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EDITED BY
Kulasekaran Ramesh,
Indian Institute of Oilseeds Research (ICAR), India

REVIEWED BY
Debaditya Gupta,
Indian Institute of Technology Guwahati, India
Ramaraj A. P.,
India Meteorological Department, India

*CORRESPONDENCE
Botir Khaitov
✉ bhaitov@yahoo.com

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Efficiency of drip irrigation in amaranth production using the HYDRUS-1D model

Akmal Karimov[1], Bakhodir Khalikov[2], Sabirjan Isaev[1], Obidjon Sindarov[1], Kholmurod Khayitov[1], Mirzoolim Avliyakulov[2], Anvarjon Isashov[3], Perizat Bulanbayeva[4], Altingul Djumanazarova[5], Yo'ldoshbek Muhammadov[6], Nurmamat Rajabov[1], Gulnoza Murtazayeva[1], Shaniyaz Kurbanov[7], Kholik Allanov[8] and Botir Khaitov[8]*

[1]National Research University Tashkent Institute of Irrigation and Agricultural Mechanical Engineers, Tashkent, Uzbekistan, [2]Cotton Breeding, Seed Production and Agrotechnologies Research Institute, Tashkent, Uzbekistan, [3]Andijan Institute of Agriculture and Agrotechnologies, Andijan, Uzbekistan, [4]Department of Water Resources and Land Management, Korkyt Ata Kyzylorda University, Kyzylorda, Kazakhstan, [5]Institute of Agriculture and Agrotechnologies of Karakalpakstan, Nukus, Karakalpakstan, Uzbekistan, [6]Center of Genomics and Bioinformatics, Academy of Sciences of the Republic of Uzbekistan, Tashkent, Uzbekistan, [7]Department of Physiology, Karshi State University, Karshi, Uzbekistan, [8]Department of Agriculture and Land Reclamation, Tashkent State Agrarian University, Tashkent, Uzbekistan

The negative impact of climate change is potentially damaging agroecosystem services that have constrained agricultural production and caused water scarcity in Central Asian countries, particularly in Uzbekistan. This study evaluates the efficiency of full (FDI) and deficit (DDI) drip irrigation regimes for amaranth (Amaranthus spp.) cultivation in the Tashkent region of Uzbekistan using the HYDRUS-1D simulation model. Field experiments were conducted over two growing seasons, accompanied by soil moisture monitoring, root zone analysis, and crop performance measurements while the accuracy of the obtained results was assessed against ground measured data. The results showed that compared to the FDI regime, amaranth under the DDI improved water productivity by 56.5% while exhibiting tolerance to water scarcity. The Pearson correlation analysis revealed a strong relationship between the simulated and observed SWC data for both irrigation regimes (R^2 = 0.862 for FDI and R^2 = 0.936 for DDI), indicating the model's predictive reliability. Although FDI produced higher yield (2004 kg/ha) over the two-year period, which was 25% (2 t ha^{-1}) higher than the DDI regime (1,604 kg/ha). However, DDI demonstrated significantly greater water productivity (56.5% higher), attributed to reduced unproductive evaporation and the C4 nature of amaranth. Root system analysis revealed deeper penetration under DDI, suggesting adaptive responses to water stress. The findings of this study suggest that implementing precise irrigation technology in amaranth cultivation combined with the use of the HYDRUS-1D model in the context of inevitable climate change, can ensure the long-term sustainable management of water and land resources in arid regions.

KEYWORDS

amaranth, arid region, crop yield, drip irrigation, HYDRUS-1D simulation model, water use efficiency

1 Introduction

The growing demand for water and food, driven by climate change and population growth, places increasing pressure on agriculture to enhance productivity while diversifying crop production in irrigated lands. In Uzbekistan, most irrigated land is still dominated by the cotton–winter wheat rotation, leaving farmers with limited opportunities to cultivate alternative crops (Rustamova et al., 2023). Recognizing the need for diversification, the government has introduced policies to promote crop rotation and sustainable agricultural practices. However, achieving this goal is severely challenged by water scarcity, which remains a critical limiting factor in crop production, particularly in arid regions (Nurbekov et al., 2025).

Water shortages have had a detrimental impact on agriculture and food security. Between 1980 and 2025, Uzbekistan experienced a 20–30% reduction in crop production due to decreasing water availability, significantly increasing risks to the food supply. The situation is further aggravated by rising temperatures (1.5–2.0°C) caused by the adverse effects of climate change (Bobojonov et al., 2016). Although agriculture accounts for approximately 90% of the region's total water withdrawals, inefficient irrigation methods—such as furrow irrigation—and poor water management result in substantial losses, low water-use efficiency, and declining agricultural productivity (Li et al., 2020). Currently, only about 35% of the water withdrawn from rivers is used for crop evapotranspiration, while the remainder either infiltrates into the groundwater table or forms drainage runoff, averaging 30–40% of total withdrawals. An estimated 15% of irrigation water percolates into brackish groundwater, while another 15% contributes to surface runoff and widespread drainage discharge (Atamurodov et al., 2022). The inefficiency of water delivery systems exacerbates the problem; on average, only 63% of the water diverted from rivers reaches farm gates. Filtration losses from canals and deep percolation from irrigated fields contribute to rising saline groundwater tables, increasing the risk of secondary soil salinization (Djumaboev et al., 2017; Ibragimov et al., 2021). To mitigate salt accumulation, intensive leaching is required, consuming an additional 20% of irrigation water (Kulmatov et al., 2015; Reddy et al., 2013). As a result, water shortages are particularly severe in dry years, exacerbating stress on river systems and contributing to environmental crises such as the desiccation of the Aral Sea (Babakholov et al., 2022; Carli et al., 2014).

To address these challenges, the Government of Uzbekistan has implemented policies to promote water-saving technologies, particularly drip irrigation. In 2017, several policy documents introduced financial incentives for farmers to adopt efficient irrigation methods. According to the Concept of Water Management Development in the Republic of Uzbekistan for 2020–2030, the area under drip irrigation is expected to expand from 250,000 hectares to 600,000 hectares (Decree of the President of the Republic of Uzbekistan, 2020). This expansion is projected to reduce irrigation water depletion by 1.5 km^3 per year, lower groundwater levels, and mitigate soil salinization (Hamidov et al., 2022). By minimizing deep percolation losses and excess drainage flow, drip irrigation acts as a preventive measure against land degradation in irrigated regions. In addition to improving irrigation efficiency, crop diversification in arid environments is a promising adaptation strategy (Chathuranika et al., 2022; Khaitov et al., 2021).

Recent studies indicated that certain climate-smart crops, such as amaranth, exhibit strong tolerance to saline and arid conditions (Hoidal et al., 2019). Amaranth is a fast-growing C4 crop that thrives under challenging conditions, particularly heat and drought. It demonstrates superior water-use efficiency by converting atmospheric carbon into plant sugars at a higher rate per unit of water lost compared to traditional C3 crops. Due to its strong tolerance to major abiotic stresses, amaranth holds significant potential for diversifying cropping systems in arid regions, making it an adaptive solution to climate change while addressing the growing nutritional demands of the population (Kameswara, 2014). This is especially crucial in the southern parts of Central Asia, where rising temperatures and increasing drought frequency pose serious challenges for farmers.

Amaranth is a non-traditional crop in Uzbekistan but is well adapted to semi-arid environments. It possesses drought-resistant mechanisms that enable it to thrive in poor soils and extreme climates (Mlakar et al., 2012). Limited research is available on the effects of different drip irrigation regimes combined with modeling approaches on the growth and productivity of climate-resilient crops. Increasing water productivity can be achieved by reducing water consumption for transpiration or productive use, while actual water savings depend on how the remaining water is managed. Previous studies related to this research have evaluated the effectiveness of the HYDRUS-1D model in simulating soil water content across various crops (Kanzari et al., 2020; Iqbal et al., 2020). Their findings suggest that the HYDRUS-1D model is a reliable and advanced tool for simulating soil water dynamics, with considerable potential to enhance water-use efficiency in agricultural production.

This study aims to evaluate the response of amaranth to full (FDI) and deficit drip irrigation (DDI) conditions and to identify optimal irrigation strategies using the HYDRUS-1D model with multi-source data. Specifically, it tests two hypotheses: (i) the agronomic performance of amaranth under drip irrigation in water-scarce conditions, and (ii) the accuracy and applicability of the HYDRUS-1D model through a comparative analysis of drip irrigation regimes. By addressing these objectives, the study aims to enhance understanding of water-use efficiency with HYDRUS-1D model and crop resilience in arid environments. The findings will support the adoption of advanced precision irrigation technologies for producing drought- and salinity-tolerant crops, contributing to improved agricultural sustainability and food security in Uzbekistan.

2 Materials and methods

2.1 Field study area

This field experiment was conducted at the Research and Training Farm of the Tashkent Institute of Irrigation and Agriculture Mechanization in the midstream of the river Chirchik (41°2' N, 69°15′E, elevation of 396 m). The farm gets water from a Chirchik-Ahangaran Irrigation Administration, which supplies water for farmlands on the right bank of the Syrdarya River midstream. The Irrigation Administration manages all water withdrawals for irrigation purposes from two rivers, the Chirchik River and the Ahangaran River, forming dense populated joint valley with intensive agriculture. Both rivers flow to the Syrdarya River. The valley is limited by mountain ridges representing Tyan-Shan Mountains on the north-west, the east and on the south-east, and open to the Syrdarya River on the south-west. The valley has a little slope from the north-east to the south-west to the Syrdarya river bed.

The climate is continental-subtropical; summer is hot and long with the average temperature +27°C. Maximum air temperature in July reaches up to +44°C. The winter average temperature in January is −1°C (Figure 1).

Relative humidity is from 50 to 70% in September through mid-May and below 40% in summer months. The mean annual precipitation is 375 mm with 90% occurring from October till May. There was 124 mm of precipitation during vegetation season of amaranth in 2022, which is about the long-term average (Figure 1). The average annual standard evapotranspiration is about 1,200 mm, or ten times higher than the annual mean precipitation. The number of sunshine hours is 2,700 h, in average.

Relative humidity varies in wide range – (50–70%) in mountain zone during winter season and drops from March through summer' months. Precipitation depends on altitudes and varies from 250 to 300 mm in valley to 800 mm in the mountains, while in the valley potential evapotranspiration is 1,000 mm. According to predictions using ECHAM4 model, by 2030, average monthly temperatures are expected to increase by 1.7–2°C in January–February and 0.5–0.9°C in June through August against the average temperatures. All this indicates the importance of selecting suitable crops for new climate conditions.

According to the field studies soil is silt loam up to 160 cm deep, excluding soil layer of 63–91 cm where soil texture is loam. The soil humus content is typical for this area ranging between 0.85–1.31%. The soil pH was determined in a 1:2.5 soil-to-water suspension using a pH meter, and the value recorded was 7–7.2, indicating neutral soil conditions.

A groundwater table is deep, at 4.0 m, during the crop growing season. The topsoil is well supplied by potassium and undersupplied by P_2O_5. The soil samples were analyzed for chemical properties using standard procedures developed by the National Institute of Agricultural Science and Technology (NIAST, 2000). Soil physical and chemical properties for the research site were given in Table 1.

2.2 Experiment methods

Field studies were carried from during two vegetation seasons, April 2022 to October 2023. The site has 5 ha area of drip irrigation systems. IKBA-TDAU-1 variety of amaranth were sown on plots of 1,275 m^2 area, each equal six plots. Treatments arranged in a split plot design with three replications, were as follows: (1) drip irrigation with a distance between emitters at 20 cm (representing full irrigation); (2) drip irrigation with a distance between emitters at 50 cm (representing deficit irrigation). Each block consisted of four 37 m long rows spaced 70 cm (Figure 2).

The total number of driplines at each plot was 15, the distance between drip lines of perennial use was 1.2 m, and 33 cm between drippers. The width of each plot was 17 m and the length of drip lines 10 m.

Drip irrigation hoses were installed at the field at the second half of June. Intervals between irrigation events reduced to 4 days during hot summer days. Irrigation applications were measured by

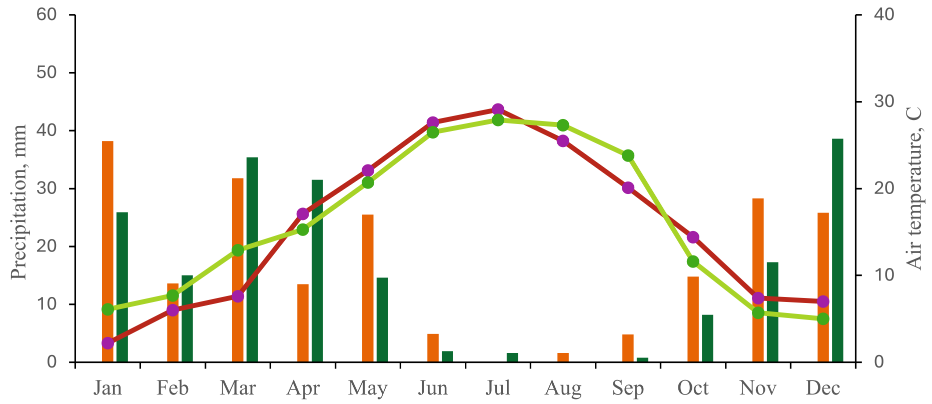

FIGURE 1
Weather conditions during 2021–2022 growing seasons.

TABLE 1 Physical and chemical properties of soil at the research site.

Soil layer	Texture, %			Soil type	Soil bulk density	Humus	P_2O_5	K_2O
Cm	Sand	Silt	Clay		g/cm^3	%	mg/kg	mg/kg
0–30	15.4	68.2	16.4	SL	1.73	1.31	12.1	216.7
30–60	15.0	68.6	16.4	SL	1.86	1.25	12.5	180.6
60–90	37.3	46.3	16.4	L	1.65	0.84	8.5	240.8
90–120	12.6	72.0	15.4	SL	1.76	0.79	8.2	252.8
120–160	17.4	67.2	15.4	SL	1.83	0.85	7.9	132.4

accounting water flow discharge from an emitter per minute at three spots in each control row: five meters after the beginning, in the middle and five meters before the end of the control rows (Figure 3).

2.3 Irrigation applications

Irrigation duration was 3 h, each, providing application of irrigation at 350 m^3/ha. After germination, manual weed control was applied once. In total, 12 irrigation applications were applied. The irrigation applications and dates are given in Figure 1. Water applied for irrigation had turbidity at 0.275 kg/m^3. Irrigation was carried out using high-quality water sourced from the Chirchik River, commonly used for human consumption, which had no adverse effects on soil properties or crop development. Water was through a drip irrigation system, and the total applied water volume was measured using inline water meters.

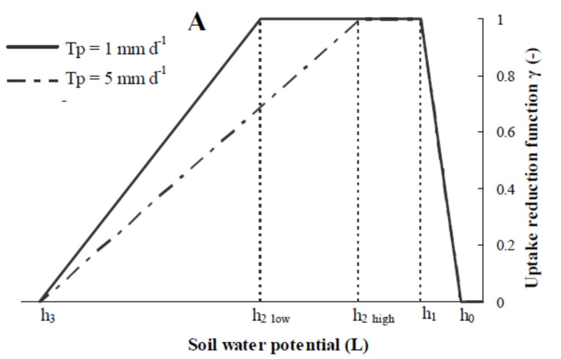

FIGURE 2
Root water uptake reduction function (Feddes et al., 1978). Where, h1 = the soil water potential is low enough to avoid oxygen stress, h2 = drought-stress threshold parameter at which, uptake starts to reduce from the potential, h3 = wilting point.

Two following irrigation regimes were applied:

(A) Full irrigation (FI) - according to crop water requirements; emitters located after each 20 cm. Irrigation was applied once per 4 days in summer hot days from mid-June through August; this regime was modified when necessary based on a soil moisture content. Total irrigation applied amounted to 1810 m^3/ha.

(B) Deficit irrigation (DI) – 2 times less than the crop water requirements; emitters located after each 50 cm. Plants were irrigated once per 5–10 days in summer hot days from mid-June through August; this regime was modified when necessary based on a soil moisture content. Total irrigation applied amounted to 905 m^3/ha.

2.4 Field management and experimental setup

Seeds were sown in mid-April, 2022 at a sowing depth of 2.5–3.0 cm, the distance between plants was 33–35 cm. Before sowing the field was tilled 25 cm deep and then coarse-levelled using tractor MTZ 40. Seeds were sown in two sides, 15 cm far from driplines – the distance between the crop lines was 90 cm and 30 cm, and along the dripline, the distance between crops was 15 cm – 'dense' sowing of crops was applied at the side. Plants were irrigated once per 4 days from the second half of June through August, when necessary, the irrigation regime was modified based on a soil moisture content. First irrigation was late in the end of June due to rainy April and May, when the sum of precipitation exceeded 120 mm. Weed control and crop harvest were applied manually.

Soil moisture content was measured from the same spots by soil sampling and using drying method at laboratory conditions. Soil samples were collected before each irrigation event from the depth of 0–15, 15–30, 30–45, 45–60, 60–75, 75–90, 90–105, 105–120, and 120–150 cm below the soil surface. Phenology studies included measurements of crop height, leaves number, panicle length and weight, dates of crop development stages and seed yields.

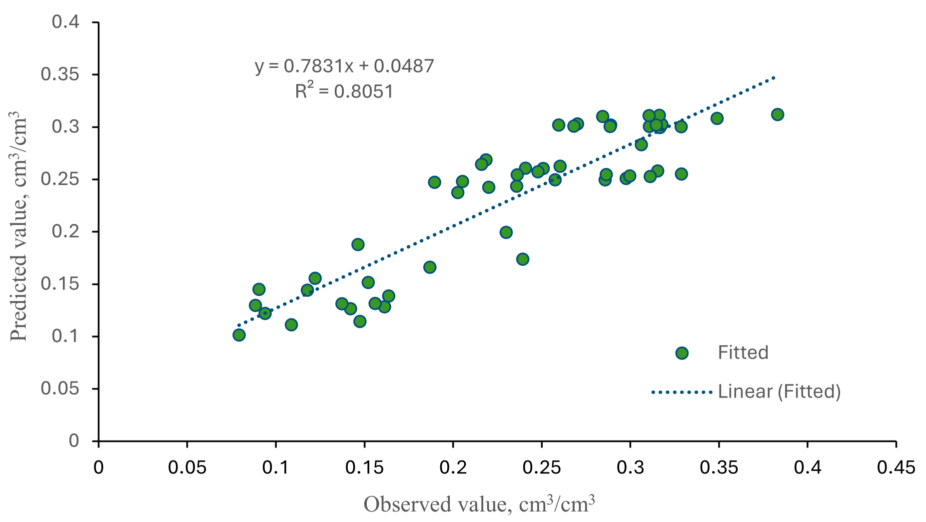

FIGURE 3
Regression of predicted vs. observed values of SWC and related model evaluation indexes.

Seeds of amaranth plants were harvested in the beginning of October. Ten randomly selected plants were collected from the monitoring spots at the time of harvest to measure growth parameters consisting of height of plants, leaf number, stem and leaf fresh and dry weights. Plants, harvested below the first leaf node were weighted. The dry weight was determined after drying the plant material at 40°C in a forced air oven. Leaf to stem weight ratio was calculated.

2.5 Modeling studies

To make the results of the field experiment more generic and applicable, this study applies the model HYDRUS 1D (Šimůnek et al., 2008a), which was developed jointly by the U.S. Salinity Laboratory of the USDA, Agricultural Research Service, and the University of California, Riverside to simulate water flow and solute transport processes in soils and groundwater under different crop production and irrigation strategies. To our knowledge, the HYDRUS model has not been applied for Amaranth crop. This study used the HYDRUS 1D software to examine the effects of deficit irrigation on potential water savings and to estimate amaranth crop transpiration and evaporation. The research question of this study was to estimate T/ET ratio under full (FI) and deficit (DI) irrigation, in order to contribute to the discussion on water saving effect of drip irrigation.

For this reason, the HYDRUS-1D modeling was involved based on inverse solutions from historical data parameters (e.g., soil hydraulic properties, root water uptake). This approach helps improve model accuracy and reliability by calibrating it against real-world conditions.

Silt loam soils, dominating in the study area, were selected for this modeling. Results of the field studies were base for this analysis. The results of the modeling exercise could contribute to the discussion on water saving potential of drip irrigation and options available for enhancing the food security through planning C4 crops in the river basins that are prone to water scarcity, and are facing water and land use challenges similar to the mid-stream of the Syrdarya River.

The HYDRUS 1D software package is a finite-element numerical model, which simulates the one-dimensional movement of water, heat and multiple solutes in variably-saturated porous media (Šimůnek et al., 2008a). The model has been previously used and verified in a number of studies (Šimůnek et al., 2008a, 2008b). For instance, Forkutsa et al. (2009) used the HYDRUS-1D model to simulate irrigated cotton with shallow groundwater on loam and sandy loam soils of the Khorezm region located in the Amudarya River downstream. Shouse et al. (2011) used the model to simulate root water uptake from a shallow saline groundwater. Since the system modeled in our study is similar to these studies, hence HYDRUS-1D is a robust choice for our analysis.

The HYDRUS-1D model simulates variably-saturated water flow by solving the Richards equation (Equation 1), written as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} K \left(\frac{\partial h}{\partial z} + 1 \right) - S, \tag{1}$$

where θ is the volumetric water content (cm^3/cm^3), t represents time (day), z is the vertical coordinate (positive upward), h denotes the pressure head (cm), K is the unsaturated hydraulic conductivity [cm/day], and S is the soil water extraction rate by plant roots (cm^3/cm^3/day).

The model estimates the potential crop evapotranspiration using the Penman-Montheith equation (Allen et al., 1998). Details of the numerical approach used in the model are given by Šimůnek et al. (2008a). Based on the result of numerical simulations, the yield and water productivity of alternative cropping systems were estimated (Equation 2). The yield of crops was found using the FAO's expression of the yield response to ET (Steduto et al., 2012):

$$\left(1 - \frac{Y_a}{Y_x}\right) = k_y \left(1 - \frac{ET_a}{ET_x}\right), \tag{2}$$

where Y_x and Y_a are the maximum and actual yields, ET_x and ET_a are the maximum and actual evapotranspiration, and k_y is a yield responses factor, representing the effect of a reduction in evapotranspiration on yield losses.

The upper boundary condition was defined in HYDRUS-1D using the atmospheric boundary condition with a surface layer. The meteorological parameters were measured at the Tyuabuguz weather station, located at a longitude of 69.25°, a latitude of 41.04°, and an elevation of 396 m asl. They included daily maximum and minimum air temperatures (°C), relative humidity (%), sunshine hours, rainfall (mm), and wind speed (km/day). The lower boundary condition was set to a free drainage since groundwater table at the research site is at 4 m depth below the ground. The solute stress was not considered in the modeling exercise. Soil texture and soil bulk density data obtained from the research site were used in the model. The calculation depth of the soil profile was 1.60 meter. The soil texture throughout the entire soil profile was found, according to the USDA classification, to be silt loam, excluding soil layer of 63–91 cm where soil texture is loam. For the purpose of numerical modeling, the soil profile was divided into 9 numerical layers and grouped into two soil materials, determined by a soil description. The canopy ground cover was used to calculate the potential evapotranspiration, and to separate from it soil evaporation and transpiration.

The root water uptake method proposed by Feddes et al. (1978) and modified by van Genuchten (1980) was used to describe water stress conditions (Equation 3). The study used exponential distribution of roots proposed by Vrugt et al. (2001):

$$\beta(z) = \left[1 - \frac{Z}{Z_m}\right] e^{\frac{Pz|Z* - Z|}{Zm}} \tag{3}$$

where *β(z) is* the dimensionless spatial root distribution with depth, Zm is the maximum rooting depth (L), Z* (L) represents the soil depth with the highest concentration of roots, and Pz (−) is an empirical shape parameter.

The advantage of the applied formula ([3]) over the linear distribution of roots lies in its ability to characterize root density profiles with varying degrees of 'linearity' or 'exponentiality', in accordance with the Pz parameter, that is important for systems with drip irrigation, when roots have high density in the upper 0–40 cm zone and less intensive below. The study used a piecewise linear formula, represented as a shape factor given in Figure 4, for water uptake reduction due to water stress proposed by Feddes et al. (1978).

The crop development is given in the model using a daily crop height, soil crop cover and a root depth (Table 2). Crop parameters were different for the full and deficit irrigation scenarios, simulated in the model.

The van Genuchten-Mualem model (van Genuchten, 1980) with an air-entry value of −2 cm was selected to obtain a predictive equation for the unsaturated hydraulic conductivity function. The soil texture and bulk density was used in the Rosetta Lite v. 1.1 to determine initial values of the van Genucthen-Mualem parameters, describing the soil hydraulic properties of each layer (Table 3). Then, these values were modified by the inverse solution with input of soil moisture data from the amaranth field. Modified values of the parameters are given in Table 3, where Q_{res} is the residual soil water content, Q_{sat} is the saturated soil water content, a and n are shape parameters, K_s is the saturated soil hydraulic conductivity, and l is the pore-connectivity parameter (Table 4).

Using these parameters, simulations were carried out for a period of 188 days. Climate data from the Tyuabuguz climate station were used from April 3, 2022 to October 1, 2022, representing climate conditions during the field studies.

3 Results and discussion

3.1 Calibration of soil water content parameters (inverse solution)

Figure 3 shows the correlation between predicted and observed SWC parameters used in the inverse solution during the calibration of the two modeled drip irrigation regimes for amaranth. The results

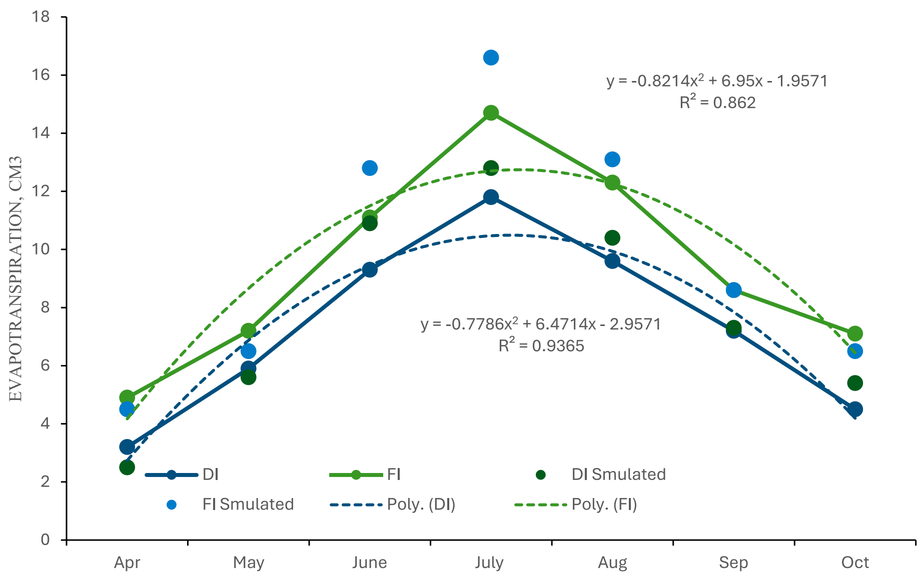

FIGURE 4
Simulated and observed evapotranspiration coefficient under full (FI) and deficit (DI) conditions during amaranth growth.

TABLE 2 Two regimes of irrigation of amaranth—full irrigation (FI) and deficit irrigation (DI), tested at the research site.

Treatments	Unit	Irrigation application dates			Total irrigation, m^3/ha
		June	July	August	
Full irrigation (FI)	m^3/ha	600	700	510	1810
Deficit irrigation (DI)	m^3/ha	300	350	255	905

TABLE 3 Main crop parameters for amaranth*.

Crop parameters	Unit	Amaranth
Crop height, max	cm	225
Root depth, max	cm	80
LAI/Crop cover, max		1
Crop vegetation season		03/04–1/10
Crop harvesting at		7/10
Yield, max	t/ha	3

*Data from field studies.

indicate a strong correlation between simulated and observed data, especially in SWC in the 0–30 cm soil layer where significant fluctuations occur between the irrigation treatments. In contrast, deeper soil layers exhibit more stable water content variations. The simulation accuracy remained consistent, with a moderate correlation coefficient (R^2 = 0.8051) between predicted and observed soil moisture values.

Despite notable differences between the two irrigation treatments, the average deviation between simulated and observed values was 3.2%, with a maximum deviation of 7.4%. The error between predicted and observed values might related to the difference of air temperature, solar radiation and precipitation. The model's parameterization of soil hydraulic properties was effectively achieved, as evidenced by these strong fitting results. This is further supported by the close alignment between measured and simulated matric potentials while maintaining consistency across multiple performance indices (Han et al., 2015; Angaleeswari and Ravikumar, 2019).

The error between predicted and observed root water uptake values was slightly adjusted, as shown in Table 5. Since the HYDRUS database does not include specific root water stress parameters for amaranth, parameters from another C4 crop were initially used and subsequently modified to maximize the R^2 value for the regression of predicted versus observed data (Hupert et al., 2003; Krounbi, 2011; Hartmann et al., 2017) (Table 2). The optimization process for the maximum value was conducted using the following constraints: −100 cm ≥ P2H ≥ −200 cm; −300 cm ≥ P2L ≥ −600 cm; −2000 cm ≥ P3 ≥ −35,000 cm.

As highlighted in previous studies, understanding the limitations of the calibration process and the interactions between input parameters is essential to ensure the accuracy and practicability of the model (Boulange et al., 2025). The HYDRUS-1D model, used in this two-year experiment, demonstrated near-optimal performance in accurately predicting SWC and other parameters. These results align with previous findings (Yu et al., 2022; Zhang, 2023), highlighting the importance of system modeling to develop efficient management approaches for irrigated agriculture and achieve maximum returns (Li et al., 2023).

3.2 Water use efficiency

The results displayed in Table 6 show that under total water availability (irrigation, precipitation, and soil moisture reserves) of 531 mm, the actual root water uptake (Ta) for amaranth was 247 mm, with evaporation accounting for 42.3 mm under full irrigation. The actual yield of the amaranth crop was 67% of its potential, and water productivity reached 0.69 kg/m^3. Unproductive evaporation losses represented 15% of the total water consumption, while the remaining water was used for productive processes.

Under DDI, crop transpiration reduced by 24.9%, and actual evapotranspiration (ETa) decreased by almost two times than that of FDI. During the vegetative development stage, the application of DDI decreased soil evaporation by 16 mm and crop transpiration by 125.1 mm as compared to the FDI regime. A substantial difference in actual crop evapotranspiration potential (ETp) between FDI and DDI reached 18.0 cm^3/yr., while the difference in actual crop evapotranspiration (ETa) between the two irrigation treatments was 14.11 cm^3/yr. These findings align with the widely promoted use of drip irrigation technologies in arid and semi-arid regions to reduce soil surface evaporation (Quan et al., 2024; Zubillaga et al., 2021). Water productivity,

TABLE 4 Van Genuchten-Mualem parameters describing soil hydraulic properties.

Soil layer, cm	0–65	65–160
Soil type/Parameters	Silt loam	Loam/Silt loam
Q_{res} [cm^3/cm^3]	0.010075	0.0010
Qs_{at}[cm^3/cm^3]	0.39859	0.50
a [−]	0.00021631	0.00018757
N [−]	1.9721	2.5
K_s [cm/d]	0.23848	0.1
I [−]	0.94035	0.001

TABLE 5 Root water uptake – water stress reduction parameters (Feddes et al., 1978) used in the HYDRUS model.

Root water uptake parameters	Unit	Amaranth (Initial value)	Amaranth* (Modified)
PO	cm	−17.2	−15
POpt	cm	−94.4	−30
P2H	cm	−10623.2	−200
P2L	cm	−1,500	−300
P3	cm	−28468.2	−15,000
r2H	cm/day	0.5	0.5
r2L	cm/day	0.1	0.1

Modified value obtained by the inverse solution. *Modified by maximizing RSQUARE for regression of predicted vs observed in the inverse solution.

TABLE 6 Water use of amaranth crop under full and deficit irrigation.

Parameters	Index	Unit	Full drip irrigation (FDI)	Deficit drip irrigation (DDI)
Potential transpiration	Tp	cm^3/yr	41.58	25.18
Evaporation	E	cm^3/yr	4.23	2.63
Crop evapotranspiration potential	ETp	cm^3/yr	45.81	27.81
Precipitation	P	cm^3/yr	12.35	12.35
Irrigation, net	I	cm^3/yr	18.10	9.05
Transpiration	T	cm^3/yr	24.68	12.17
Actual crop evapotranspiration	Eta	cm3/yr	28.91	14.802
Yield maximum	Ym	kg/ha	3,000	3,000
Yield actual	Ya	kg/ha	2004	1,604
Water productivity (Ya/ETa)	WP	kg/m^3	0.69	0.108

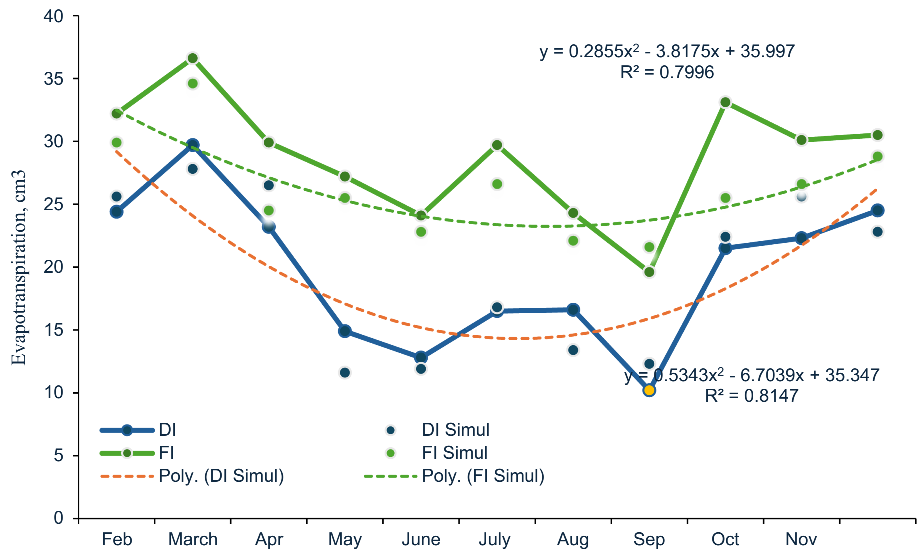

FIGURE 5
Simulated and observed soil moisture content under full (FDI) and deficit (DDI) conditions during amaranth growth.

often referred to as water-use efficiency, was 0.69 kg/m^3 for FDI and 0.108 kg/m^3 for DDI.

The higher water productivity observed under the DDI treatment is attributed to a significant reduction in soil evaporation and actual crop evapotranspiration during the vegetative development stage. This increase may be attributed to the C4 photosynthetic pathway of the amaranth crop and site-specific crop physiology which enhances water-use efficiency under water-limited conditions (Jamalluddin et al., 2021). The root system penetrated deeper under DDI, with 67% located in the 0–30 cm soil layer, compared to 91% under FDI. This may be because improved irrigation level under FDI increased the root system's volume, allowing to absorb more water and nutrients (Alrajhi et al., 2017). Introducing drip irrigation in water-scarce areas, where timely irrigation is not always possible, may reduce crop transpiration (Nyathi et al., 2018; Pulvento et al., 2022). However, the amount of unproductive evaporation may remain unchanged as shown by the results of the field studies.

As shown in Figure 4, the evapotranspiration coefficient increased with rising air temperatures, reaching its peak in July for both irrigation regimes. During this period, the highest total actual evapotranspiration was recorded at 14.7 cm^3 for FDI and 11.8 cm^3 for DDI. The results of the Pearson correlation analysis for ETp showed strong correlation between the simulated and observed data for both irrigation regimes, $R^2 = 0.862$ for FDI and $R^2 = 0.936$ for DDI.

Soil evaporation reduced as the water deficit increased. Consistent with this observation, previous studies also confirmed that high evapotranspiration might generate good biomass accumulation and crop yield depending on environmental conditions (Delgoda et al., 2016; Jo et al., 2021). Therefore, evapotranspiration was generally higher under FDI than DDI throughout the vegetation period, providing substantial ratio of the two indicators (Figure 5).

During the hot growing season - June, July, and August, soil moisture in the FDI plot was 11.3, 13.27, and 7.7% higher in the 0–30 cm monitored soil layer, respectively, compared to the DDI plot. The lowest soil moisture content (10.2% for DDI and 19.6% for FDI) was recorded in September when irrigation ceased as the crop entered the ripening phase. Soil drying during the seed-filling stage did not significantly affect crop yield

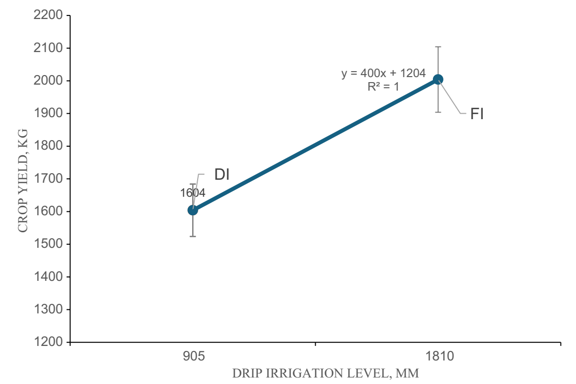

FIGURE 6
The relation between yield of amaranth and seasonal irrigation using drip system.

components. This indicates that amaranth exhibits tolerance to soil drying at this growth phase, as the crop had already achieved maximum growth and absorbed sufficient nutrients before drought occurred. Additionally, deficit irrigation can enhance water productivity and conserve substantial amounts of irrigation water (Fasinmirin et al., 2008; Bhavsar et al., 2023).

The accuracy of the simulation decreased as the growth stages progressed, while the highest error points were observed during hot summer period. At the same time, a high level of agreement was found between the predicted and observed values ($R^2 = 0.79$ for FDI and $R^2 = 0.81$ for DDI) and did not exhibit a distinct pattern. This outcome indicates that the HYDRUS-1D model can accurately predict soil moisture under drip irrigation. Furthermore, the error between the predicted and observed values was slightly larger in the FDI regime compared to the DDI treatment.

3.3 Crop yield

According to Figure 6, better moisture availability in the FDI plot supported productive crop growth, which was also influenced by irrigation levels. The results of amaranth yield were contradictory. With an irrigation application of 1810 m^3/ha, the yield reached 2 t/ha. When the irrigation amount was reduced by 50% to 905 m^3/ha, the yield decreased by 25%, while water productivity increased by 56.5%. This indicates that reducing irrigation improved water-use efficiency, although it led to a moderate decline in crop yield.

Amaranth contains a high percentage of sugar as compared plants have strong, wide stems and leaves, and this is probably a reason for significant losing the biomass under the low-rate irrigation.

The results of the field studies showed amaranth did illustrate good tolerance to water scarcity at 50%, water productivity is even increased by 56.5% under the scarce water treatment. A strong correlation was observed between the irrigation rate and amaranth yield ($R^2 = 1$), highlighting that adequate irrigation is a key factor in achieving optimal crop yield. Furthermore, the estimated yield data from field experiments exhibited errors below the acceptable level ($p < 0.05$). As expected, FDI produced a higher yield, likely due to improved irrigation levels that expanded the area available for the root system to absorb water and nutrients. It is important to note that water and nutrient uptake are significantly influenced by soil texture and water-holding capacity (Lakhiar et al., 2024).

The modeling exercise indicated that deficit irrigation using a drip system can enhance the water productivity of this C4 crop, with water shortages being mitigated by the crop's drought-tolerance mechanisms rather than relying solely on irrigation water in the soil (Joshi et al., 2018; Jain, 2023). Existing studies also confirmed that the rational allocation of limited water to crops based on their water demand through drip irrigation can mitigate water shortages by enhancing water use efficiency (Homaee, 1999; Dizyee et al., 2020; Abioye et al., 2023).

The HYDRUS-1D model is designed to enhance water use efficiency and has demonstrated its effectiveness in mitigating water shortages by facilitating the precise allocation of limited water resources according to the site-specific demands of crops. In the context of climate change, implementing drip irrigation alongside precise and digitalized simulation models is essential to improve efficiency and support environmental sustainability (Morcillo et al., 2025). In addition, innovative farming methods such as mulching the soil surface, conservation agriculture, and the application of hydrogels that must be adapted to suit drip irrigation systems to enhance irrigation efficiency (Kahil et al., 2015; Allanov et al., 2019).

To our knowledge, this water-saving agricultural research pioneered to present the effectiveness of implementing innovative drip irrigation technologies in association with the HYDRUS-1D model for amaranth production on irrigated agricultural lands and to alleviate water shortages in arid regions.

4 Conclusion

This study facilitated proactive adjustments of drip irrigation and the Hydrus-1D model for amaranth production that provided an opportunity to disclose unexpected impacts of introducing precise irrigation technologies. Compared to the FDI regime, amaranth under DDI improved water productivity by 56.5%. However, the highest crop yield (2004 kg/ha) was achieved under FDI, surpassing the yield under DDI (1,604 kg/ha) over the two-year period.

The findings of this study indicate that combining drip irrigation with the HYDRUS-1D model offers a smart and robust strategy to enhance water use efficiency in crop production, thereby increasing climate resilience in arid regions. These technological advancements can serve as an efficient and reliable tool for evaluating crop water efficiency while maintaining potential yield and minimizing water waste in arid regions.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AK: Conceptualization, Investigation, Writing – review & editing, Writing – original draft, Supervision, Software. BaK: Data curation, Conceptualization, Software, Writing – original draft, Writing – review & editing. SI: Writing – original draft, Methodology, Writing – review & editing, Data curation, Investigation. OS: Writing – review & editing, Investigation, Resources, Writing – original draft, Validation. KK: Writing – original draft, Visualization, Data curation, Writing – review

& editing, Methodology. MA: Conceptualization, Methodology, Validation, Writing – review & editing, Writing – original draft. AI: Investigation, Resources, Writing – review & editing, Writing – original draft, Formal analysis. PB: Writing – original draft, Software, Investigation, Writing – review & editing. AD: Methodology, Writing – review & editing, Formal analysis, Validation, Writing – original draft. Y'lM: Software, Investigation, Writing – original draft, Writing – review & editing, Conceptualization. NR: Software, Writing – original draft, Methodology, Writing – review & editing. GM: Formal analysis, Writing – original draft, Writing – review & editing, Methodology. SK: Data curation, Writing – review & editing, Formal analysis, Writing – original draft. KA: Writing – original draft, Writing – review & editing, Resources, Conceptualization, Investigation. BoK: Project administration, Writing – review & editing, Validation, Supervision, Writing – original draft, Formal analysis.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

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