatal closure, less carbon dioxide can be taken up, leading to less carbohydrate production. As a result, there is less material available to fill the grain, resulting in a decline in yield (Begna 2020). Water stress leads to cowpea seed yield losses and hence an observed decline in yield and biomass (Peksen 2007).

It was observed that SAP reduces the effects of water stress on cowpea. The simulation of SAP in AquaCrop revealed increases in field capacity moisture of 12%, 13%, 14% and 14% for S_2 (0.05% SAP), S_3 (0.1% SAP), S_4 (0.15% SAP) and S_5 (0.2% SAP), respectively. The AquaCrop model performed well in simulating cowpea yield and biomass in response to SAP-treated soil under greenhouse conditions. However, the model simulation accuracy slightly decreased with increasing water stress for all the SAP treatments. This is similar to Nassiri-Mahallati and Jahan (2020) findings. The complex interaction of SAP, water, soil and the cowpea crop could have contributed to this.

An increase in yield, biomass and water productivity was observed for the treatments with SAP (S_2, S_3, S_4 and S_5) both observed and simulated, similar to the results of the AquaCrop simulation of sesame under SAP-treated soils and irrigation (Nassiri-Mahallati and Jahan 2020). For both the observed and simulated values, an increase in water stress increased cowpea yield, biomass and water productivity in the SAP treatment groups. SAP absorbs and retains water during

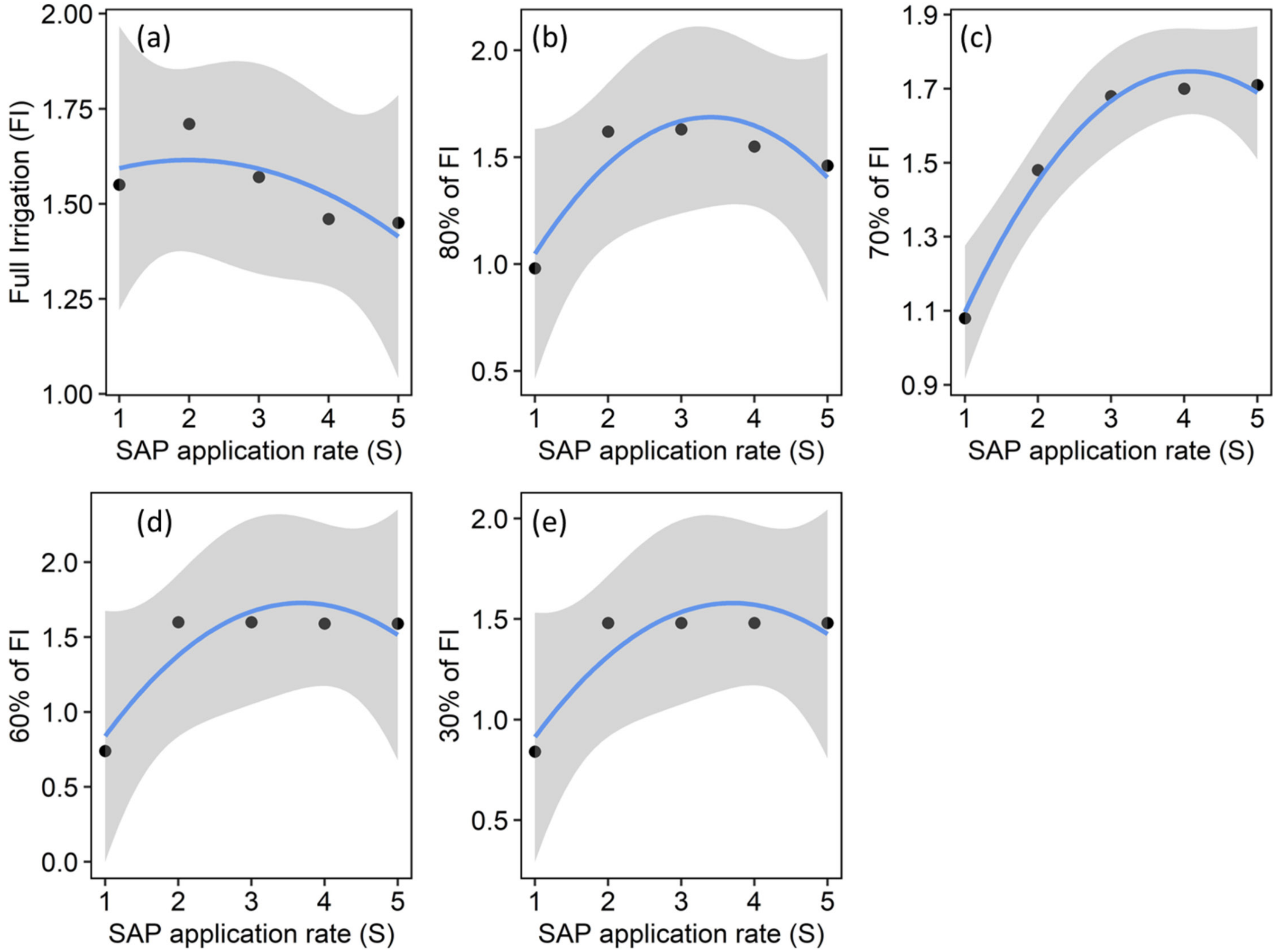

FIGURE 6 | Simulated cowpea water productivity (WPET, kg/m³)) over varying SAP application rate and water deficit (a) full irrigation (FI) vs SAP application rate (S1 (no SAP), S2 (0.05% SAP), S3 (0.1% SAP), S4 (0.15% SAP), and S5 (0.2% SAP)); (b) 80% of FI vs SAP application rate; (c) 70% FI vs SAP application rate; (d) 60% FI vs SAP application rate; and (e) 30% FI vs SAP application rate.

supply and provides a constant supply of water to the roots of plants when needed, hence reducing the effects of water stress on plants. This delays leaf senescence and increases plant yield, biomass and water productivity (Saha, Sekharan, and Manna 2020; AbdAllah, Mashaheet, and Burkey 2021). The use of SAP reduces crop irrigation requirements, increasing irrigation water use efficiency (Cerasola et al. 2022). According to the simulations, SAP increased cowpea water productivity (WP_{ET}) by an average of 10%. The findings of increased WP_{ET} with the application of SAP under water stress conditions align with research conducted on a wide range of crops and regions via similar technologies (Akhter et al. 2004; Kassim, El-Koly, and Hosny 2017; Rezashateri et al. 2017; Lal et al. 2021). However, the generalizability of these findings beyond the specific conditions of this experiment depends on several factors, including crop type, climate, soil properties and agricultural practices (Zheng et al. 2023). For example, SAP increased the yield, biomass and water use efficiency of sesame under limited irrigation conditions (Nassiri-Mahallati and Jahan 2020). The SAP conserves irrigation water by reducing the amount of irrigation water while maintaining production. This can help reduce the frequency of irrigation and improve water productivity in ASALs.

However, for both the observed and simulated values of the treatments with SAP, yield, biomass and water productivity tended to increase with increasing water stress up to a certain optimum and then started to decrease. Similarly, Zhu et al. (2024) reported an increase followed by a decrease in maize yield and water use efficiency with increasing irrigation. SAPs have a limit on how much water they can absorb and retain. Increasing the SAP application rate beyond this threshold can lead to over-saturation of the soil, reducing aeration, thus suppressing plant growth and reducing crop yield. There is a need to determine the optimal SAP dosage for different soil types and crop systems to avoid negative effects on aeration and nutrient balance, with a focus on maximizing crop yield and water efficiency while maintaining soil health. The AquaCrop model was useful for optimizing cowpea yield and biomass production at a 0.1% SAP application rate and

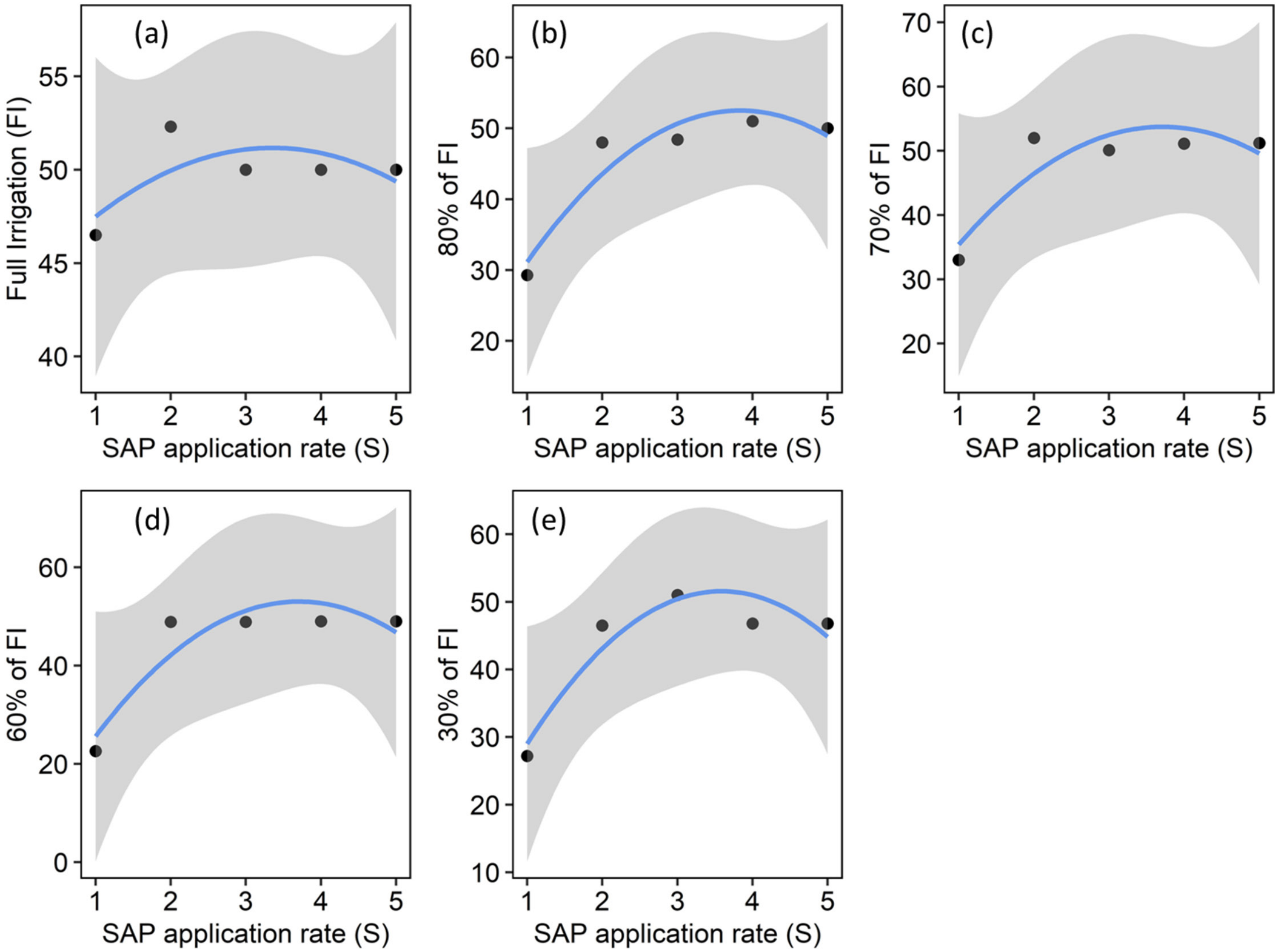

FIGURE 7 | The trend of simulated cowpea harvest index over varying SAP application rate and water deficit (a) full irrigation (FI) vs SAP application rate [S1 (no SAP), S2 (0.05% SAP), S3 (0.1% SAP), S4 (0.15% SAP), and S5 (0.2% SAP)]; (b) 80% of FI vs SAP application rate; (c) 70% of FI vs SAP application rate; (d) 60% of FI vs SAP application rate; and (e) 30% of FI vs SAP application rate.

20% water stress and water productivity at a 0.1% SAP application rate and 70% water stress for cowpea under sandy clay loam SAP-treated soil in greenhouse conditions.

5 | Conclusion

The AquaCrop model was calibrated and validated to simulate cowpea yield and biomass for SAP-treated soil under greenhouse conditions. Compared with the observed values, the AquaCrop model simulations performed satisfactorily. Despite the limitations of the AquaCrop model in simulating the complex interactions between SAP, soil, water and cowpea crops, the model simulations closely agreed with the observed values. Increasing WP_{ET}, particularly through technologies such as SAP, can produce more with less water, thus contributing to water conservation, resilience to climate change and sustainable agricultural practices, which are crucial in regions with severe water scarcity. The good performance of the AquaCrop model in simulating cowpea yield and biomass in SAP-treated soil makes it a resourceful tool in decision making for optimizing irrigation water productivity, particularly in ASALs where water resources are limited. SAP application rates optimized in a greenhouse might need adjustment for open field conditions to account for more variable water availability and environmental conditions. Therefore, further experiments need to be performed to cover other environmental conditions, explore the long-term sustainability of crop production within regions facing severe water scarcity and refine parameters related to the harvest index in the AquaCrop model to improve future yield simulations.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data will be made available upon request.

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