EDITORIAL CSIC

Spanish Journal of Agricultural Research
24 (1) January-March 2026, 21785
ISSN-L: 1695-971X, eISSN: 2171-9292
https://doi.org/10.5424/sjar/2026241-21785

ARTICLE

RESEARCH ARTICLE

Assessment and simulation of crop water productivity under different soil moisture conditions in irrigated fields

Evaluación y simulación de la productividad hídrica de los cultivos en diferentes condiciones de humedad del suelo en campos de regadío

Davis Sibale
West African Centre for Water, Irrigation and Sustainable Agriculture (WACWISA), University for Development Studies, School of Engineering, P.O. Box TL 1882, Tamale, Ghana
Department of Land and Water Resources, Lilongwe University of Agriculture and Natural Resources (LUANAR-NRC Campus), P.O. Box 143, Lilongwe, Malawi
Corresponding author: dsibale@luanar.ac.mw, https://orcid.org/0000-0002-5416-1040

Gordana Kranjac-Berisavljevic
West African Centre for Water, Irrigation and Sustainable Agriculture (WACWISA), University for Development Studies, School of Engineering, P.O. Box TL 1882, Tamale, Ghana
https://orcid.org/0000-0002-3960-4472

Shaibu Abdul-Ganiyu
West African Centre for Water, Irrigation and Sustainable Agriculture (WACWISA), University for Development Studies, School of Engineering, P.O. Box TL 1882, Tamale, Ghana
https://orcid.org/0000-0001-6431-8083

Rodrick Mlewa
Department of Land and Water Resources, Lilongwe University of Agriculture and Natural Resources (LUANAR-NRC Campus), P.O. Box 143, Lilongwe, Malawi
https://orcid.org/0009-0002-6385-1681

Eston Malinda
Department of Land and Water Resources, Lilongwe University of Agriculture and Natural Resources (LUANAR-NRC Campus), P.O. Box 143, Lilongwe, Malawi
https://orcid.org/0000-0002-0393-3370

Phillip Kamwendo
Department of Agriculture and Food Systems, Lilongwe University of Agriculture and Natural Resources (LUANAR-NRC Campus), P.O. Box 143, Lilongwe, Malawi
https://orcid.org/0009-0006-3817-8885

Zakaria Issaka
Department of Agricultural Engineering, Tamale Technical University, P.O. Box 3 E/R, Tamale, Ghana
https://orcid.org/0000-0001-5057-1424

Sylvester Chikavumbwa
Department of Geography and Environmental Studies, Catholic University of Malawi, P.O. Box 5452, Limbe, Malawi
https://orcid.org/0000-0003-0823-4867

Abstract: *Aim of the study:* To assess and simulate crop water productivity (CWP) under different soil moisture conditions in irrigated fields. *Area of the study:* The study was undertaken in Bontanga irrigation scheme in the Northern Region of Ghana. *Materials and methods:* The experiment was laid out in a randomized complete block design. Three irrigation blocks were selected. Each block had two plots of chilli pepper and two plots of okra such that each crop was subjected to water stress and non-water stress conditions under furrow irrigation. At the end of the growing season, the collected data on crop yield and the amount of water applied were used to estimate CWP. The AquaCrop model was applied to simulate CWP under non-water-stress and water-stress conditions. *Main results:* Results revealed that, by maintaining an ideal volumetric moisture content of 15.4–22 % in sandy loam soils, CWP values of 2.08 and 1.40 kg m^{-3} can be attained for okra and chilli pepper, respectively. However, under water stress conditions with a volumetric moisture content in the range 12–15.4 %, simulated results showed that CWP could drop to 1.82 and 1.34 kg m^{-3} for okra and chilli pepper, respectively. *Research highlights:* The study underscores the importance of soil moisture management in agricultural fields in order to improve CWP. These efforts will help in implementing sustainable water management strategies aimed at maximizing crop yield per water drop under changing climatic conditions, thereby supporting Sustainable Development Goals (SDGs) 2, 6, and 13.

Keywords: AquaCrop; chilli pepper; crop yield; okra; volumetric moisture content; water management; water stress.

Resumen: *Objetivo del estudio:* Evaluar y simular la productividad del agua de los cultivos (CWP) en diferentes condiciones de humedad del suelo en campos irrigados. *Área de estudio:* El estudio se llevó a cabo en el sistema de riego de Bontanga en la región norte de Ghana. *Material y métodos:* El experimento se diseñó en bloques completos aleatorios. Se seleccionaron tres bloques de riego. Cada bloque contaba con dos parcelas de chile y dos de okra, de modo que cada cultivo estuviera sujeto a condiciones de estrés hídrico y sin estrés hídrico mediante riego por surcos. Al final de la temporada de crecimiento, se utilizaron los datos recopilados sobre el rendimiento del cultivo y la cantidad de agua aplicada para estimar el CWP. Se aplicó el modelo AquaCrop para simular el CWP en condiciones de estrés hídrico y sin estrés hídrico. *Resultados principales:* Los resultados revelaron que, manteniendo un contenido de humedad volumétrica ideal del 15,4 al 22 % en suelos franco arenosos, se pueden alcanzar valores de CWP de 2,08 y 1,40 kg m^{-3} para la okra y el chile, respectivamente. Sin embargo, en condiciones de estrés hídrico con un contenido de humedad volumétrica en el rango de 12 a 15,4 %, los resultados simulados mostraron que el CWP podría caer a 1,82 y 1,34 kg m^{-3} para el quingombó y el chile, respectivamente. *Aspectos destacados de la investigación:* El estudio destaca la importancia de la gestión de la humedad del suelo en los campos agrícolas para mejorar la CWP. Estos esfuerzos ayudarán a implementar estrategias de gestión sostenible del agua destinadas a maximizar el rendimiento de los cultivos por gota de agua en condiciones climáticas cambiantes, apoyando así los Objetivos de Desarrollo Sostenible (ODS) 2, 6 y 13.

Palabras clave: AquaCrop; chile picante; contenido de humedad volumétrica; estrés hídrico; gestión del agua; okra; rendimiento del cultivo.

Received: 10-05-2025 / **Accepted**: 19-12-2025 / **Published**: 07-07-2026

Citation: Sibale, D; Kranjac-Berisavljevic, G; Abdul-Ganiyu, S; Mlewa, R; Malinda, E; Kamwendo, P; Issaka, Z; Chikavumbwa, S (2026). Assessment and simulation of crop water productivity under different soil moisture conditions in irrigated fields. Spanish Journal of Agricultural Research, Volume 24, Issue 1, 21785. https://doi.org/10.5424/sjar/2026241-21785

Supplementary information ↓

1. INTRODUCTION

Agriculture plays a vital role in meeting the increasing food demand, and water is a key resource for sustainable crop production. Globally, the food demand is expected to rise substantially, with a potential increase of 70% by 2050 (Van-Dijk et al., 2021). Due to the changing climate, decreasing water availability, and rapid increase in global population, the increasing competition for water resources has led to an urgent need for increasing crop water productivity (CWP). Mutema et al. (2023) pointed out that 70% of the world's freshwater resources are used for agriculture and 40% of this share is wasted through poor water management and irrigation methods.

Crop water productivity is a comprehensive performance indicator for irrigated agriculture. It reveals the level of irrigation, soil, and crop management practices (Li et al., 2016). A larger CWP indicates a high crop production with less water. Therefore, a comprehensive understanding of CWP is imperative to develop and sustain agriculture under limited water supply. In regions with water scarcity, the biggest challenge for agriculture is how to increase crop production using less water (Salman et al., 2021).

Field management practices play a crucial role in crop production, as they significantly affect dynamic soil properties such as bulk density, soil structure, organic matter content, infiltration rates, and water-holding capacity (Özdemi et al., 2022). These dynamic soil properties significantly affect CWP by influencing root development, soil nutrient density, nutrient uptake, plant growth, and yield. Changes in soil properties over time due to field management lead to changes in soil moisture levels (O'Geen, 2013). It should be noted that poor monitoring and management of soil moisture affect plant growth and development, which in turn have an impact on CWP.

Globally, researchers are actively engaged in enhancing CWP through proper allocation of limited water resources (Gu et al., 2017). Integrating the application of crop simulation models into water management strategies can help improve CWP and contribute to sustainable water resources management. Crop modelling can simulate different scenarios to optimize input use and assess crop performance. In this context, simulation of different soil moisture scenarios and their impact on CWP can be done using crop simulation models. These crop models are used as decision-support tools for improving efficiency in planning and management of crop production processes. Examples of well-known crop simulation models include: Decision Support System for Agrotechnology Transfer (DSSAT), Agricultural Production Systems Simulator (APSIM), Python Crop Simulation Environment (PCSE), Cropping System Simulation Model (Cropsyst), AquaCrop, STICS, and WOFOST (Garofalo et al., 2025). In this study, the AquaCrop model was applied because of its simplicity, accuracy, less input data requirement, and availability with a user-friendly interface (Dhouib et al., 2022).

The current need for improvements in CWP by agricultural systems requires a holistic assessment and simulation of CWP under various soil moisture levels. Arunadevi et al. (2023) assessed the sustainability of okra yield under optimum irrigation schedule based on soil moisture depletion. They recommended that irrigation be scheduled at 20 % soil moisture depletion in order to attain a sustainable yield of okra. Alegewe et al. (2023) determined the optimum levels of irrigation regime and irrigation schedule for effective water productivity (WP) of pepper. Their results showed that irrigating at 60% ETc coupled with split irrigation gave significantly higher yields and CWP. However, they recommended that further research is needed to identify the optimal levels of these factors and the most effective irrigation strategies for the crop in different environmental conditions. Pinheiro et al. (2019) performed agro-hydrological simulations using the SWAP model integrated with the WOFOST crop growth model. Simulated results from their study indicated that the yield response was affected by soil-specific conditions strictly related to water availability based on the length and timing of drought stress.

Water scarcity is a major global challenge affecting billions of people, the situation is worsening in sub-Saharan Africa. Ghana has experienced decreasing water availability over the years due to climate change, rapid population growth, and unsustainable water usage practices (Yeleliere et al., 2018). The northern region of Ghana is particularly vulnerable to water scarcity, often facing prolonged dry spells and insufficient water resources (Incoom et al., 2020; Adonadaga et al., 2022). These prolonged dry spells affect the production of chilli pepper and okra which are important vegetables grown in all agro-ecological zones in Ghana. These vegetables are sources of livelihood for the majority of farmers in terms of domestic consumption and income generation (Adekaldu et al., 2021; Cobbinah and Kwoseh, 2021). Therefore, there is a need to improve their CWP in order to meet the increasing demand. To address the complexities of CWP and improve sustainable crop production under changing climatic conditions and limited water availability, the study provides a better understanding of maintaining appropriate soil moisture levels in irrigated fields in order to improve CWP. It also supports Sustainable Development Goal (SDG)-United Nations No. 2, 6 and 13 through improvement of irrigated agriculture as a way of increasing agricultural production to meet the growing food demand due to increasing human population whilst sustainably satisfying competing water demands under changing climatic conditions. Therefore, the objective of this study was to assess and simulate the CWP of chilli pepper (*Capsicum annuum* L.) and okra (*Abelmoschus esculentus* L.) under different soil moisture conditions at the Bontanga irrigation scheme in the Northern Region of Ghana, in order to provide evidence-based recommendations for improving irrigation management and water use efficiency.

2. MATERIAL AND METHODS

2.1. Study area

The study was conducted in Bontanga irrigation scheme located in Kumbungu district of the Northern Region of Ghana. The scheme is located between latitudes 9° 30′ and 9° 37′ N and longitude 1° 00′ and 1° 03′ W. Figure 1 shows the location of the study area.

The study area is characterised by a unimodal rainfall pattern and hot, dry weather conditions. The long dry season starts from November and ends in April/May, thereafter, the rainy season begins and ends in September/October, with the highest rainfall occurring in August and September. The area receives a total annual rainfall of 1,100 mm. The temperatures are normally high with a yearly mean temperature of 29 °C. During the dry season, the relative humidity is generally low with an average value of 50% (Ahiamadia et al., 2024).

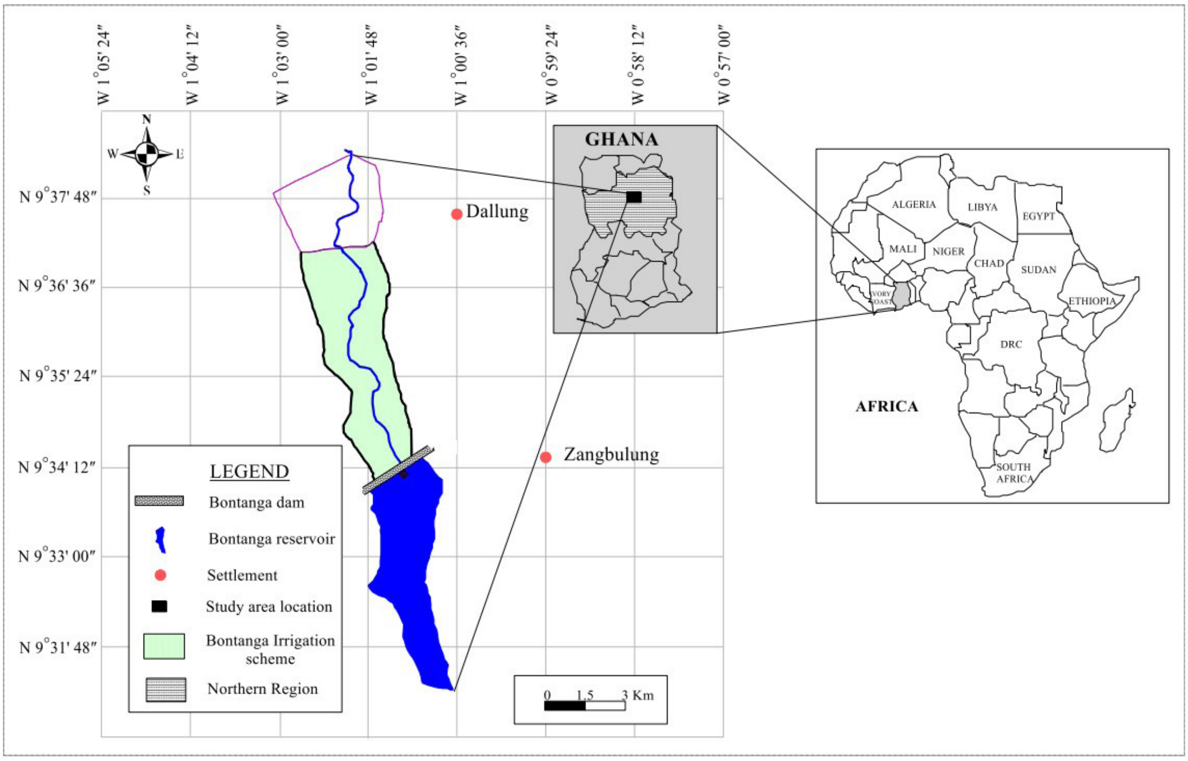

Figure 1. Location of Bontanga irrigation scheme in Ghana (*Source:* Authors construct, 2024).

2.2. Field experimental set-up

This study was conducted at the Bontanga irrigation scheme, and two common vegetable crops were selected: chilli pepper (*Capsicum annuum* L.) and okra (*Abelmoschus esculentus* L.). Chilli pepper 'Legon 18' and okra 'Essoumtem' were the varieties used in the study. The crop water requirement was determined on the basis of Equation 1 as guided by Allen et al. (1998).

$$ET_c = K_c \times ET_o \tag{1}$$

Where ET_c is the crop evapotranspiration (mm·day^{-1}), K_c is the crop coefficient, and ET_o is the reference evapotranspiration (mm·day^{-1}).

Details of the experimental set-up are presented in Figure 2.

A field plot of 28 m long × 16 m wide was divided into twelve equal plots of 6 m × 4 m and there was a buffer strip of 1 m between plots to prevent moisture cross-contamination. Each plot accommodated a plant density of 2 plants per m^2 and 4 plants per m^2 for okra and chilli pepper, respectively. The experimental set-up followed the randomized complete block design. Three irrigation blocks were selected in the scheme. Each block had two plots of chilli pepper and two plots of okra such that each crop was subjected to water stress and non-water stress conditions. Soil moisture depletion exceeding 30% was allowed under water stress conditions before the next irrigation, while under non-water stress conditions, 0 – 30% soil moisture depletion was allowed before the next irrigation. All agronomic practices were kept normal and uniform for all treatments.

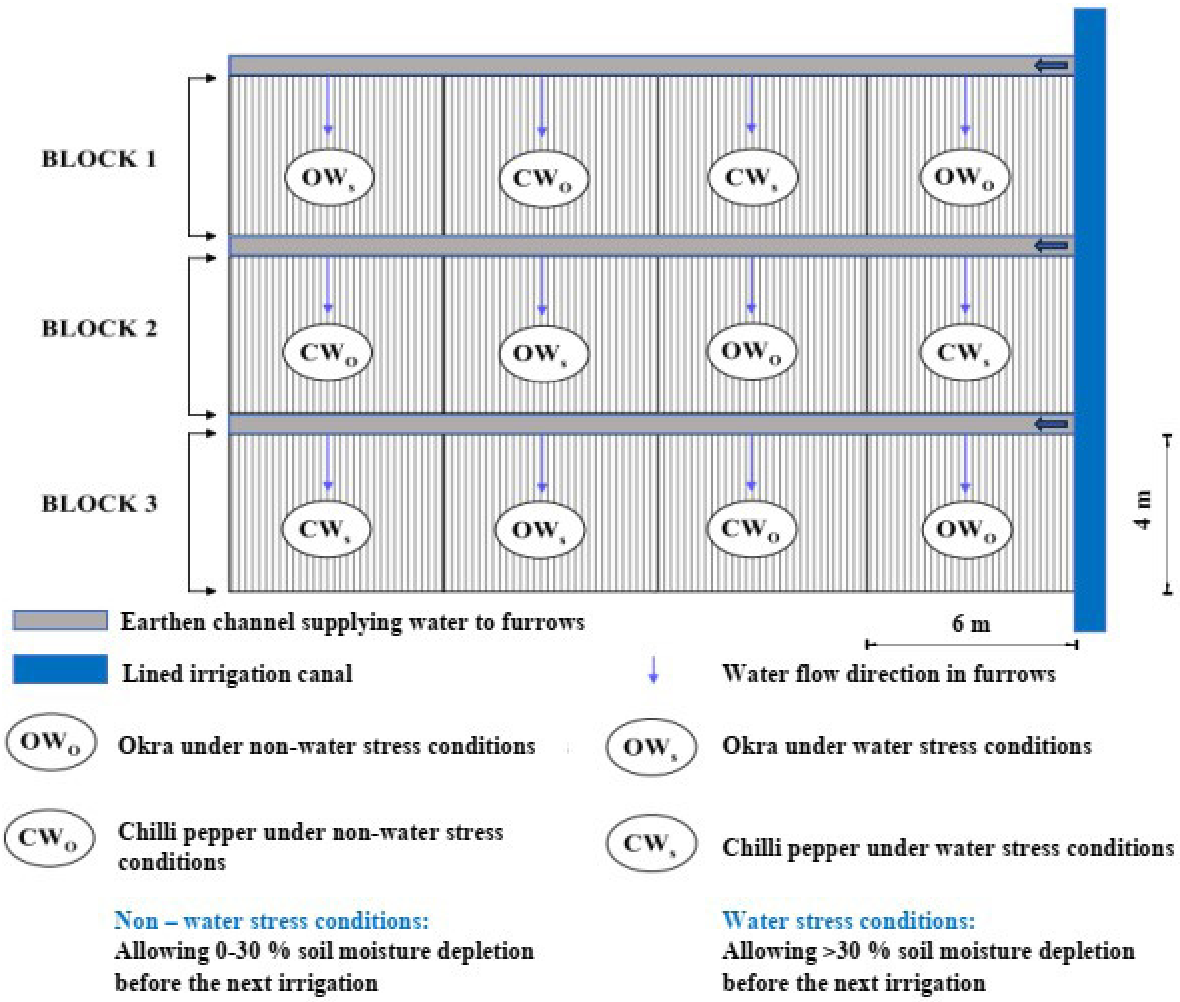

Figure 2. Field experimental set-up in Bontanga irrigation scheme in Ghana (*Source:* Authors construct, 2024).

2.3. Determination of physico-chemical properties of the soil

In this study, the soil physico-chemical properties were used to create the soil file in AquaCrop and to make appropriate assumptions regarding fertility, salinity, and water stress during the CWP simulation process. Therefore, before sowing, soil samples were collected at depths of 0 – 20 cm, 20 – 40 cm, 40 – 60 cm using the soil auger. The collected soil samples were sieved through a 2 mm sieve to remove gravel and other debris. Thereafter, the sieved samples were subjected to a range of laboratory analyses in order to assess physical and chemical properties of the soil.

Soil texture was determined using the hydrometer method as described by Acevedo et al. (2021). Soil samples were oven-dried for 24 h at 105 °C. 50 g of soil, 100 mL of distilled water, 20 mL of Hydrogen peroxide (H_2O_2), 50 mL of Calgon (sodium hexametaphosphate-SHMP) were used to form a soil solution. The mixture was transferred to a plastic bottle and shaken for 2 h on a mechanical shaker. The dispersed solution was placed in a standard sedimentation cylinder (1L) and stirred for 1 min. Hydrometer and temperature readings were then obtained at 40 s and 2 h. The hydrometer and temperature readings were used to compute the percentages of sand, silt, and clay in the soil sample. The soil textural triangle was used to determine the textural class of the soil.

The bulk density of the soil was determined using the core cylinder method. Following FAO (2023), the standard procedure for soil bulk density involves collecting an undisturbed soil sample at the desired depth using a core cylinder with a diameter and height of 5 cm each. The collected undisturbed soil sample was dried in an oven for 24 h at 105 °C. After removing the soil sample from the oven, it was weighed and the bulk density was determined using Equation 2:

$$Bulk\ density(g/cm^3) = \frac{Mass\ of\ oven\ dried\ soil\ (g)}{Total\ volume\ of\ the\ soil\ (cm^3)} \quad (2)$$

The soil's saturated hydraulic conductivity was determined using the falling head permeability test as guided by Steiakakis et al. (2012). The saturated hydraulic conductivity was computed using Equation 3.

$$K = 2.304 \frac{aL}{At} log \frac{h_o}{h_f} \quad (3)$$

Where, *K* is the saturated hydraulic conductivity of the soil sample (cm s^{-1}), α is the internal cross-sectional area of the standpipe (cm^2), *A* is the cross-sectional area of the sample (cm^2), *L* is the sample length (cm), h_o is the initial head of water (cm) measured in the standpipe at time *"t"* = 0, and h_f is the final head of water (cm) measured in the standpipe at time *"t"* in s.

Following FAO (2021), 10 g of air-dried soil was mixed with 25 mL of distilled water forming a soil to water ratio of 1:2.5. The soil–water mixture was shaken thoroughly for 60 min. After shaking, the mixture was allowed to settle. Using a mechanical extractor, the soil extract was obtained and the pH was then measured with a pH meter.

The electrical conductivity of the soil is a key parameter for describing the salinity of the soil. Following FAO (2021), 20 g of air-dried soil was mixed with 100 mL of distilled water forming a soil to water ratio of 1:5. The soil–water mixture was shaken thoroughly for 60 min. After shaking, the mixture was allowed to settle. The soil extract was obtained and the electrical conductivity (dS m^{-1}) was then measured with an EC meter.

The Cation Exchange Capacity (CEC) is defined as the sum of exchangeable cations. Examples of such cations include calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+) ions. CEC is a measure of the soil's ability to retain positive ions (cations) and is a crucial indicator of its capacity to store essential nutrients. CEC was determined using the ammonium acetate (NH_4OAc) saturation method as described by FAO (2022). The process involved mixing 5 g of sieved soil with 1 normal ammonium acetate solution buffered at pH 7.0 to facilitate displacement of all other cations on soil's exchange sites by NH_4^+ ions. Ethanol (95 %) was then used to remove any excess ammonium ions that were not bound to the exchange sites. From the extracted solution, the concentration of each cation was determined using the spectrophotometer in which the desired wavelengths for cations were as follows: Ca^{2+} = 422.7 nm; Mg^{2+} = 285.2 nm; Na^{+} = 589.0 nm; and K^{+} = 766.5 nm. After knowing the concentration of exchangeable cations in the extracted solution, the CEC was determined using Equation 4.

$$CEC = \sum \left[Exchangeable\ cation\ concentration\ (ppm) \div \left(\frac{atomic\ weight\ of\ the\ exchangeable\ cation\ (g)}{valence\ of\ the\ exchangeable\ cation} \times 10 \right) \right] \quad (4)$$

Where *CEC* is the Cation Exchange Capacity (Meq/100 g soil) and 10 is the conversion factor of gram equivalent weight to milliequivalent of the exchangeable cation per 100 g of soil. The milliequivalent of exchangeable cation per 100 g of soil was then converted to cmolc kg^{-1} (1 Meq $(100g)^{-1}$ = 1 cmolc kg^{-1}).

The Exchangeable Sodium Percentage (ESP) is the best indicator of soil sodicity. It is usually defined as the ratio of exchangeable sodium to the CEC, both expressed in cmolc kg^{-1}. With guidance from Gharaibeh et al. (2021), the ESP was computed using Equation 5.

$$ESP = \frac{ExchangeableNa^{+}}{CEC} \times 100 \quad (5)$$

Where, ESP is the Exchangeable Sodium Percentage and CEC is the Cation Exchange Capacity.
The determination of soil organic carbon (SOC) was based on the Walkley-Black potassium dichromate method as described by FAO (2019). The method involved the use of 0.5 g of soil, 10 mL of potassium dichromate ($K_2Cr_2O_7$) solution, 20 mL of concentrated sulfuric acid (H_2SO_4), 0.5N Ferrous Ammonium Sulphate (FAS), 200 mL of distilled water, 10 mL of Orthophosphoric acid, and 1 mL of Diphenylamine indicator. The final solution was titrated until the colour changed to dark green. The same process was repeated for the standardized blank solution (without addition of soil). Computation of the percentage organic carbon was done using Equation 6 as guided by Hossain et al. (2023).

$$Organic\ carbon\ (\%) = \frac{(V_B - V_S) \times N \times 0.003 \times 1.33}{m} \times 100 \quad (6)$$

Where, V_B is the volume of ferrous solution used in the blank titration (mL), V_S is the volume of ferrous solution in the sample titration (mL), N is the normality of FAS solution, m is the mass of the sample used in the analysis (g), 1.33 is the oxidation correction factor.

The available nitrogen (N) in the soil was determined using the Kjeldahl method as described by FAO (2021). The method involved the use of 1g of air-dried soil, 2g of a catalyst mixture formed from a mixture of copper sulphate pentahydrate ($CuSO_45H_2O$) and potassium sulphate (K_2SO_4), 20 mL of distilled water, 20 mL of boric acid (H_3BO_3) solution, 0.01 M sulfuric acid (H_2SO_4), and sodium hydroxide (NaOH). The test involved digestion, distillation, and titration processes. Computation of available nitrogen (N) in the soil was done using Equation 7 as guided by FAO (2021).

$$N = \frac{(V_1 - V_0) \times c(H^{+}) \times MN}{m} \quad (7)$$

Where, N is the concentration of nitrogen in the soil (mg g^{-1}), V_1 is the volume of H_2SO_4 solution used in the titration of the sample (mL), V_0 is the volume of H_2SO_4 solution used in the titration of the blank test (mL), $c(H^+)$ is the concentration of H^+ in the H_2SO_4 solution (mmol/mL), MN is the molar mass of N (14.0067 mg $mmol^{-1}$), and m is the mass of the sample used in the analysis (g).

The Olsen method, as described by FAO (2021), was used to determine the available phosphorus (P) in the soil. 5 g of dry soil was weighed and mixed with a sodium bicarbonate (0.5M $NaHCO_3$) solution. A half teaspoon of phosphate-free activated charcoal (approximately 0.5 g) was added to the solution to remove impurities and make potassium free in the solution. The solution was then shaken for 30 min. The soil solution was allowed to settle, then filtered to get a clear liquid. The soil extract was placed in a spectrophotometer, and absorbance was measured at 880 nm to estimate the phosphorus concentration.

Available potassium from the soil was determined using Morgan's solution method as guided by Bell et al. (2021). The process involved mixing 5g of sieved soil with 1 mmol/L ammonium acetate solution buffered at pH 7.0 to facilitate displacement of potassium ions on soil's exchange sites by NH_4^+ ions. Ethanol (95%) was then used to remove any excess ammonium ions that were not bound to the exchange sites. From the extracted solution, the concentration of potassium ions was determined using the spectrophotometer at a wavelength of 766.5 nm.

2.4. Irrigation and soil moisture measurement

A surface irrigation system with furrows as the in-field water supply method was used for irrigation. During each irrigation session, the amount of water released into the furrows was measured by the Replogle-Boss-Clemmens (RBC) flume in which the sill-referenced head (Sh_1) was measured on the gauging point located at the upstream section of the flume. The discharge was computed as a function of the sill-referenced head using Equation 8 as guided by Wahl et al. (2005).

$$\mathrm{Q} = \mathrm{K_1}(\mathrm{Sh_1} + \mathrm{K_2})^{\mathrm{u}} \tag{8}$$

Where, Q is the flume discharge (L s^{-1}), Sh_1 is the measured sill-referenced head (mm), K_1 is 0.002189, K_2 is 5.457, and u is 1.879.

The computed discharge through the RBC flume and the irrigation duration were used to estimate the volume of water delivered to the field.

Before and after irrigation, the soil moisture status was monitored by the portable Hydro-Sense II soil moisture sensor. The device measures soil moisture based on the principle of time domain reflectometry (Jadhav et al., 2024). During soil moisture measurement, the sensor probe rods were inserted into the soil within the crop root zone and the Volumetric Water Content (VWC) readings were recorded. With the known field capacity of the soil and the measured VWC, the depleted soil moisture was estimated. Irrigation water was applied based on the treatment soil moisture depletion level to bring the soil to field capacity. Using the soil moisture sensor, the moisture content of the soil was monitored until the soil moisture depletion level approached the treatment level.

2.5. Assessment and simulation of crop water productivity

Crop water productivity (CWP) is an important indicator for assessing the effectiveness of water management in irrigation schemes. Blatchford et al. (2019) defined CWP as crop yield per unit volume of water consumed, incorporating all water inputs during the growing season. The performance of each crop following changes in soil moisture conditions was assessed by relating crop yield and the total amount of water used during the growing season. Matured chilli pepper and okra fruits were harvested and weighed using an electronic balance. The total yield for each crop was recorded and extrapolated to kilograms per hectare. In reference to Adekaldu et al. (2021), Equation 9 was used to calculate CWP.

$$CWP = \frac{Total\ crop\ yield\ (\ kg)}{Total\ amount\ of\ water\ used\ for\ crop\ production\ (m^3)} \tag{9}$$

Where, CWP is the crop water productivity (kg m^{-3}).

In this study, the AquaCrop model was applied to simulate CWP under different soil moisture conditions. AquaCrop is a crop water productivity model developed by the Land and Water Division of FAO (Raes et al., 2022). For the model to run, it requires the following important input variables: climatic data, crop characteristics, soil characteristics, and management practices that define the environment in which the crop develops (Garofalo et al. 2025). Climatic data included maximum and minimum air temperature, solar radiation, relative humidity, and wind velocity which were collected from the Savanna Agricultural Research Institute (SARI), Northern Region of Ghana. The climatic data for a period of 32 years (1990–2022) were used to estimate reference evapotranspiration (ETo) and create a climate file in AquaCrop. The ET_o was estimated by the ET_o calculator, a software developed by the Land and Water Division of FAO and integrated in AquaCrop (Raes, 2023). The ET_o forms part of the key inputs when creating the climate file in AquaCrop (Yadav et al., 2017). Computation of ET_o was based on FAO Penman Monteith equation (Masaliyeva et al., 2024).

The crop characteristics data were used to create and develop a crop file in AquaCrop. The data involved type of crop, planting method, row and plant spacing, date of planting, length of growing cycle, effective root zone depth, and yield data. The soil data were used to create the soil file and it required data on soil moisture content, saturated hydraulic conductivity, soil texture and existence of restrictive layer. Extra soil data such as soil electrical conductivity (EC), soil pH, cation exchange capacity (CEC), exchange sodium percentage (ESP), soil organic carbon (SOC), available nitrogen (N), phosphorus (P), and potassium (K) were required to make proper assumptions on fertility, salinity, and water stresses during CWP simulation process.

Data on field management practices were used to create the field management file in AquaCrop. Such data included soil surface cover (mulches) and field surface practices preventing run-off. An irrigation file was also created and it involved data on irrigation method, salinity of irrigation water, type of irrigation schedule, and root zone moisture depletion. Furthermore, the groundwater table and its salinity data were used to create the groundwater table file.

The AquaCrop simulation process is highlighted in Figure 3.

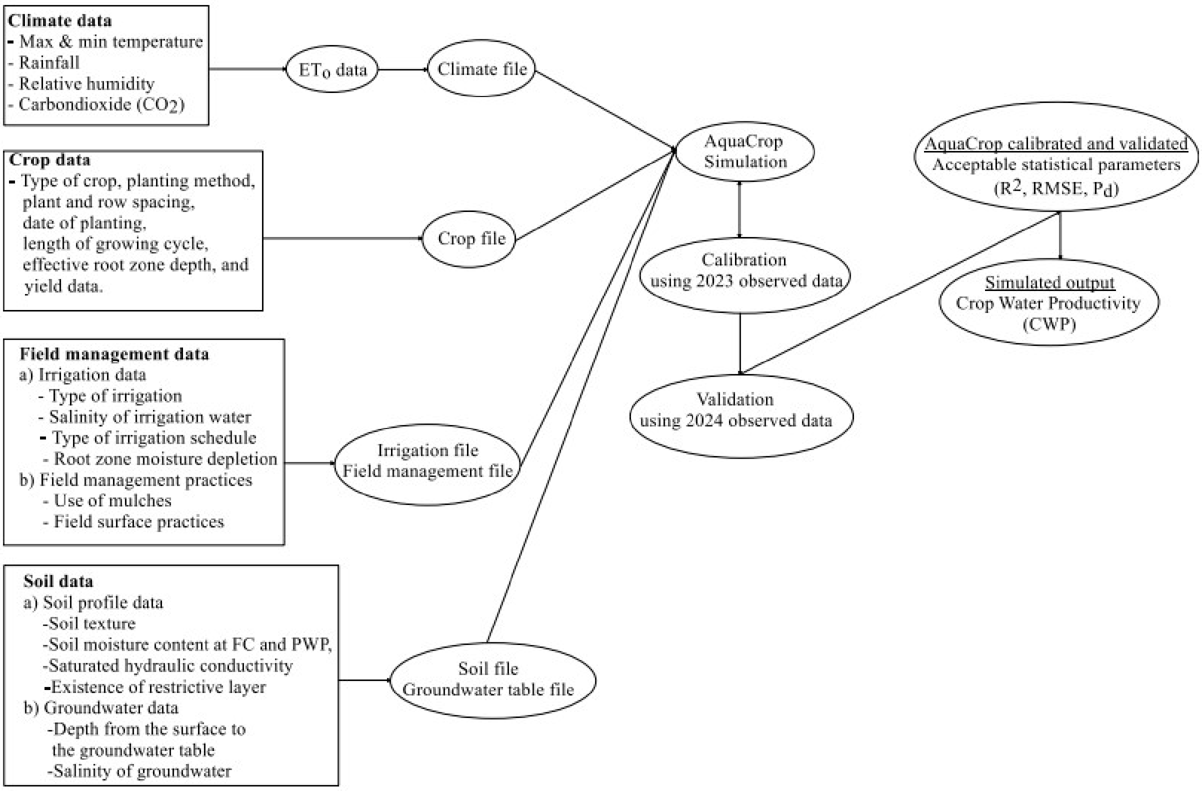

Figure 3. Flow-Chart showing AquaCrop simulation process (*Source:* modified from Oke et al., 2023).

After creating the climate, crop, irrigation, field management, soil, and groundwater table files in AquaCrop, the simulation period, initial soil moisture conditions, and salinity content in the soil profile were defined at the start of the simulation process. Water stress was dependent on fractional depletion of available soil moisture. Based on the soil analysis, fertility and salinity were considered as non-limiting factors in the simulation process. Crop yield was sensitive to the timing and magnitude of water stress in the root zone, and the key output of the simulation process was the yield response to water.

2.6. Calibration, validation, and performance evaluation of AquaCrop model

To evaluate the performance and applicability of the AquaCrop model, calibration and validation processes played a crucial role. Part of the calibration process involved adjustment of specific model parameters to align with field conditions for okra and chilli production. Such model parameters included crop coefficients, plant density, effective root zone, allowable moisture depletion, and reference harvest index. Furthermore, the model was calibrated using yield data from the first irrigation season (2023). Simulated crop yields from the model were compared with actual yields obtained from the field. In the validation phase, yield data from the second irrigation season (2024) were used.

The calibration and validation processes ensured that the AquaCrop model provides accurate and reliable predictions of crop yield which further influences CWP. After successful calibration and validation, simulation results were finally obtained from the complete dataset and used for model evaluation. The model evaluation involved comparing field experimental data with the model simulated results. Statistical indicators such as coefficient of determination (R^2), Root Mean Square Error (RMSE), and percentage deviation (P_d) were used to analyze the model output. Performance of the model was rated based on statistical parameters highlighted in Table 1.

Table 1. Statistical performance indicators for analysis of model output

Statistical parameter	Range	Model performance	Source
R^2	$R^2 > 0.90$	Very good	Terán-Chaves et al. (2022)
	$0.70 \le R^2 \le 0.90$	Good	
	$0.50 \le R^2 \le 0.70$	Moderately good	
	$R^2 < 0.50$	Poor	
RMSE	Low RMSE	Very good performance	Jamil and Akhtar (2017)
	High RMSE	Poor performance	
P_d	$P_d < 15$ %	Acceptable	Adeboye et al. (2021)*
	$P_d > 15$ %	Not acceptable	

R^2: coefficient of determination, RMSE: root mean square error, P_d: percentage of deviation. *According to Adeboye et al (2021), the P_d was computed using Equation 12 (see section Material and methods).

Following Terán-Chaves et al. (2022), R^2 and RMSE were computed using Equations 10 and 11, respectively. According to Adeboye et al (2021), the P_d was computed using Equation 12.

$$R^2 = \left(\frac{\sum_{i=1}^{n} (O_i - \bar{O})(P_i - \bar{p})}{\sqrt{\sum_{i=1}^{n} (O_i - \bar{O})^2} \sqrt{\sum_{i=1}^{n} (P_i - \bar{p})^2}} \right)^2 \quad (10)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n}} \quad (11)$$

$$P_d = \frac{(P_i - O_i)}{O_i} \times 100 \quad (12)$$

Where, O_i is the observed data, $\bar{O}$ is the average of observed data, P_i is the simulated data, $\bar{p}$ is the average of simulated data, and n is the number of observations in the data set.

2.7. Data analysis

Data on CWP were subjected to Analysis of Variance (ANOVA) using GenStat Version 12.1. To assess differences among treatment means, the protected Fisher's least significant difference (LSD) was applied as a post-hoc comparison test, with $p \leq 0.05$ considered significant (5 % level of significance).

2.8. A summary of the study design approach

With emphasis on okra and chilli pepper which are important vegetables grown in all agro-ecological zones in Ghana, the study focussed on identifying the best soil moisture level that contributes to optimum CWP, and further recommend the best performing crop under such moisture level conditions.

The study involved setting up a field experiment and various data were collected on crop and soil characteristics, climate variables, method of irrigation and amount of water applied, field management practices, ground water table details and its quality. Part of the data e.g. crop yield and amount of water used during the growing season were used to estimate CWP. The other data were crucial in simulating CWP under different soil moisture conditions using AquaCrop model. Upon successful calibration and validation of AquaCrop model, simulated results provided a better understanding on magnitude of soil moisture levels and their impact on CWP which complements efforts in promoting more crop yield per unit drop of water. Furthermore, a recommendation was made on the best crop that should be prioritized under field moisture conditions studied. Figure 4 provides a summary of the study approach.

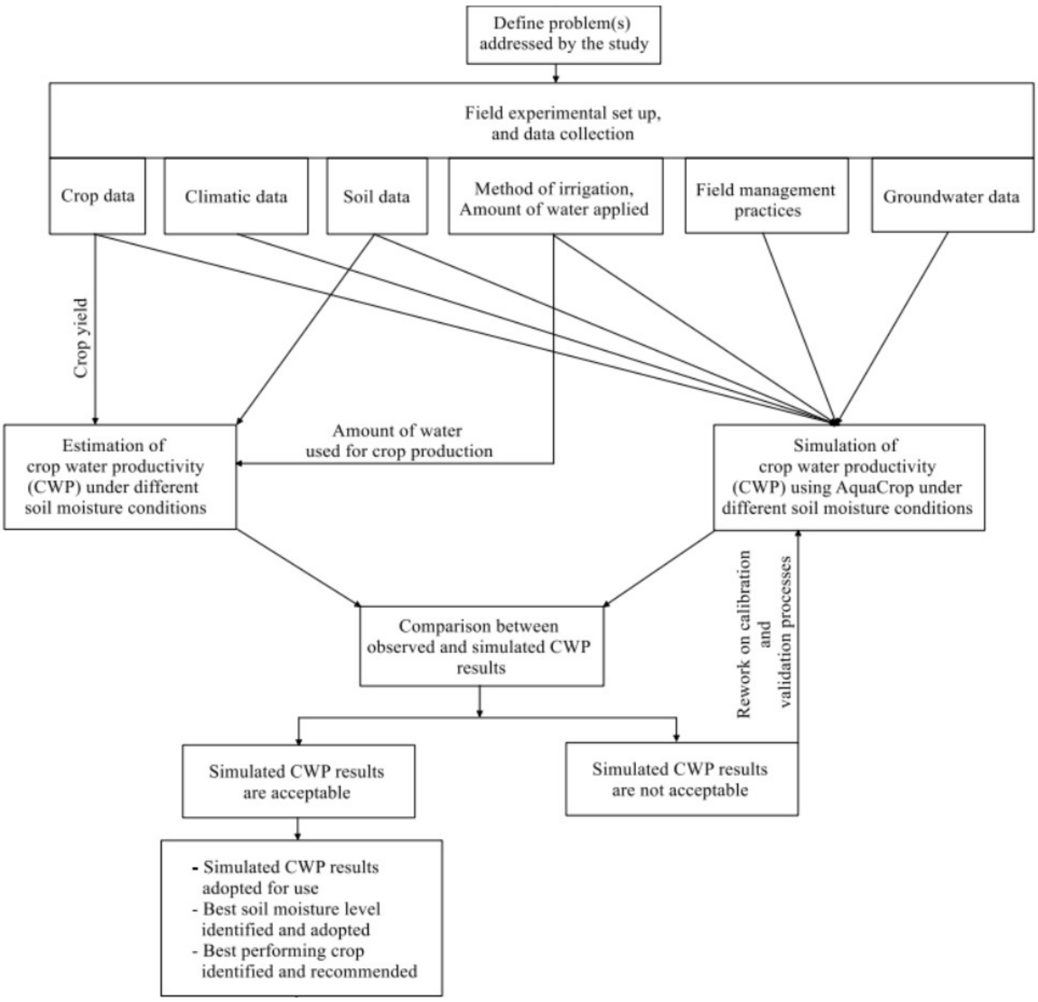

Figure 4. Flowchart of the research study design (*Source:* Authors construct, 2024).

3. RESULTS

3.1. Actual crop water productivity

The actual CWP of chilli pepper and okra was determined from measured yield and actual seasonal evapotranspiration of each crop. From the details of actual CWP under different soil moisture conditions presented in Table 2, chilli pepper recorded a higher yield in both soil moisture conditions as compared to okra. Despite having such yield results, okra recorded higher CWP than chilli pepper in both soil moisture conditions. Under non-water stress conditions, actual CWP was 2.04 kg m^{-3} and 1.30 kg m^{-3} for okra and chilli pepper, respectively. However, under water stress conditions, the actual CWP dropped to 1.64 kg m^{-3} and 1.19 kg m^{-3} for okra and chilli pepper, respectively. Actual CWP results showed significant variation ($p < 0.001$) between water stress and non-water stress conditions.

Table 2. Actual crop water productivity of chilli pepper and okra

Key parameters	Non-water stress conditions (soil moisture depletion from 0–30%)*		Water stress conditions (soil moisture depletion >30%)**	
	Chilli pepper	**Okra**	**Chilli pepper**	**Okra**
Actual yield (kg ha^{-1})	8806.25	7262.00	2840.80	2501.50
Actual ET (m^3 ha^{-1})	6774.04	3559.80	2387.23	1525.30
Actual CWP (kg m^{-3})	1.30	2.04	1.19	1.64

*Soil moisture depletion from 0–30 % corresponds to the range of available volumetric soil moisture content between 15.4 % and 22 %, including both 15.4 % and 22 % (non-water stress conditions) .

**Soil moisture depletion >30 % corresponds to the range of available volumetric soil moisture content between 12 % and 15.4 %, excluding 12 % and 15.4 % (water stress conditions).

ET: evapotranspiration, CWP: crop water productivity.

3.2. Simulated crop water productivity

AquaCrop model was applied to simulate CWP under different soil moisture conditions. The physical and chemical properties of the soil presented in Table 3 were also incorporated in the simulation process and the results revealed that production of okra and chilli pepper was not negatively affected by the existing characteristics of the soil. Hence, the simulation of CWP was run with the assumption that crop growth, development, and yield were not limited by soil physical properties, salinity, and fertility stresses. From the details of simulated crop water productivity under different soil moisture conditions presented in Table 4, simulated results showed higher crop water productivity for okra than chilli pepper in both soil moisture conditions. Under non-water stress conditions, the simulated CWP was 2.08 and 1.40 kg m^{-3} for okra and chilli pepper, respectively. Under water stress conditions, the simulated CWP dropped to 1.82 and 1.34 kg m^{-3} for okra and chilli pepper, respectively. Simulated CWP results showed significant variation ($p < 0.001$) between water stress and non-water stress conditions.

Table 3. Soil physico-chemical properties

Sr. No	Soil property	Value/description
1	Soil texture	Sandy loam (Sand: 74 %, Silt: 8 %, and clay: 18 %)
2	Bulk density (g cm^{-3})	1.42–1.47
3	Saturated hydraulic conductivity (mm hr^{-1})	46.62–47.02
4	Field capacity (Vol %)	22
5	Permanent wilting point (Vol %)	12
6	Soil moisture content under non-water stress conditions (Vol %)	15.4–22
7	Soil moisture content under water stress conditions (Vol %)	12 < Vol < 15.4*
8	Soil pH	5.67–6.43
9	Electrical Conductivity (EC)- dS m^{-1}	0.025–0.039
10	Exchangeable Sodium Percentage (ESP) - %	2.31–4.68
11	Soil Organic Carbon (SOC) - %	3.1–4.3
12	Cation Exchange Capacity (CEC) - Cmol+ kg^{-1}	15.2–18.5
13	Available nitrogen (N) – kg ha^{-1}	270.5–350.4
14	Available phosphorus (P) – kg ha^{-1}	14.4–18.9
15	Available potassium (K) – kg ha^{-1}	136–220.5

12 < Vol < 15.4 reflects the range of available volumetric soil moisture content between 12 % and 15.4 %, excluding 12 % and 15.4 % (water stress conditions)*.

Table 4. Simulated crop water productivity of chilli pepper and okra

Key parameter	Non-water stress conditions (soil moisture depletion from 0–30%)*		Water stress conditions (soil moisture depletion >30%)**	
	Chilli pepper	Okra	Chilli pepper	Okra
Simulated CWP (kg m^{-3})	1.40	2.08	1.34	1.82

*Soil moisture depletion from 0–30 % corresponds to the range of available volumetric soil moisture content between 15.4 % and 22 %, including both 15.4 % and 22 % (non-water stress conditions).

**Soil moisture depletion >30 % corresponds to the range of available volumetric soil moisture content between 12 % and 15.4 %, excluding 12 % and 15.4 % (water stress conditions).

CWP: crop water productivity.

3.3. Comparison between actual and simulated crop water productivity

The results of actual and simulated CWP helped evaluate the accuracy of a model in predicting the amount of water that can be used to produce a certain quantity of crop yield. This is crucial in development and application of sustainable water management practices. Figure 5 shows a clear view on how simulated CWP matched with actual CWP under different soil moisture conditions. Simulated CWP results were steadily over-estimated for both crops under all soil moisture conditions. Okra recorded the highest actual and simulated CWP (2.04 and 2.08 kg m^{-3}, respectively) when the percentage volumetric moisture content was in the range of 15.4–22 %. Comparing actual and simulated CWP values, the minimum P_d and RMSE were 1.96 % and 0.0424 kg m^{-3}, respectively. The highest R^2 (0.94) was observed in okra production under non-water stress conditions. The maximum P_d and RMSE were 12.60 % and 0.169 kg m^{-3}, respectively. The lowest R^2 (0.82) was observed in chilli pepper production under water stress conditions.

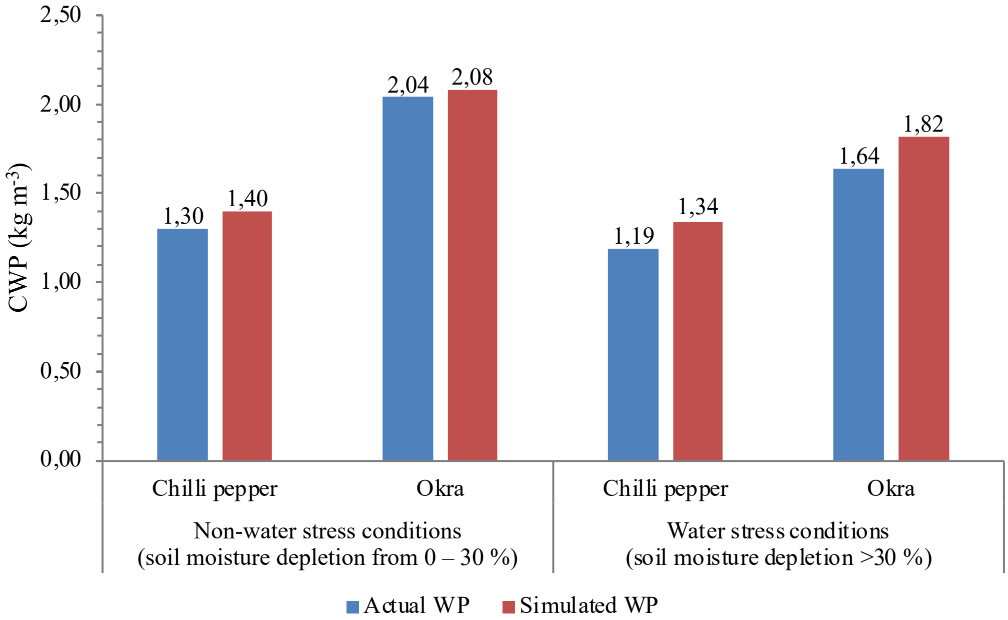

Figure 5. Actual and simulated crop water productivity (CWP) under different soil moisture conditions for chilli pepper and okra.

4. DISCUSSION

4.1. Crop water productivity under different soil moisture conditions

Non-water stress conditions with optimum volumetric moisture content (15.4%–22 %) had a positive significant effect on CWP of chilli pepper and okra. The positive impact on CWP was attributed to adequate aeration in the root zone, soil drainage, enhanced root growth, increased nutrient availability, and uptake by the roots, which eventually improved crop yields as supported by Mangosongo et al. (2019) and Ćirić et al. (2023). Even though a high yield was observed in chilli pepper, a comparison of CWP between okra and chilli pepper revealed a significantly higher CWP (2.08 kg m^{-3}) for okra than chilli pepper (1.40 kg.m^{-3}). This indicates that 1 m^3 of water was used to produce 2.08 kg of okra while the same volume of water was used to produce 1.40 kg of chilli pepper. Okra's lower seasonal water usage, its inherent capacity to retain water, and higher photosynthetic efficiency contributed to higher water productivity.

Under water stress conditions, plants typically exhibit stomatal closure, resulting in reduced stomatal conductance and limitations on photosynthetic activity (Liu et al., 2013; Dąbrowski et al., 2019). These conditions negatively affect crop yield. In general terms, water stress reduces crop yield which further lowers CWP. Interestingly, despite chilli pepper registering higher yield than okra under water stress conditions (12% < Vol < 15.4%), it exhibited a lower CWP (1.34 kg.m^{-3}) than okra (1.82 kg.m^{-3}). This indicates that 1 m^3 of water was used to produce 1.34 kg of chilli pepper while the same volume of water was used to produce 1.82 kg of okra under water stress conditions. The results indicate that okra was also more water-efficient in water-stressed conditions, a finding that highlights how water use efficiency can vary between crops even when yields are affected differently by water scarcity. This phenomenon suggests that a crop's ability to maintain CWP depends on its capacity to use water more effectively relative to its yield, even if the absolute yield is lower. A similar trend was reported by Bao et al. (2024) whose study revealed that under water-stressed conditions, wheat exhibited an increased CWP by 6.6 %, but this was accompanied by a significant 16.2 % decrease in yield.

The study has also shown that soil moisture conditions can also affect the accuracy of CWP simulation process. A strong correlation between actual and simulated CWP was observed in okra production under non-water stress conditions while a weak correlation was observed in chilli pepper production under water stress conditions. Allowing adverse soil moisture depletion beyond 30% negatively affected simulated CWP results. While allowing soil moisture depletion in the range of 0–30 % in order to maintain volumetric moisture content of 15.4%–22 %, positively affected simulated CWP results.

This implies that water stress conditions affected the accuracy of simulated CWP results. A similar observation was noted by Eshete et al. (2022) who stated that the water stress level affects the performance of the AquaCrop model. Even though water stress conditions affected accuracy of the simulation process, the simulated CWP results were still acceptable as revealed by Omotayo et al (2024) who stated that R^2 > 0.80 and P_d < 15 % are recommended for crop simulation studies. A comparison between actual and simulated CWP has provided an insight on the importance of soil moisture management in irrigated fields.

Plants possess adaptive mechanisms that compensate for unfavourable conditions. The study has shown that okra has the capacity to adapt better to water stress conditions, and its yield is less impacted by water stress conditions as compared to chilli pepper, making it more productive under a wider range of soil moisture conditions and achieve higher overall CWP compared to chilli pepper. In both optimal and water stress conditions, okra has proved to be more productive in terms of its water conversion efficiency compared to chilli pepper, as evidenced from CWP values. Since each crop responds uniquely to soil moisture conditions, the findings of this study are crucial for understanding how to manage irrigation for different crops under water-scarce environments. Therefore, with emphasis on maximizing crop yield per drop of water, okra should be prioritized over chilli pepper at the study site. The study has also shown that simulation of CWP is an effective approach. The simulated results can be readily translated into practical actions to improve water use efficiency as a way of maximizing crop yield per unit drop of water.

4.2. Limitations of the study and future research studies

The AquaCrop model did not incorporate the effects of pests and diseases on crop yield. This might have led to overestimation of yield, which also contributed to higher simulated CWP values. However, the capacity of the AquaCrop model to simulate CWP under varying soil moisture conditions has provided a better understanding of the effect of soil moisture on WP of okra and chilli pepper. Therefore, future studies should explore more on the sensitivity of our results to a much wider range of soil profile and spatial heterogeneity of the soil. The same study approach should be extended to other vegetable crops such as onion, tomato, and garden egg grown in Bontanga irrigation scheme. In order to widen the application of models to estimate CWP, other models e.g. Soil and Water Assessment Tool (SWAT) should also be applied to estimate WP of the tested crops in the study area under similar studied conditions.

5. CONCLUSIONS

The study was conducted to assess and simulate CWP of chilli pepper and okra under different soil moisture conditions in Bontanga (Ghana) irrigation scheme. Study findings have revealed that CWP varies between crops as the yields are affected differently by soil moisture conditions. The study has shown that okra has the capacity to adapt better to water stress conditions, and its yield is less impacted by water stress conditions as compared to chilli pepper, making it more productive under a wider range of soil moisture conditions and enabling it to achieve a higher overall CWP compared to chilli pepper. In order to optimize the CWP for both okra and chilli pepper, the ideal soil moisture conditions should have the volumetric moisture content in the range of 15.4–22 %. Overall simulated CWP results indicated good performance of AQUACROP model, justifying the need to incorporate CWP simulation as an important decision supporting tool to maximize crop yield per unit drop of water. For CWP to be improved in Bontanga irrigation scheme, sustainable soil moisture management practices should be promoted. Examples of such practices include: effective irrigation scheduling, the use of organic manure, and mulching. Soil moisture levels before and after irrigation should be monitored to implement effective irrigation scheduling. Efforts to implement field tailwater recovery and management should be initiated; however, careful attention should be paid to water quality before reuse. Before implementation of the suggested measures, farmers should be trained on causes of water losses in an irrigation scheme, irrigation scheduling, flow measurement, field methods for estimating soil moisture levels, basic principles on soil quality assessment, and the synergy between crop yield and the amount of water used. The study provides insights into a better understanding on magnitude of soil moisture levels and their impact on CWP which complements efforts in promoting more crop yield per drop of water.

Supplementary information ↑

Funding sources

The authors received no specific funding for this work.

Supplementary material

Not applicable.

Data availability

Data will be made available upon request.

Acknowledgements

Authors would like to extend great thanks to Bontanga irrigation scheme farmers, WUA executive members, and the irrigation scheme manager for their support during the study. Furthermore, authors wish to extend their gratitude to West African Centre for Water, Irrigation and Sustainable Agriculture (WACWISA), University for Development Studies, Tamale, Ghana for the support towards implementation of the research study.

Authorship contribution statement

Davis Sibale: Writing – original draft, Visualization, Validation, Methodology, Investigation, Software, Formal analysis, and Conceptualization.

Gordana Kranjac-Berisavljevic: Writing – review & editing, Supervision, Project administration, Methodology, and Conceptualization.

Shaibu Abdul-Ganiyu: Writing – review & editing, Supervision, Methodology, and Conceptualization.

Rodrick Mlewa: Writing – review & editing, Methodology, Software, and Formal analysis.

Eston Malinda: Writing – review & editing, Methodology, Validation, and Formal analysis.

Phillip Kamwendo: Writing – review & editing, Methodology, and Formal analysis.

Zakaria Issaka: Writing – review & editing, Methodology, and Supervision.

Sylvester Chikavumbwa: Writing – review & editing, Methodology, and Formal analysis.

Competing interests

The authors have declared that no competing interests exist.

Statement on the use of Artificial Intelligence

The author(s) employed Google Translator in order to translate the title, abstract and keywords from English to Spanish while preparing this work. Following their use, the author(s) assumed full responsibility for the publication’s content and reviewed and edited it as necessary.

REFERENCES

Acevedo SE, Contreras CP, Ávila CJ, Bonilla CA, 2021. Testing the integral suspension pressure method for soil particle size analysis across a range of soil organic matter contents, International Agrophysics, 35: 357-363. https://doi.org/10.31545/intagr/144387

Adeboye OB, Schultz B, Adeboye AP, Adekalu KO, Osunbitan JA, 2021. Application of the AquaCrop model in decision support for optimization of nitrogen fertilizer and water productivity of soybeans, Information Processing in Agriculture, 8(3): 419-436, ISSN 2214-3173. https://doi.org/10.1016/j.inpa.2020.10.002

Adekaldu E, Amponsah W, Tuffour WO, Adu MO, Agyare WA, 2021. Response of chilli pepper to different irrigation schedules and mulching technologies in semi-arid environments, Journal of Agriculture and Food Research, 6: 100222, ISSN 2666-1543. https://doi.org/10.1016/j.jafr.2021.100222

Adonadaga MG, Ampadu B, Ampofo S, Adiali F, 2022. Climate Change Adaptation Strategies Towards Reducing Vulnerability to Drought in Northern Ghana. European Journal of Environment and Earth Sciences, 3(4): 1-6. https://doi.org/10.24018/ejgeo.2022.3.4.294

Ahiamadia D, Ramilan T, Tozer PR, 2024. Enhancing climate resilience in northern Ghana: A stochastic dominance analysis of risk-efficient climate-smart technologies for smallholder farmers, Environmental Development, 51: 101031, ISSN 2211-4645. https://doi.org/10.1016/j.envdev.2024.101031

Alegewe R, Abdul-Ganiyu S, Akubu SZ, 2023. Optimization of Water Management for Green Pepper Production in a Water-Limiting Tropical Savanna Agroecological Zone Based on Crop Water Productivity, Journal of Engineering, Article ID 9970714 https://doi.org/10.1155/2023/9970714

Allen R, Pereira L, Raes D, Smith, M, 1998. FAO Irrigation and drainage paper No. 56. Rome: Food and Agriculture Organization of the United Nations. 56: 26-40. https://www.researchgate.net/publication/284300773_FAO_Irrigation_and_drainage_paper_No_56 [8 April, 2025].

Arunadevi K, Singh M, Khanna M, Mishra AK, Prajapati VK, Denny F, Ramachandran J, Maruthi-Sankar GR, 2023. Soil-Matric-Potential-Based Irrigation Scheduling to Increase Yield and Water Productivity of Okra. Water, 15: 4300. https://doi.org/10.3390/w15244300

Bao X, Zhang B, Dai M, Liu X, Ren J, Gu L, Zhen, W, 2024. Improvement of grain weight and crop water productivity in winter wheat by light and frequent irrigation based on crop evapotranspiration, Agricultural Water Management, 301:108922, ISSN 0378-3774. https://doi.org/10.1016/j.agwat.2024.108922

Bell MJ, Thompson ML, Moody PW, 2021. Using Soil Tests to Evaluate Plant Availability of Potassium in Soils. In: Murrell, T.S., Mikkelsen, R.L., Sulewski, G., Norton, R., Thompson, M.L. (eds) Improving Potassium Recommendations for Agricultural Crops. Springer, Cham. https://doi.org/10.1007/978-3-030-59197-7_8

Blatchford ML, Mannaerts CM, Zeng Y, Nouri H, Karimi P, 2019. Status of accuracy in remotely sensed and in-situ agricultural water productivity estimates: A review, Remote Sensing of Environment, 234: 111413, ISSN 0034-4257. https://doi.org/10.1016/j.rse.2019.111413

Ćirić V, Prekop N, Šeremešić S, Vojnov B, Pejic B, Radovanović D, Marinkovic D, 2023. The Implication of Cation Exchange Capacity (CEC). Assessment for Soil Quality Management and Improvement. *Journal* Agriculture and Forestry. 69 (4): 113-133. https://doi.org/10.17707/AgricultForest.69.4.08

Cobbinah P, Kwoseh C. 2021. Okra Production Constraints and Awareness of Seed-Borne Fungi Infection in Ten Major Okra Growing Communities of the Ashanti Region of Ghana. Asian Journal of Advances in Agricultural Research. 15(4): 1-9.

Dąbrowski P, Baczewska-Dąbrowska AH, Kalaji HM, Goltsev V, Paunov M, Rapacz M, Wójcik-Jagła M, Pawluśkiewicz B, Bąba W, Brestic M, 2019. Exploration of chlorophyll a fluorescence and plant gas exchange parameters as indicators of drought tolerance in perennial ryegrass. Sensors, 19(12): 2736. https://doi.org/10.3390/s19122736

Dhouib M, Zitouna-Chebbi R, Prévot L, Molénat J, Mekki I, Jacob F, 2022. Multicriteria evaluation of the AquaCrop crop model in a hilly rainfed Mediterranean agrosystem Agric. Water Manag., 273: 107912. https://doi.org/10.1016/j.agwat.2022.107912

Eshete DG, Sinshaw BG, Gizaw HD, 2022. Simulating maize water productivity at deficit irrigated field in north west Ethiopia. Sustain. Water Resources Management. 8 (6): 186. https://doi.org/10.1007/s40899-022-00771-5?urlappend=%3Futm_source%3Dresearchgate.net%26utm_medium%3Darticle

FAO, 2019. Standard operating procedure for soil organic carbon. Walkley-Black method, Titration and colorimetric method.

FAO, 2021. Standard operating procedure for soil available phosphorus - Olsen method. Rome.

FAO, 2021. Standard operating procedure for soil nitrogen - Kjeldahl method. Rome.

FAO, 2021. Standard operating procedure for soil electrical conductivity, soil/water, 1:5. Rome.

FAO, 2021. Standard operating procedure for soil pH determination. Rome.

FAO, 2022. Standard operating procedure for cation exchange capacity and exchangeable bases 1N ammonium acetate, pH 7.0 method. Rome.

FAO, 2023. Standard operating procedure for soil bulk density, cylinder method. Rome.

Garofalo P, Riccardi M, Tommasi D, Tedeschi A, Rinaldi M, De Lorenzi F, 2025. AquaCrop model to optimize water supply for a sustainable processing tomato cultivation in the Mediterranean area: A multi-objective approach, Agricultural Systems 223:104198. https://doi.org/10.1016/j.agsy.2024.104198

Gharaibeh MA, Albalasmeh AA, Pratt C, Hanandeh AE, 2021. Estimation of exchangeable sodium percentage from sodium adsorption ratio of salt-affected soils using traditional and dilution extracts, saturation percentage, electrical conductivity, and generalized regression neural networks, CATENA, 205: 105466, ISSN 0341-8162, https://doi.org/10.1016/j.catena.2021.105466

Gu Z, Qi Z, Ma L, Gui D, Xu J, Fang Q, Yuan S, Feng G, 2017. Development of an irrigation scheduling software based on model predicted crop water stress. Comput Electron Agric, 143:208–221. https://doi.org/10.1016/j.compag.2017.10.023

Hossain SA, Mazrin M, Habibullah, M, 2023. Determination of Organic Carbon of Soil by the Walkley & Black Method. https://doi.org/10.13140/RG.2.2.32699.80162/1

Incoom ABM, Adjei KA, Odai SN, 2020. Rainfall variabilities and droughts in the Savannah zone of Ghana from 1960-2015. Scientific African 10: e00571. ISSN 2468-2276. https://doi.org/10.1016/j.sciaf.2020.e00571

Jamil, B, Akhtar, N, 2017. Comparative analysis of diffuse solar radiation models based on sky-clearness index and sunshine period for humid-subtropical climatic region of India: A case study, Renewable and Sustainable Energy Reviews, 78:329-355, ISSN 1364-0321. https://doi.org/10.1016/j.rser.2017.04.073

Jadhav AM, Gupta S, Jadhav OS, 2024. Review of Campbell soil moisture sensors working on the principle of time domain reflectometry. International Research Journal of Modernization in Engineering Technology and Science, 6(4), e-ISSN: 2582-5208.

Liu D, Wu L, Naeem MS, Liu H, Deng X, Xu L, Zhang F, Zhou W, 2013. 5-Aminolevulinic acid enhances photosynthetic gas exchange, chlorophyll fluorescence and antioxidant system in oilseed rape under drought stress. Acta Physiologiae Plantarum 35:2747-59. https://doi.org/10.1007/s11738-013-1307-9

Li X, Zhang X, Niu J, Tong L, Kang S, Du T, Li S, Ding R, 2016. Irrigation water productivity is more influenced by agronomic practice factors than by climatic factors in Hexi Corridor, Northwest China, Scientific Reports 6:37971. https://doi.org/10.1038/srep37971

Mangosongo HM, Lyaruu HV, Mneney EE, 2019. Assessment of Soil Physico-Chemical Properties in Selected Natural Habitats of the Wild Rice (*Oryza Longistaminata*) and their Effects on the Species Morphological Characters, Huria Journal, 26 (1): 12-29.

Masaliyeva Z, Karimov A, Adhamov J, 2024. Estimating reference evapotranspiration using the Hargreaves - Samani formula for end-user applications. E3S Web of Conferences 563, 03081. International Conference on Environmental Science, Technology and Engineering (ICESTE 2024). https://doi.org/10.1051/e3sconf/202456303081

Mutema M, Dhavu K, Vorster S, Reinders F, Sivhagi P, Sekgala M, Benadé N, 2023. The State of Irrigation Water Losses and Measures to Improve Water Use Efficiency on Selected Irrigation Schemes. Water Research Commission (WRC) Report No. 2970/1/23, ISBN 978-0-6392-0482-6.

O'Geen AT, 2013. Soil Water Dynamics. Nature Education Knowledge 4(5): 9. https://www.nature.com/scitable/knowledge/library/soil-water-dynamics-103089121 [7 April, 2025)

Omotayo A, Bart s, Amaka a, Abebe C, Kabiru S, 2024. Assessment of AquaCrop model to simulate the impact of soil fertility management on evapotranspiration, yield, and water productivity of maize (Zea May L.) in the sub-humid agro-ecology of Nigeria. Discover Agriculture, 2:1-21

Oke A, Zemadim B, Amankwaa-Yeboah P, Cofie O, 2023. Simulation of Rice Performance Using AquaCrop Model Under Different Water Management Regimes in Ghana: Methodological Report and Progress. Ibadan, Nigeria: IITA. https://hdl.handle.net/10568/138168 [8 April, 2025]

Özdemir N, Demir Z, Bülbül E, 2022. Relationships between some soil properties and bulk density under different land use. Soil Studies, 11(2): 43-50. https://doi.org/10.21657/soilst.1218353

Pinheiro EAR, Van Lier Q, Šimůnek J, 2019. The role of soil hydraulic properties in crop water use efficiency: A process-based analysis for some Brazilian scenarios, Agricultural Systems, 173: 364-377, ISSN 0308-521X. https://doi.org/10.1016/j.agsy.2019.03.019

Raes D, Steduto P, Hsiao TC, Fereres E, 2022. Chapter 2: users guide. AquaCrop Version 7.0. Reference Manual. Food Agricultural Organization (FAO), Rome, Italy, pp. 2–372.

Raes D, Steduto P, Hsiao TC, Fereres E, 2023. Chapter 1: FAO crop-water productivity model to simulate yield response to water, AquaCrop Version 7.1 Reference manual. Food and Agriculture Organization of the United Nations, Rome, Italy. pp.1-19.

Salman M, García-Vila M, Fereres E, Raes D, Steduto P, 2021. The AquaCrop model – Enhancing crop water productivity. Ten years of development, dissemination and implementation 2009–2019. FAO Water Report No. 47. Rome, FAO.

Steiakakis E, Gamvroudis C, Alevizos G, 2012. Kozeny-Carman Equation and Hydraulic Conductivity of Compacted Clayey Soils. Geomaterials, 02(02), 37–41.

Terán-Chaves CA, García-Prats A, Polo-Murcia SM, 2022. Calibration and Validation of the FAO AquaCrop Water Productivity Model for Perennial Ryegrass (*Lolium perenne* L.). Water, 14(23): 3933. https://doi.org/10.3390/w14233933

Van Dijk M, Morley T, Rau ML, Saghai Y, 2021. A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. Nat. Food 2021, 2: 494–501. https://doi.org/10.1038/s43016-021-00322-9?urlappend=%3Futm_source%3Dresearchgate.net%26utm_medium%3Darticle

Wahl TL, Clemmens AJ, Replogle JA, and Bos MG, 2005. Simplified design of

Flumes and Weirs. Irrigation and Drainage., 54:231-247. https://doi.org/10.1002/ird.160

Yadav D, Awasthi MK, Nema RK, 2017. Estimation of reference evapotranspiration using AquaCrop model for agro-climatic conditions of Madhya Pradesh. Indian J. Agric. Res., 51(6): 596-600.

Yeleliere E, Cobbina SJ, Duwiejuah AB, 2018. Review of Ghana's water resources: the quality and management with particular focus on freshwater resources. Applied Water Science **8**, 93. https://doi.org/10.1007/s13201-018-0736-4