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Water use and yield response of rainfed safflower (*Carthamus tinctorius* L.) in Vertisols with varying soil depths

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Abstract

Safflower (*Carthamus tinctorius* L.) is an edible oilseed crop mainly cultivated in marginal lands. This study evaluates safflower crop water requirements to understand its feasibility to cultivate under rainfed ecosystem through a field experiment undertaken at the International Crops Research Institute for the Semiarid Tropics research farm, India. Eight improved and stress-tolerant safflower cultivars (five spiny and three non-spiny) were evaluated in Vertisols at three soil depths, that is, shallow: <0.60 m, medium: 0.60–1.20 m, and deep:1.20–1.80 m, over 3 years (2009–2012). Wet, normal, and deficit rainfall years were experienced during 2009/2010, 2010/2011, and 2011/2012, respectively. Soil moisture, crop yield, and growth parameters were measured, and field-scale hydrology was captured through a calibrated one-dimensional water balance model. Safflower responded to available residual soil moisture which varied with soil depth and rainfall received in different years. Total crop water use was 300–320 mm during the postrainy season, of which about 70% was extracted in deep Vertisols and 55% in medium Vertisols through residual soil moisture. In addition, 30% of water requirement was met through postrainy season rainfall. Safflower grown in shallow Vertisols could only meet 40% of crop water requirement. Spiny cultivar NARI-H-15 grown in deep soil recorded a maximum yield of 1890 kg ha^{-1} in the wet year. Seed yield from spiny cultivars grown in deep and medium soils was nearly similar (1500–1600 kg ha^{-1}) during wet and normal years; a significant reduction in yield (>50%) occurred in shallow soils and also during a rainfall deficit year. Spiny cultivars produced 10%–50% higher seed yield compared to non-spiny cultivars. Growing safflower in medium and deep Vertisols provides opportunities for crop intensification.

1 | INTRODUCTION

Safflower (*Carthamus tinctorius* L.) is a drought-tolerant oilseed crop mainly cultivated in marginal lands and with low inputs in the arid and semiarid tropics (Bijanzadeh et al., 2022). With growing demand for vegetable oils, safflower is a feasible option to meet global demand for edible oil when grown under conditions of limited land and water (Abdipour et al., 2019; Bouhouhou & Mohamed, 2016; Hamza & Abdalla, 2015). In India, safflower is cultivated in the postrainy season (September/October to January/February),

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Abbreviations: ET, evapotranspiration; ICRISAT, International Crops Research Institute for the Semiarid Tropics; WIC, water impact calculator.

mostly in Vertisols (DoR, 2007). India ranked fifth in global safflower production (64,000 tonne) from 84,000 ha in 2022/2023, which is 10% of global production. However, safflower yield in India is relatively low (767 kg ha^{-1}) compared to the global average of 859 kg ha^{-1} (ICAR-IOR, 2015). This low productivity in India is due to various factors such as high temperature and scarcity of water during its growth, cultivation on degraded lands, low mechanization, and knowledge of production practices among the farmers (ICAR-IOR, 2015). Another constraint in its cultivation is the spiny leaves that hinder harvesting. Therefore, efforts are ongoing to develop non-spiny cultivars that will facilitate harvesting and increase the area under them (V. Singh & Nimbkar, 2018).

In a resource-limited country like India, where food and water demands of the growing population are rapidly increasing (Biggs et al., 2007), enhancing resource use efficiency is critical. Preference for irrigation water is given to staple crops such as paddy rice, wheat, and cash crops like sugarcane. However, there is a need to harness the huge untapped potential of rainfed ecologies adopting a range of landscape and crop management technologies (Anantha et al., 2021, 2022; Molden et al., 2007; R. Singh et al., 2022). In the rainfed ecology of India (i.e., 45% of total cultivable land), agricultural land is single cropped despite receiving moderate to good rainfall (700–1100 mm), and significant area remains fallow, particularly during the postrainy season (Gautam et al., 2021). It is estimated that nearly 19.6 million ha in different states of India are left fallow during the postrainy season (Gumma et al., 2016), of which 11.7 million ha are rainfed. Safflower is moderately tolerant to water stress and salinity (Bassil et al., 2002) and has a strong taproot that may utilize in situ soil moisture from subsurface layers (Weiss, 2000).

Safflower taproots anchor down to a soil depth of 2.2 m and can efficiently use available soil moisture to fulfill the crop's water requirement (S. Singh et al., 2016). Usually, preseason irrigation is recommended to prevent water stress, especially when irrigation systems cannot meet peak water requirements during in-season growth stages (Schlegel et al., 2012). Though there is limited extraction of water from the deeper profile, moisture stored from the previous season can significantly cushion stress at critical growth stages, reduce the competition for in-season irrigation, and contribute to yield (Bhattarai et al., 2020).

Even though there is information on water and agronomic management in safflower (Bijanzadeh et al., 2022; Istanbulluoglu, 2009; S. Singh et al., 2017), there is limited understanding about crop water requirement, particularly in rainfed ecologies. To address these issues, the current experiment was designed in a micro-watershed of Vertisols at International Crops Research Institute for the Semiarid Tropics (ICRISAT) in Hyderabad, India. Soils have a natural variability in soil depth within a 200-m transect and are characterized by different soil moisture regimes. We hypothesized that soil depth is one of the major factors determining yield potential in the given landscape in a rainfed ecology.

The objectives of this study include (1) evaluating safflower production in spiny and non-spiny cultivars at various soil depths (shallow, medium, and deep) in Vertisols; (2) estimating crop water requirement and developing a production function for safflower, that is, the relationship between evapotranspiration (ET) and crop yield; and (3) assessing the technical and economic feasibility of cultivating safflower under different typologies in a rainfed system.

Core Ideas

- Safflower, cultivated during the postrainy season in semiarid tropics, requires 300–320 mm of water.
- Residual soil moisture contributes about 30%–35%, 50%–60% and 65%–80%, of the crop's water requirement in shallow, medium, and deep Vertisols.
- Yield potential of safflower grown in shallow Vertisols was low and was constrained due to moisture stress in the rainfed ecology.
- Spiny safflower cultivars performed better (10%–50% higher yields) compared with non-spiny cultivars.

2 | MATERIALS AND METHODS

2.1 | Site description

The ICRISAT, Patancheru, India, is at 17.53° N latitude and 78.27° E longitude (545 m.s.l.). Rainfall is highly erratic, both in total amount and its distribution over time. The mean annual rainfall at the site is 850 mm, of which 85% is from June to September. Rainfall data show that moisture stress longer than 5–7 days are common and occur three to eight times per season. Moisture stress lasting 10–15 days or longer may also occur during the rainy season (Garg et al., 2022a). Post monsoon season in this region experiences moderate winter (minimum air temperature between 10°C and 16°C and maximum air temperature between 26°C and 30°C in January), followed by a hot summer (minimum air temperature 21°C–26°C and maximum air temperature 33°C–40°C in May). Strong winds are common during the rainy season, particularly at the beginning, and average wind speeds of up to 30–32 km h^{-1} are possible in June. Sunshine varies from 4 to 10 h during the rainy season (average of 5 h during June–October) and 6–11 h during the postrainy season (average of 8 h during November–May) (Rao & Wani, 2011).

TABLE 1 Biophysical properties of soils used in evaluating rainfed post-monsoonal water use and yield response of safflower at different soil rooting depths, International Crops Research Institute for the Semiarid Tropics (ICRISAT), Patancheru, India (2009/2010–2011/2012).

Parameters	**Shallow**		**Medium**		**Deep**	
Number of samples analyzed	10		11		11	
Soil depth (m)	<0.60		0.60–1.20		1.20–1.80	
Plant extractable water (mm)	80		160		230	
Physical properties						
Soil layers (m)	0–0.15	0.15–0.30	0–0.15	0.15–0.30	0–0.15	0.15–0.30
Sand (%)	23	21	22	22	22	22
Silt (%)	20	19	19	19	20	21
Clay (%)	57	60	59	59	58	59
Bulk density (kg m^{-3})	1380	1420	1400	1440	1390	1430
Organic C (g kg^{-1})	7.8	5.5	8.0	5.6	8.0	5.4
Field capacity (m^3 m^{-3})	0.50	0.51	0.52	0.50	0.52	0.50
Permanent wilting point (m^3 m^{-3})	0.31	0.32	0.33	0.32	0.33	0.32
Soil nutrient parameters						
pH	7.4	7.7	7.4	7.9	7.3	7.9
Electrical conductivity (ds m^{-1})	0.2	0.2	0.2	0.2	0.2	0.2
Available sulfur (mg kg^{-1})	6.1	3.5	6.2	3.4	6.1	3.5
Available boron (mg kg^{-1})	0.29	0.20	0.30	0.22	0.30	0.22
Available zinc (mg kg^{-1})	0.82	0.60	0.86	0.63	0.86	0.64
Available phosphorous (mg kg^{-1})	13	09	15	11	15	14
Available potassium (mg kg^{-1})	200	140	210	160	212	160

Both Alfisols and Vertisols are found on the ICRISAT campus. Since safflower is grown predominantly in Vertisols, this experiment was conducted in one of the heritage watersheds of Vertisols. The soils in the experimental watershed are black and belong to the very fine, clayey, montmorillonite, calcareous hyperthermia family of Typic Pellusterts (Pathak et al., 2013; Virmani et al., 1991). The watershed soil profile varies in depth from 0.40 to 1.50 m within a distance of 200 m, underlaid by a relatively coarse and hard-weathered material locally known as "*murrum*" (Pathak et al., 2016). The soil profile depth from the surface to the parent material (or hard bed) is relatively mild, with negligible root penetration below hard bed (Wei & Bing, 2014). Given the natural variability in soil depth, the whole watershed area was divided into shallow (<0.60 m), medium (0.60–1.20 m), and deep (>1.20 m) categories, with plant extractable water being 80, 160, and 230 mm, respectively (Table 1). Vertisols are self-mulching, exhibit cracking and swelling, harden when dry, and become sticky when wet. Under dry conditions, these soils develop deep and wide cracks, reflecting substantial shrinkage. The site's key physical and chemical properties are shown in Table 1.

The methodology followed in this study is outlined in Figure 1. Data collected from 3 years of field experiments were used to understand the performance of both spiny and non-spiny safflower cultivars. Soil moisture data collected from the research trial along with simulation modeling using the water impact calculator (Garg et al., 2016) were used to understand crop water requirement and capture field-scale hydrology, including actual ET at various soil depths. A safflower production function was developed (using measured crop yield and simulated ET) for spiny and non-spiny cultivars, which further estimated the technical and economic feasibility of safflower production in rainfed ecology.

2.2 | Details of field experiments

A 3-year field experiment was conducted during the postrainy seasons (October–February) of 2009/2010, 2010/2011, and 2011/2012. Eight safflower cultivars, including spiny (Annigeri-1, Bhima, Sharda, NARI-38, NARI-H-15) and non-spiny (NARI-6, PBNS-40, NARI-NH-1) varieties/hybrids (Table 2), were evaluated at three soil depths. The experiment was laid out in a randomized block design with two factors: (i) soil depth (shallow: <0.60 m, medium: 0.60–1.20 m, and deep: >1.20 m) and (ii) cultivars (spiny and non-spiny cultivars) (Figure 2). Each block was divided into 24 subplots to arrange eight cultivars with three replications randomly. Thus, the entire experimental setup was divided into 72 subplots (3 soil depths × [8 cultivars × 3 replications]). The size of each subplot was 30 m^2.

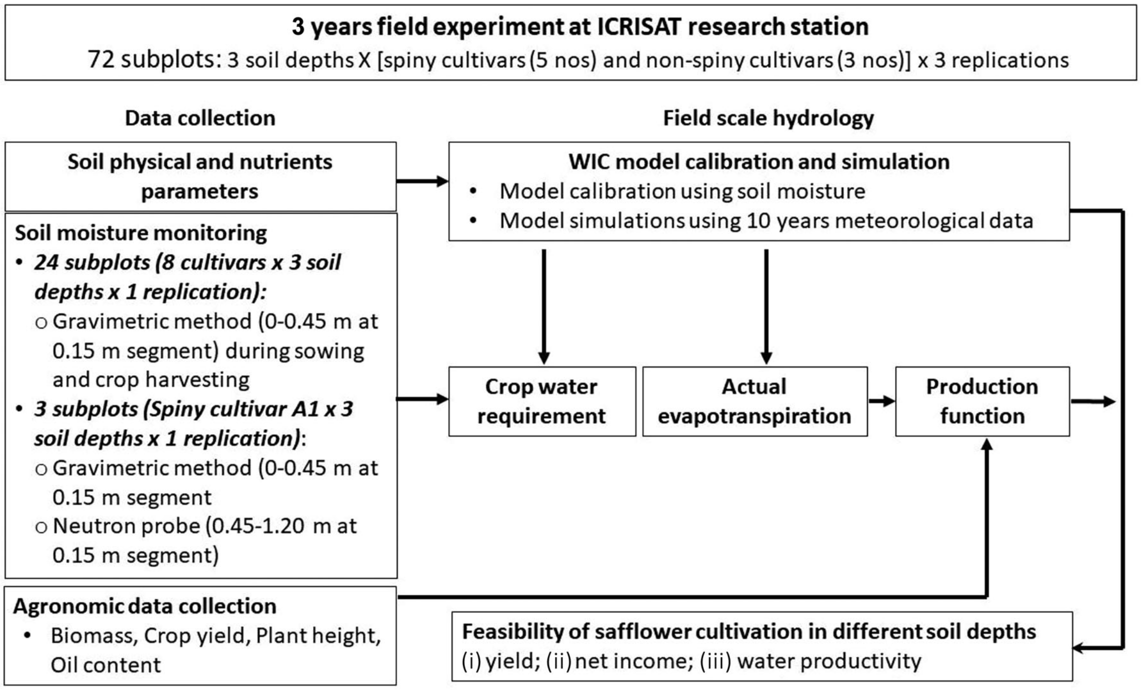


FIGURE 1 The methodology followed in 3 years field experiments describing number of subplots with cultivar types, soil moisture monitoring, and field-scale hydrology modeling and feasibility analysis to cultivate safflower in varying soil depths. WIC, water impact calculator.

TABLE 2 Test safflower cultivars evaluated and their main traits for evaluating rainfed post-monsoonal water use and yield response, International Crops Research Institute for the Semiarid Tropics (ICRISAT) research farm, Patancheru, India (2009/2010–2011/2012).

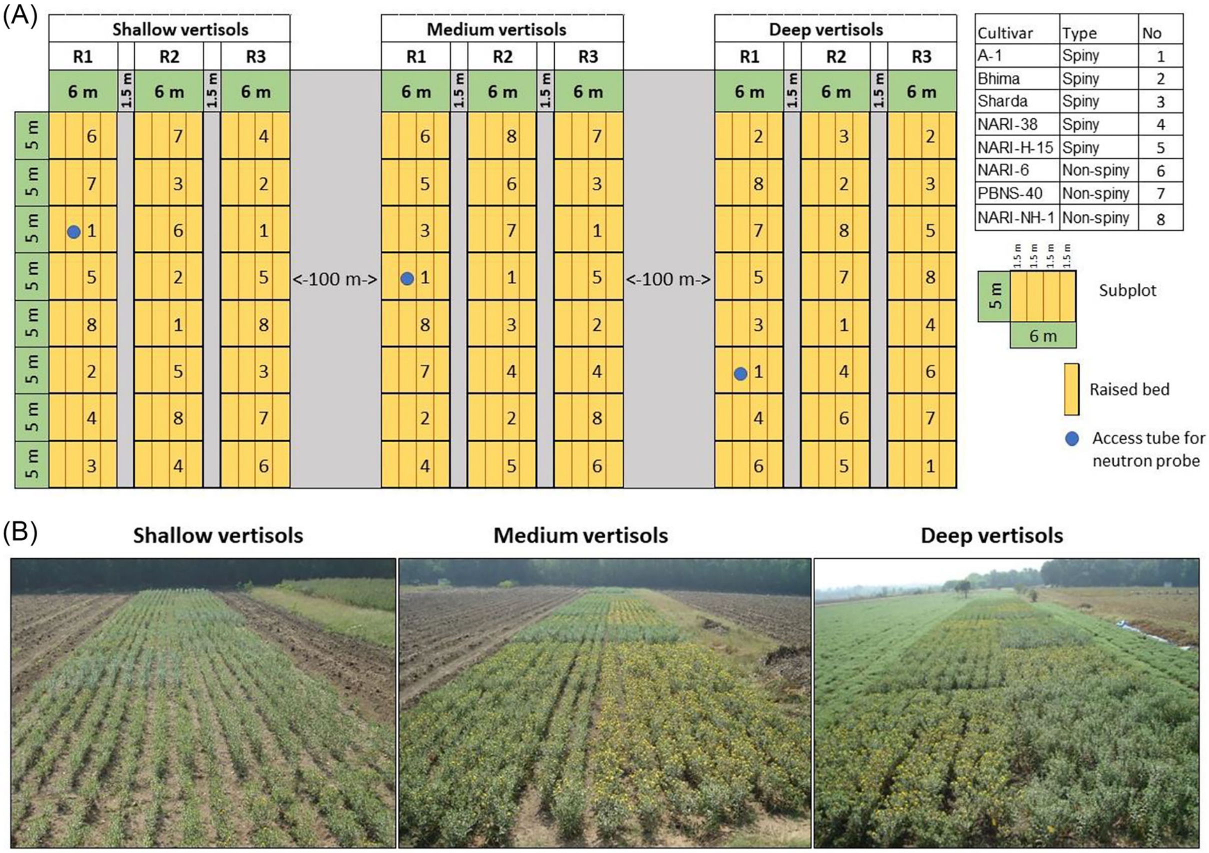
Cultivar	Type	Year of release	Oil content (%)	100 seed weight	Days to maturity	Traits
Annigeri-1 (A-1)[a]	Spiny	1969	28	5.1	125–130	Moderately tolerant to wilt, aphid
Bhima	Spiny	1982	29	5.3	135–140	Moderately tolerant to wilt, aphid
Sharda	Spiny	1990	29	4.7	125–130	Moderately tolerant to wilt, aphid
NARI-38	Spiny	2007	28	4.9	125–130	Moderately tolerant to wilt, aphid
NARI-H-15	Spiny	2005	28	4.3	126–129	Moderately tolerant to aphid
NARI-6	Non-spiny	2000	30	4.3	126–128	Moderately tolerant to wilt
PBNS-40	Non-spiny	2006	27	4.1	118–128	Moderately tolerant to wilt, Alternaria leaf blight and aphid
NARI-NH-1	Non-spiny	2002	30	4.5	127–130	Moderately tolerant to Alternaria leaf blight and aphid

[a] The test cultivar (benchmark) used to evaluate the performance of safflower.

Source: https://icar-iior.org.in/technology/cultivars/safflower

Safflower is sown on a raised bed (broad bed 0.9 m and furrow 0.6 m) with zero tillage immediately after harvesting the rainy season mung bean (*Vigna radiata* L.) crop. Raised bed is one of the improved management practices in drylands that facilitates the capture of additional moisture and also safely dispose excess surface runoff during heavy downpours (Garg et al., 2022b). A bullock-drawn tropicultor was used for sowing on broad bed (Maurya & Devadattam, 1990). Three rows of safflower (0.45 m apart) with seed rate of 10 kg ha^{-1} were sown on broad bed with 40:25:25 N:P_2O_5:K_2O kg ha^{-1} fertilizer application in rows. Plants were thinned 20 days after sowing (DAS) to maintain an intra-row spacing of 0.20 m. Aphids were controlled by spraying insecticide (Dimethoate 30 EC @ 0.06% concentration) during the vegetative stage twice every year.

Total rainfall received during both cropping seasons (June–February) was 995 mm in 2009/2010, 1121 mm in 2010/2011, and 525 mm in 2011/2012. The portion received during the safflower period (post-monsoon) was 225, 138, and 47 mm in 2009/2010, 2010/2011, and 2011/2012, respectively.



	Shallow vertisols			Medium vertisols			Deep vertisols		
	R1	R2	R3	R1	R2	R3	R1	R2	R3
	6 m	6 m	6 m	6 m	6 m	6 m	6 m	6 m	6 m
5 m	6	7	4	6	8	7	2	3	2
5 m	7	3	2	5	6	3	8	2	3
5 m	● 1	6	1	3	7	1	7	8	5
5 m	5	2	5	● 1	1	5	5	7	8
5 m	8	1	8	8	3	2	3	1	4
5 m	2	5	3	7	4	4	● 1	4	6
5 m	4	8	7	2	2	8	4	6	7
5 m	3	4	6	4	5	6	6	5	1

Cultivar	Type	No
A-1	Spiny	1
Bhima	Spiny	2
Sharda	Spiny	3
NARI-38	Spiny	4
NARI-H-15	Spiny	5
NARI-6	Non-spiny	6
PBNS-40	Non-spiny	7
NARI-NH-1	Non-spiny	8

FIGURE 2 (A) The experimental layout describing the size of the subplot, buffer distance, cultivar types, number of raised beds, and access tubes installed for moisture measurement (2009/2010–2011/2012) at International Crops Research Institute for the Semiarid Tropics (ICRISAT) research farm, Patancheru, India; (B) The snapshot of experimental layout depicting shallow, medium, and deep Vertisols showing the visible difference in crop growth at International Crops Research Institute for the Semiarid Tropics (ICRISAT) research farm, Patancheru, India.

TABLE 3 Sowing, harvesting dates, and days to maturity of safflower during the study period (2009/2010, 2010/2011, and 2011/2012) at International Crops Research Institute for the Semiarid Tropics (ICRISAT) research farm, Patancheru, India.

Year	2009/2010	2010/2011	2011/2012
Date of sowing	September 24, 2009	October 4, 2010	October 4, 2011
Date of harvesting	February 4, 2010	February 12, 2011	January 23, 2012
Days to maturity	133	131	111

Long-term rainfall data showed that the study area had received average annual rainfall of 887 mm (ranging widely from 494 to 1474 mm) during 1974–2021. During the 3 years of the study, the crop experienced mean maximum and minimum temperatures of 29.0˚C and 16.5˚C in 2009/2010, 28.7˚C and 16.0˚C in 2010/2011, and 30.3˚C and 15.6˚C in 2011/2012, respectively. In addition to deficit rainfall in 2011/2012, the crop experienced heat stress for 71 of 120 days (maximum air temperature of >30˚C) versus 41 days in 2009/2010 and 26 days in 2010/2011. The crop was sown in late September in 2009/2010 and in early October during 2010/2011 and 2011/2012. The crop was harvested at physiological maturity in the first/second week of February in 2009/2010 and 2010/2011 and late January in 2011/2012 (Table 3). The crop matured earlier by 20 days in 2011/2012. Plant stand was 85%–90% of seeding except in NARI-6 where germination was poor (~65%).

Soil moisture was measured using the gravimetric method to 0.45-m depth (in 0–0.15, 0.15–0.30, and 0.30–0.45 m segments) in 24 subplots (8 cultivars × 3 soil depths × 1 replication) during seed sowing and at maturity (Figure 1). In addition, soil moisture with spiny type Annigeri-1 in deep, medium, and shallow subplots was monitored at 15-day intervals in one of the replications. Soil moisture was measured at every 0.15-m segment using gravimetric methods at 0.45-m depth using a neutron probe (Troxler model 4302, Troxler Electronic Laboratories) between 0.45-m and 1.20-m depth (Figure 2).

2.3 | Model simulation

2.3.1 | Model description

Data collected from field experiments were used to analyze field-scale hydrology using a one-dimensional water balance model developed at ICRISAT (Garg et al., 2016, 2020). The following parameters were input into the model: (1) soil (water retention capacity and soil depth), (2) weather (ET_0 and rainfall), (3) crop growth (crop coefficients [k_c] and root growth function), (4) topography (land slope, landform conditions), and (5) crop management (date of crop sowing and harvesting). The water impact calculator (WIC) does the entire water balance on daily time scale per the mass balance approach (Equation 1).

$$\text{Rainfall} = \text{Surface runoff} + \text{deep percolation} + \text{ET} + \text{change in soil moisture storage} \qquad (1)$$

Surface runoff in the WIC was estimated by the Soil Conservation Service Curve Number method, in which the curve number is controlled by the antecedent soil moisture in the top layer (0.15 m), topography, and land management (UDSA-SCS, 1985). The amount of excess water infiltration after filling soil storage capacity drained out from a defined bottom boundary (called deep percolation). Evaporation and transpiration were estimated based on imposed surface boundary conditions (atmospheric boundary condition under rainfed system) and moisture accessibility between the soil's surface layer and the root zone. Available soil water in the top 0.10 m satisfies evaporation demand, whereas moisture available in the root zone meets the crop's water requirement. Crop water requirement is calculated as follows (Equation 2) (Garg et al., 2016):

$$\text{Crop water requirement}_{\text{day}=i} = [Kc]_{\text{day}=i} \times \left[\mathrm{ET}_0\right]_{\text{day}=i} \qquad (2)$$

$$\text{if}\ :\ \sum_{j=1}^{\text{rootzone}} \text{Available water}\ >\ \text{crop water requirements;}$$

$$\mathrm{ET}_{\text{day}=i}\ =\ \text{Crop water requirmenets}$$

$$\text{otherwise}\ \mathrm{ET}_{\text{day}=i} = \sum_{j=1}^{\text{rootzone}} \text{Available water} \qquad (3)$$

where i is days after sowing (DAS); j is each cm increment in soil layer reaching down to the root zone; K_c is crop coefficient; ET_0 is reference evapotranspiration; and ET is actual evapotranspiration. Root zone depth is a dynamic variable, controlled by crop growth stage (DAS) (Allen et al., 1998). It was assumed that evaporation from soil surface was inversely proportional to vegetative growth/stage (Tesfuhuney et al., 2015). Thus, after full vegetative growth ($K_c \geq 1.0$), evaporation from the soil surface was considered negligible. If moisture in the root zone did not adequately meet crop water requirements, then the WIC counted crop is under water stress situation (Equation 4). The WIC, model development, testing, and validation are described in Garg et al. (2016).

$$\text{Crop water stress} = 1 - \frac{\text{Actual ET}}{\text{ET under non - limiting water condition}} \qquad (4)$$

2.3.2 | Model set up and calibration

Layer wise soil moisture retention capacity at field capacity and permanent wilting point, soil depth, sowing, and harvesting details were input into the model. ET_0 was estimated using the Penman–Monteith method that measured weather parameters (maximum and minimum temperatures, solar radiation, wind speed, and relative humidity) (Allen et al., 1998). The weather parameters, such as rainfall and ET_0, were daily inputs into the model. Root growth pattern as defined by S. Singh et al. (2016) was used to capture stage-wise root growth in safflower under rainfed conditions.

Soil moisture measured at intervals in the subplots was used as an auxiliary variable for model calibration. In this process, crop coefficients were optimized at different growth stages and simulated soil moisture was compared with measured soil moisture. The model's functioning was tested by visual fit and statistical parameters as described in Section 2.5. In addition, estimated surface runoff in different years was compared with measured surface runoff from a neighboring experimental watershed with a runoff monitoring setup (Garg et al., 2022b).

2.3.3 | Production function of safflower

A linear relationship between crop yield and consumptive water use was fitted where relative yield reduction is related to the corresponding relative reduction in ET (Doorenbos & Kassam, 1979; Lovelli et al., 2007) (Equation 5; Stewart et al., 1977).

$$\left(\frac{Y_x - Y_a}{Y_x}\right) = K_y \left(\frac{\mathrm{ET}_c - \mathrm{ET}_a}{\mathrm{ET}_c}\right) \qquad (5)$$

where Y_x and Y_a are maximum and actual yields, respectively; ET_c and ET_a are maximum (non-stress) and actual ET (also known as consumptive water use), respectively; and K_y is correlation or proportionality factor between the related productivity loss and the related ET reduction (Lovelli et al., 2007). In the current study, the production function for safflower (simulated ET vs. measured crop yield) for spiny and non-spiny cultivars was ascertained from 3 years' field data. ET and other hydrological components in each of the treatment plots were estimated by applying the WIC.

2.3.4 | Safflower production potential

The production potential of safflower was analyzed using 10 years of historic rainfall and meteorological data collected at ICRISAT as input into the calibrated model. Three soil depths (shallow, medium, and deep) were simulated. Consumptive water use (ET actual) estimated from model simulations was used to calculate safflower's potential yield from the derived production function (Equation 5) for spiny cultivars. We further categorized the entire simulation period into deficit, normal, and wet years based on rainfall received. According to the India Meteorological Department, Pune, India (http://www.imdpune.gov.in), rainfall that is 20% lower than the mean (<709 mm) is categorized as a deficit year. Between -20% and $+20\%$ ($709 \text{ mm} < \text{rainfall} < 1064 \text{ mm}$) of the mean is a normal year. Rainfall greater than 20% (>1064 mm) of the mean is a wet or surplus year (IMD [India Meteorological Department], 2010).

2.4 | Crop water productivity and net income

Crop water productivity (WP) is the amount of grain yield obtained per unit of water consumption (Garg et al., 2012; Tuong & Bouman, 2003). Depending on the type of water source, WP is expressed as grain yield per unit of water evapotranspired (WP_{ET}). In this study, WP (kg m^{-3} of water) was calculated using estimated consumptive water use (ET) and crop yield in different years.

$$\text{WP}_{\text{ET}}\,(\text{kgm}^{-3)} = \frac{\text{Grain yield (kg)}}{\text{Consumptive water use (ET in m}^3)} \quad (6)$$

Gross income generated from the agricultural outputs (crop yield) was estimated from the market price. Subsequently, net income was calculated by subtracting cultivation cost from gross income. Further, economic water productivity (\$ m^{-3} of water) for all the treatment was calculated as defined in Equation 7:

$$\text{EWP}_{\text{ET}}\left(\$\ \text{m}^{-3}\right) = \frac{\text{Gross income generated}\left(\$\right) - \text{Cost of cultivation}\left(\$\right)}{\text{Consumptive water use}\left(\text{ET inm}^3\right)} \quad (7)$$

2.5 | Statistical analysis

Residual soil moisture data measured using neutron probe in selected subplots were compared with simulated soil moisture for different soil layers. The performance of the model was tested by estimating root mean square error (RMSE) and χ^2 test. Further, crop yield data obtained from different treatment plots were compared by performing *t*-test. An analysis of variance (ANOVA) was used to understand the significance of crop yield due to the soil depths and rainfall. Further, post hoc analysis was performed to understand the level of significance of different treatment groups/years. Statistical analysis was done using R package.

3 | RESULTS

3.1 | Water balance components

3.1.1 | Model calibration

Soil moisture response on the surface (0–0.15 m) and at a depth of 0.75–0.90 m in one of the subplots in medium soils with cultivar Annigeri-1, along with daily rainfall received during the 3 years of field experiments is presented (Figure 3). Simulated soil moisture and measured soil moisture were comparable. The RMSE obtained for simulated moisture was 4.5% (v/v) and 2.6% (v/v) (<10% of the total soil moisture and with satisfactory coefficient of determination ($R^2 = 0.89$ and $R^2 = 0.67$) at 0- to 0.15-m depth and 0.75- to 0.90-m depth, respectively. χ^2 test showed that the difference between observed and simulated values of soil moisture content was non-significant ($p = 0.8$). In addition, simulated runoff during the postrainy season was comparable with observed runoff (though it was measured at a micro-watershed 300 m away from the current site, which is used for another study). Runoff recorded during the postrainy season in 2009/2010, 2010/2011, and 2011/2012 was 28, 3, and 0.5 mm, respectively, while simulated runoff was 25–35, 1–2, and 0–2 mm from different subplots, respectively. The model's performance in capturing both runoff and soil moisture dynamics was satisfactory.

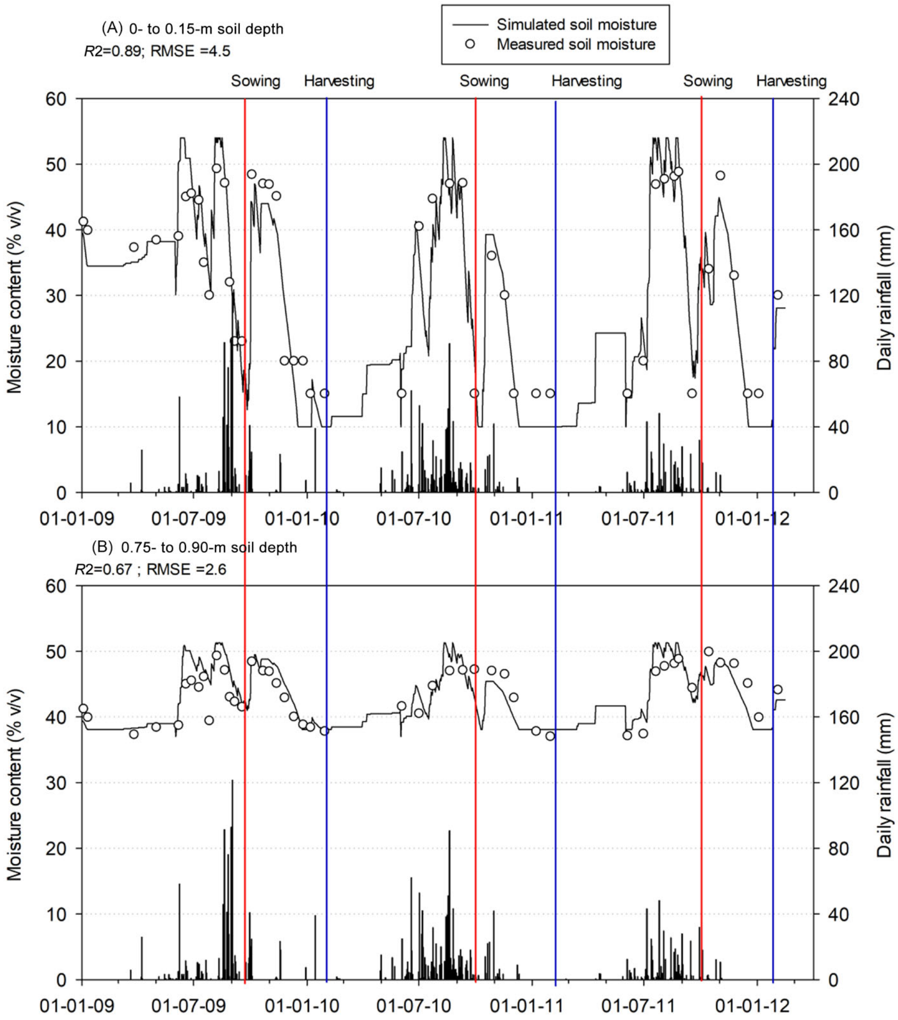


FIGURE 3 Periodic changes in soil water contents in surface 0.15 m and 0.75- to 0.90-m depth during study period in medium Vertisol. Vertical red lines indicate the sowing dates and vertical blue lines indicate harvesting dates in respective years.

3.1.2 | Soil moisture dynamics

Model calibration revealed that optimized crop coefficient (K_c) values for safflower cultivar Annigeri-1 were 0.60 for 0–30 days (germination and rosette stage), 0.85 for 31–60 days (stem elongation and branch initiation stage), 0.95 for 61–90 days (branching and flowering stage), and 0.30 for 91–120 days (seed filling and maturity stage) after sowing.

Moisture use at different soil depths starting from the surface layer of 0–0.15 m with every incremental depth of 0.15 m in a medium subplot during 2010–2011 is described (Figure 4). While each stack in the figure indicates the amount of moisture supplied by individual soil layers during the postrainy season, the different stack colors show the moisture used by the crop at different growth stages after sowing. Total moisture use was 265 mm. Surface 0.45 m soil contributed 150 mm, and the rest was from deeper soil. Of the total moisture withdrawn, 24% was used at 0–30 days, 30% at 31–60 days, 34% at 61–90 days, and 34% at 91–120 days. Deeper soil layers contributed for supplying moisture during the later stage of crop growth.

3.1.3 | Crop yield response to water availability

Year-wise measured yield from different treatment plots of spiny and non-spiny safflower cultivars with available residual soil moisture at the time of sowing is summarized in Table 4. The measured available soil moisture at 0–0.45 m ranged from 91 to 111 mm in shallow soils, 117 to 144 mm in medium soils, and 125 to 153 mm in deep soils. These moisture levels were equivalent to 45%–50% of the crop's total water requirement. In addition, 110–135 mm of additional water was received through postrainy season rainfall in wet and normal years. The crop's remaining water requirement was met from underlying soil layers in deep and medium soils. However, this was not possible from shallow soil subplots.

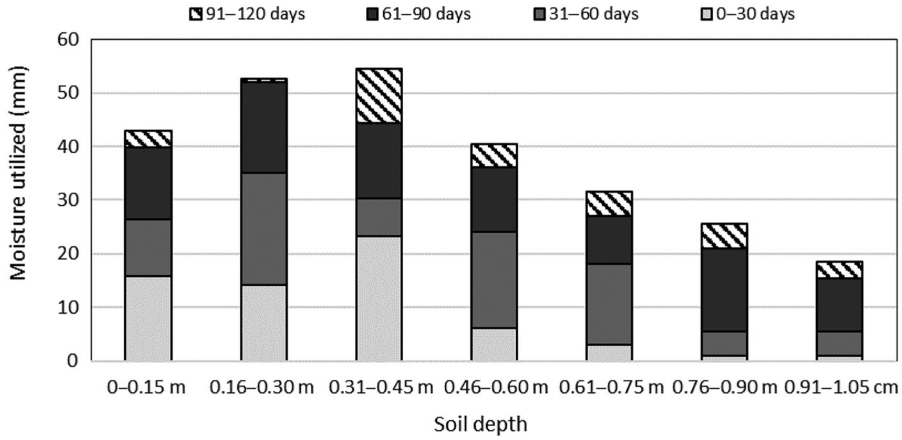


FIGURE 4 Moisture utilization at different soil depths in one medium subplot during different growth stages of the spiny cultivar Annigeri-1 during 2010-2011 (based on measured data).

TABLE 4 Water balance components, mean seed yield, and water productivity of spiny and non-spiny cultivars of safflower at different soil depths.

Year	Soil depth	Mean measured available soil moisture at 0–0.45 m at sowing (mm)	Rainfall Oct–Feb (mm)	Effective rainfall (Oct–Feb) (mm)[a]	Simulated ET (mm)	Mean seed yield (kg ha^{-1})	WP$_{ET}$ (kg m^{-3})
Spiny cultivars							
2009/2010	Shallow	111	225	115	220	753	0.34
	Medium	144	225	130	290	1498	0.52
	Deep	153	225	135	338	1696	0.5
2010/2011	Shallow	91	138	124	210	638	0.3
	Medium	134	138	123	280	1196	0.43
	Deep	145	138	117	333	1500	0.45
2011/2012	Shallow	114	47	44	140	236	0.17
	Medium	117	47	44	210	330	0.16
	Deep	125	47	44	245	652	0.27
Non-spiny cultivars							
2009/2010	Shallow	102	225	115	220	563	0.26
	Medium	144	225	130	290	798	0.28
	Deep	155	225	135	338	1487	0.44
2010/2011	Shallow	80	138	124	210	480	0.23
	Medium	140	138	123	280	707	0.25
	Deep	133	138	117	333	1233	0.37
2011/2012	Shallow	115	47	44	140	125	0.09
	Medium	119	47	44	210	162	0.08
	Deep	125	47	44	245	633	0.26

Abbreviations: ET, evapotranspiration; WP, water productivity.

[a] Effective rainfall = rainfall−surface runoff−deep percolation.

ET was a maximum of 338 mm in spiny cultivars in deep soil during 2009/2010 and a minimum of 140 mm in shallow soil during 2011/2012. For spiny cultivars, crop yield ranged from 236 (2011/2012) to 1696 kg ha^{-1} (2009/2010). For non-spiny cultivars crop yield ranged from 125 (2011/2012) to 1487 kg ha^{-1} (2009/2010). Water productivity ranged from 0.17 (2011/2012) to 0.52 kg m^{-3} (2009/2010) for spiny cultivars and for non-spiny cultivars, it ranged from 0.09 (2011/2012) to 0.44 kg m^{-3} (2009/2010) (Table 4).

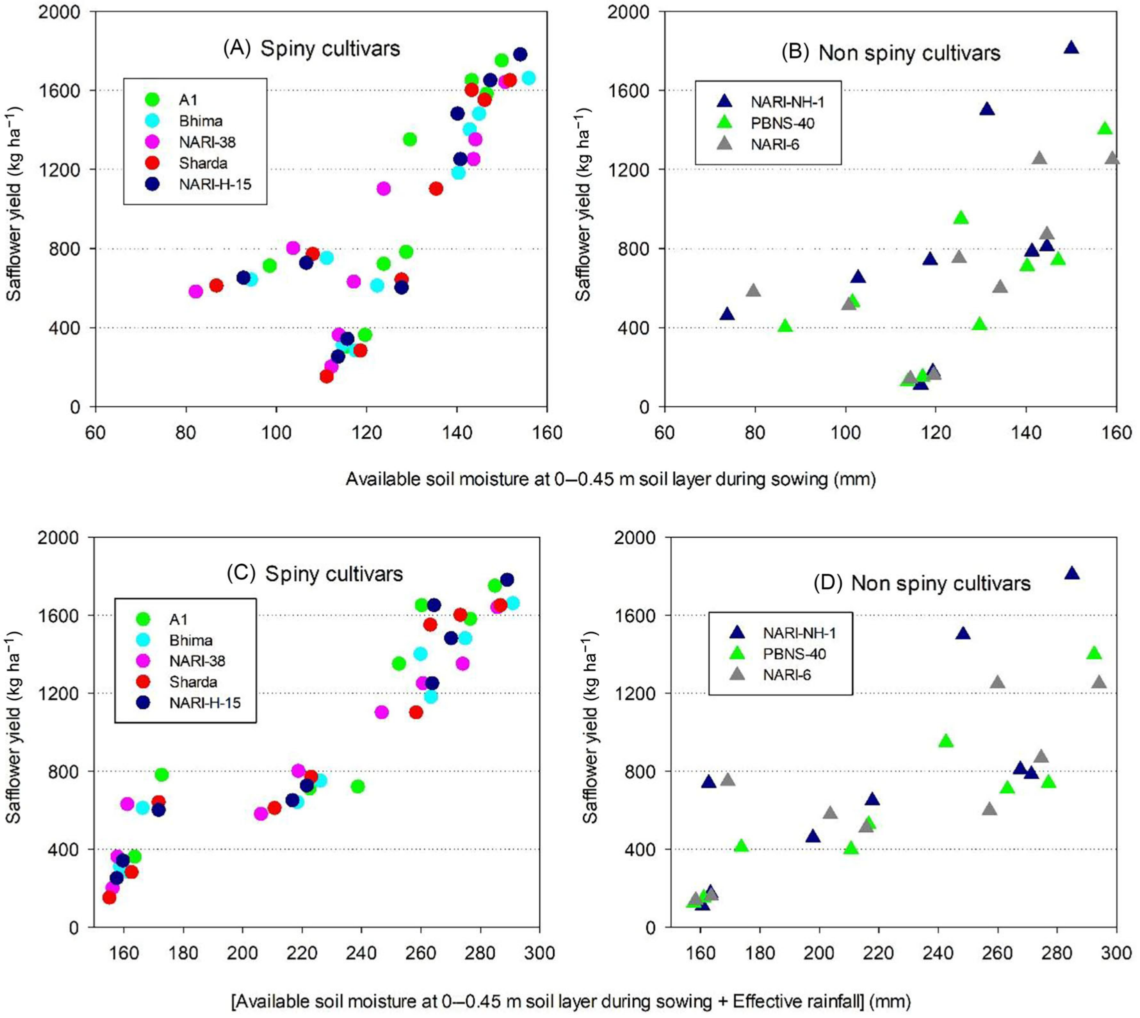


FIGURE 5 (A) and (B) Safflower (a: spiny cultivars and b: non-spiny cultivars) yield response to available residual soil moisture at the time of sowing; (C) and (D) yield response (c: spiny cultivars and d: non-spiny cultivars) to total water availability (i.e., available residual moisture at the time of sowing and postrainy season rainfall) in different years; measured yield data from 24 subplots in 2009/2010, 2010/2011, and 2011/2012.

Safflower grain yield response to available soil moisture in the 0- to 0.45-m soil layer at sowing is presented in Figure 5A,B. A strong relationship was found between available residual soil moisture and grain yield. The available soil moisture in the subplots varied due to the heterogeneity of the experimental site. However, this variation during 2009/2010 and 2010/2011 was insignificant ($p < 0.001$). Available soil moisture during 2011/2012 was significantly low in all subplots due to deficit rainfall in the rainy season; hence, safflower yield was low.

Grain yield responded to available soil moisture at sowing along with effective rainfall during the postrainy season (Figure 5C,D). The total rainfall received in 2009/2010 (October–February) was 225 mm. The model result showed that of the 225 mm, about 30 mm generated surface runoff, 70 mm partitioned into deep percolation, and the rest (125 mm as effective rainfall) was available for crop use. Rainfall received during the postrainy period in 2010/2011 and 2011/2012 was 138 and 47 mm, respectively. Ten percent was partitioned into surface runoff, while deep percolation was negligible. About 90% of the rainfall was available for crop use (as effective rainfall). Crop yield was sensitive to both postrainy season rainfall and available residual soil moisture.

The yield response in spiny cultivars was found to be linear and strong with available residue moisture and effective rainfall. However, there was greater variability in yield response in non-spiny cultivars (Figure 5).

3.2 | Yield response

3.2.1 | Yield response at different soil depths

Safflower seed and stalk yields were measured in different experimental subplots during 2009/2010, 2010/2011, and 2011/2012 (Figure 6). Vertical columns show average yield,

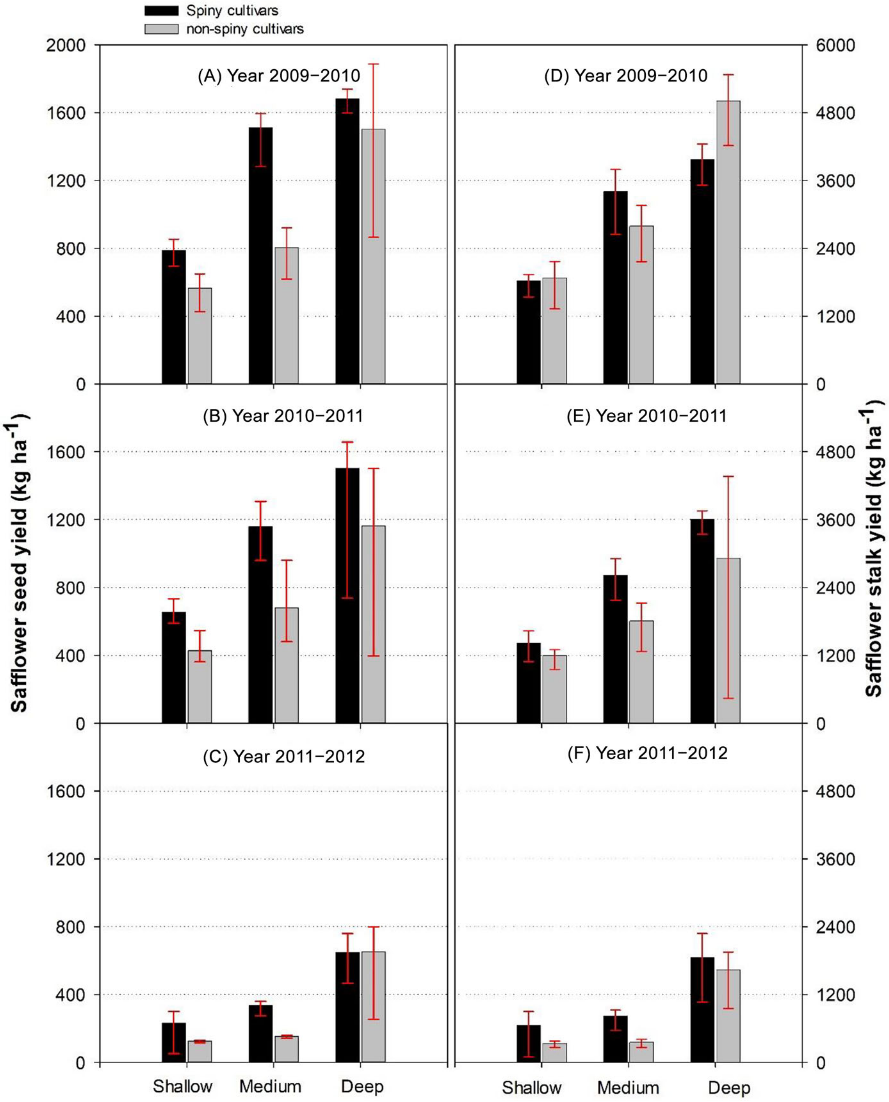


FIGURE 6 Average seed and stalk yields of Safflower along with its maximum and minimum ranges for different soil depths during 2009/2010, 2010/2011 and 2011/2012.

and the bars represent the range over replications. Safflower yield was sensitive to rainfall distribution and soil depth from year to year and plot to plot. Safflower seed and stalk yields were the highest (1696 and 4900 kg ha^{-1} in spiny cultivars, respectively) in deep soils during 2009/2010 and the lowest (125 and 450 kg ha^{-1} in non-spiny cultivars, respectively) in shallow soils during 2011/2012.

This difference in seed yield was not significant in deep soils ($p = 0.2 > 0.05$) but significantly lower with decreasing soil depth ($p < 0.05$). Non-spiny cultivars were more sensitive to water stress than spiny cultivars. This was evident in the reduced crop yield due to water stress. While average seed yields of spiny cultivars measured from deep and medium soils were similar (1500–1600 kg ha^{-1}) during wet (2009/2010) and normal years (2010/2011), yields reduced significantly (by more than 50%) in shallow soils and under deficit rainfall conditions (2011/2012). The average seed yield of non-spiny cultivars reduced significantly with decreasing soil depth and reduced rainfall.

Statistical results show significant difference in crop yield (mean yield) among different soil depths ($p < 0.05$). Further, post hoc analysis revealed this difference is significant for all soil depths, that is, shallow versus deep ($p = 0.0000$); shallow versus medium ($p = 0.0028$); and medium versus deep ($p = 0.0083$) (Table 5). Statistical results further indicate that yields obtained during different rainfall years were also significant as indicated by ANOVA test ($p < 0.05$) (Table 6). Post hoc analysis suggests yield from wet and normal years are not significant ($p = 0.1523 > p = 0.05$). The yield was found to be significantly different among normal versus dry ($p = 0.000$) and wet versus dry years ($p = 0.000$).

TABLE 5 Analysis of variance (ANOVA) (F value) and post hoc test showing effects of different soil depths on crop yield (significant at $p < 0.05$).

Soil depth	Depth (m)	Mean yield (kg ha^{-1})	F value	F critical	p-value	Significance level
Shallow	<0.60	485				Significant
Medium	0.60–1.2	838	18.93617	3.1296	2.78E-07	
Deep	>1.2	1221				
Groups			**p value (t test)**	**Alpha**[a]		
Shallow vs. deep			1E-08			Significant
Shallow vs. medium			0.0028	0.0166		Significant
Medium vs. deep			0.0083			Significant

[a]Post hoc test (Bonferroni corrected).

TABLE 6 Analysis of variance (ANOVA) (F value) and post hoc test showing effects of rainfall years on crop yield (significant at $p < 0.05$).

Year	Type	Mean yield (kg ha^{-1})	F value	F critical	p-value	Significance level
Year 2009/2010	Wet	1178				Significant
Year 2010/2011	Normal	997	30.85	3.1296	2.67E-10	
Year 2011/2012	Dry	369				
Groups			**p value (t test)**	**Alpha**[a]		**Significance level**
Wet vs. normal (year 2009/2010 vs. 2010/2011)			0.1523			Not significant
Normal vs. dry (year 2010/2011 vs. 2011/2012)			2.39725E-08	0.0166		Significant
Wet vs. dry (year 2009/2010 vs. 2011/2012)			6.4545E-10			Significant

[a]Post hoc test (Bonferroni corrected).

TABLE 7 Average seed yield of different cultivars of safflower at three soil depths.

	Normal/wet year			Deficit year		
Cultivar	**Shallow**	**Medium**	**Deep**	**Shallow**	**Medium**	**Deep**
Average seed yield of spiny cultivars (kg ha^{-1})						
Annigeri-1	800	1350	1600	210	350	860
Bhima	800	1320	1550	230	350	750
Sharda	650	1300	1600	230	310	600
NARI-38	675	1250	1550	220	300	620
NARI-H-15	705	1420	1700	220	300	610
Mean	725	1330	1600	220	320	690
Average seed yield of non-spiny cultivars (kg ha^{-1})						
NARI-6	460	850	1200	130	150	400
PBNS-40	470	700	1200	125	150	200
NARI-NH-1	550	770	1700	120	160	400
Mean	495	775	1365	125	155	335
Grand mean	610	1055	1485	175	240	515
SEM±	34	41	52	11	20	45
CD ($p = 0.05$)	100	120	150	32	60	131

Abbreviations: CD, Critical difference at 5% probability; SEM, standard error of the mean.

3.2.2 | Yield response in normal and wet years

Results were further summarized into six major groups based on rainfall (normal/wet and deficit years) and soil depth (deep, medium, and shallow) (Table 7). Soil moisture availability in deep soils was not a constraint (265 mm at sowing and 53 mm at maturity) throughout the crop's growth. Seed yields of spiny cultivars Annigeri-1, Bhima, Sharda, NARI-38, and NARI-H-15 and non-spiny hybrid NARI-NH-1 were

TABLE 8 Soil moisture availability (mm)[a] at different stages of safflower growth (measured from three subplots representing shallow, medium, and deep soils).

Days after sowing (DAS)	Crop stage	Normal/wet year			Deficit year		
		Shallow	Medium	Deep	Shallow	Medium	Deep
At sowing	At sowing	100	175	265	110	180	215
15 DAS	Germination	80	155	245	70	140	185
30 DAS	Rosette	70	140	230	50	120	165
45 DAS	Stem elongation	50	120	210	<10	70	115
60 DAS	Branch initiation	20	85	175	<10	15	55
75 DAS	Branching	15	40	130	<10	<10	15
90 DAS	Flowering	<10	15	100	<10	<10	<10
105 DAS	Seed filling	<10	<10	65	<10	<10	<10
120 DAS	Maturity	<10	<10	55	<10	<10	<10

[a] Available soil moisture (mm) = $\sum_{i}^{n}$ (Soil moisture content – permanant wilting point) × (Soil layer)$_i$.

significantly higher than those of NARI-6 and PBNS-40 (Table 7). Under ample soil moisture availability, the performance of non-spiny hybrid NARI-NH-1 and spiny cultivars was good. The seed yield of non-spiny NARI-6 was low due to poor seed germination (60%–65%).

Soil moisture availability in medium soils was a constraint from the crop branching stage (41 mm) (Table 8). Soil moisture was 175 mm at sowing and only 15 mm at flowering. Spiny hybrid NARI-H-15 recorded the highest seed yield (1420 kg ha^{-1}), which was on par with that of spiny cultivars Annigeri-1, Bhima, and Sharda (Table 8). The non-spiny hybrid NARI-NH-1, which performed well under non-moisture stress conditions, failed to withstand end-season moisture stress.

Soil moisture availability in shallow soils was a constraint from the stem elongation stage of crop growth (50 mm). The productivity of spiny cultivars was 30% higher than that of non-spiny cultivars. The productivity of Annigeri-1, Bhima, and NARI-H-15 was significantly greater than those of Sharda and NARI-38 (Table 8). Non-spiny cultivars could not produce economic yields in shallow soils even in good rainfall years.

3.2.3 | Crop yield in a deficit moisture year

The amount of rainfall received in 2011/2012 was 50% deficit, and average temperature rose by 1.5˚C compared to 2009/2010 and 2010/2011. The rainfall received during the crop's growth period was only 50 mm in 2011/2012 as against 180 mm during 2009/2010 and 2010/2011. Moreover, slightly high temperature (average of 30.3˚C as against 28.8˚C in previous years) during the crop's growth cycle affected not only its growth but also reduced the rosette stage's duration given safflower's thermosensitive nature. The rosette stage is critical under rainfed conditions because that is when the roots penetrate into deep soil layers to draw available moisture. The adverse effect of these parameters was evident in reduced dry matter production and seed yield. Less canopy coverage and high temperature resulted in high evaporative demand (5.1 mm day^{-1} vs. 4.1 mm day^{-1} in previous years).

Soil moisture availability in deep soils at the time of sowing was 210 mm. However, the crop suffered moisture stress from the branch initiation stage (50 mm), and the crop matured early by 10 days. The mean seed yield of spiny cultivars Annigeri-1, Bhima, Sharda, NARI-38, and NARI-H-15 was significantly higher (50%) than that of non-spiny cultivars NARI-6, NARI-NH-1, and PBNS-40. Among the spiny cultivars, Annigeri-1 and Bhima were significantly superior compared to other cultivars. Thus, they are ideal to grow in deep soils even under limited rainfall.

In a deficit moisture year, the soil moisture availability in medium soils at the time of sowing was 170 mm. However, the crop suffered moisture stress from the stem elongation stage of crop growth (70 mm). All spiny cultivars yielded double (320 kg ha^{-1}) compared to the very poor yields of non-spiny cultivars (155 kg ha^{-1}) (Table 7). Poor crop growth and development resulted in poor seed yield and yield attributes for non-spiny cultivars. Oil recovery was not economical due to the low test weight (Figure 7). Seeds of non-spiny cultivars can be sold as bird feed to recover the cost of cultivation.

Soil moisture availability (carryover residue moisture) in shallow soils at sowing was only 100 mm, resulting in a moisture constraint beginning at the rosette stage (50 mm). This has negatively impacted crop growth. The mean crop yield recorded in the dry year was 175 kg ha^{-1} (Table 7). Spiny cultivars yielded 220 kg ha^{-1} and non-spiny cultivars 125 kg ha^{-1}. Though germination was good (80%), plant stand at harvest was poor (60%) for all cultivars due to moisture stress in the dry year. Seed filling (<30%) and test weight

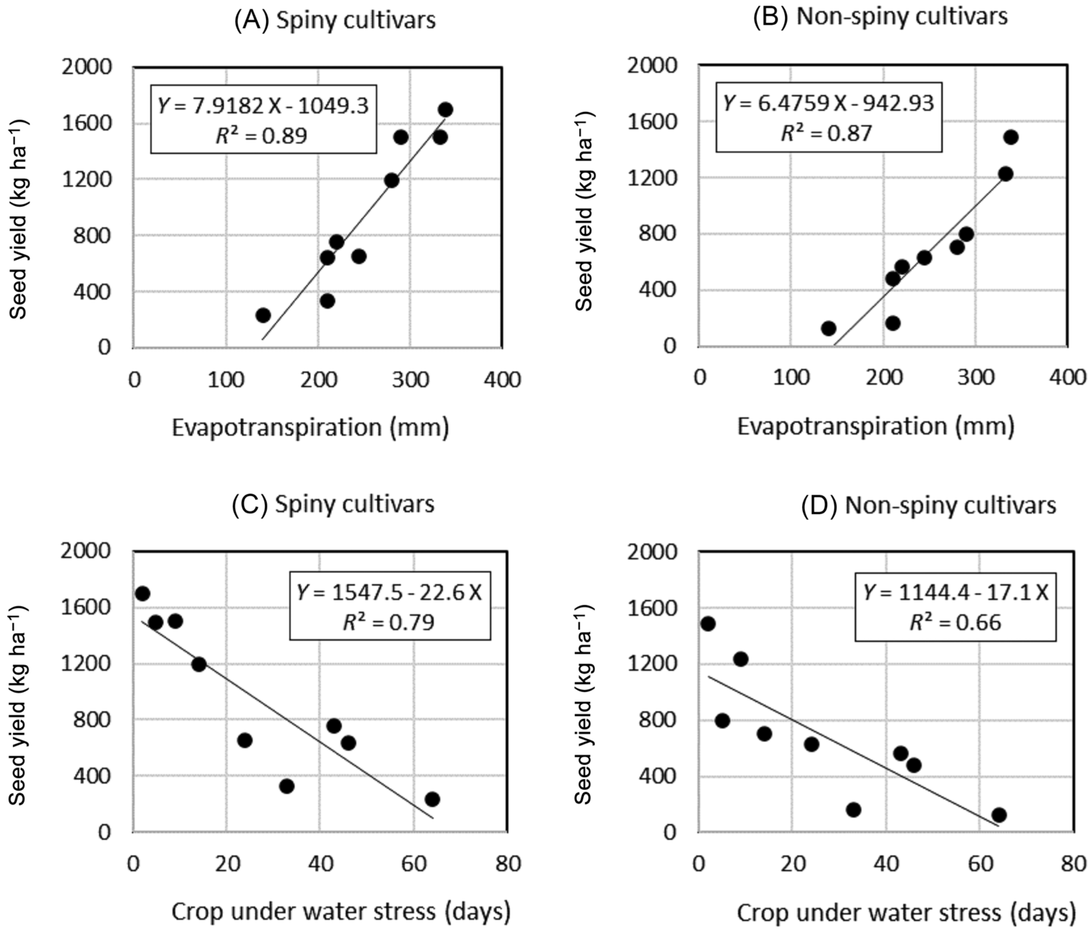


FIGURE 7 (A) and (B): Relationship between evapotranspiration (simulated consumptive water use) and seed yield (measured) for (A) spiny cultivars and (B) non spiny cultivars; (C) and (D): Relationship between number of days crop under water stress (simulated) and seed yield (measured) for (C) spiny and (D) non-spiny cultivars under rainfed conditions.

of 100 seeds (<1.5 g) were found low across all cultivars, suggesting it could only be used as fodder.

3.3 | Oil content

Seed oil concentration was measured in different experimental subplots from three year-experiments (Table 9). Seed oil percent decreased with a decrease in soil moisture availability. It was highest when safflower was grown in deep soils (27.3%) in normal and wet years and least when grown in shallow soils (24.7%) in a drought year. Severe moisture stress in shallow soils affected seed filling, and the majority of seeds were chaffy. Similarly, oil yield declined from 405 to 127 kg ha^{-1} with a decrease in soil moisture availability (Table 9). This indicates that the decline in soil moisture availability affected seed filling and led to a decline in seed oil. Among the spiny and non-spiny cultivars, the non-spiny variety PBNS-40 recorded the lowest oil concentration (20%) and oil yield (94 kg ha^{-1}) at all levels of soil moisture availability. All other cultivars were statistically similar (p = 0.6–0.8) and superior to PBNS-40. Similar findings have been reported by Yau (2006), Eslam et al. (2010), and Sharghi and Bagheri (2011).

3.4 | Production function and simulated yield potential

Irrespective of rainfall and soil depth, the production function describes safflower crop yield response to consumptive water use (ET). A positive linear relationship was observed between ET (simulated) and measured seed yield (Figure 7A,B). For spiny cultivars, the established empirical relationship was: Yield (Y) = 7.9182 × ET −1049.3 (R^2 = 0.89); and for non-spiny cultivars: Yield (Y) = 6.4759 × ET −942.93 (R^2 = 0.87). Further relative reduction in crop yield due to water stress was defined for spiny cultivars: Yield (Y) = 1547.5–22.6 × stress days (R^2 = 0.79) and for non-spiny cultivars: Yield (Y) = 1144.4–17.1 × stress days (R^2 = 0.66). Stress days indicate the number of days a crop experienced water stress in the entire crop growth period (i.e., unmet water demand) (Figure 7C,D).

TABLE 9 Oil concentration and oil yield of different spiny and non-spiny safflower cultivars measured at three soil depths in experimental subplots (values based on average of 3 years).

	Oil concentration (%)			Oil yield (kg ha^{-1})		
Soil depth	**Deep**	**Medium**	**Shallow**	**Deep**	**Medium**	**Shallow**
Spiny cultivars						
Annigeri-1	27.6	27.2	25.5	442	367	204
Bhima	28.3	28.2	24.1	439	372	193
Sharda	28.1	27.0	26.6	450	351	173
NARI-38	26.6	26.4	26.0	412	330	176
NARI-H-15	26.8	25.7	25.7	456	365	181
Mean	27.5	26.9	25.6	440	358	186
Non-spiny cultivars						
NARI-6	27.7	26.0	24.4	388	221	112
PBNS-40	24.5	22.3	20.1	294	156	94
NARI-NH-1	28.7	28.1	26.8	431	216	147
Mean	27.0	25.5	23.8	369	198	118
SEM±	0.7	1.0	1.4	27.6	22.7	24.6
CD ($p = 0.05$)	2.0	2.9	4.2	80	68	74

Abbreviations: CD, Critical difference at 5% probability; SEM, standard error of the mean.

To understand the current yield gap and production potential, we further analyzed safflower yield for spiny cultivars using model simulation (Table 10). Out of 10 years, four were deficit years with rainfall less than 20% of average (Garg et al., 2022b). Simulations were made for three soil depths (deep, medium, and shallow) to capture land heterogeneity. The simulated average safflower yield (spiny) in deep soils was estimated to be between 1090 and 1215 kg ha^{-1}. Normal and wet years produced slightly better yields (by 5%–10%) compared to deficit years but this difference was not significant (shown by *t*-test). Net income estimated from deep soils ranged from \$605 to \$700 ha^{-1} and yields simulated from all the years were found remunerative. Plants suffered negligible water stress (<5–6 days) and estimated ET was in the range of 300–310 mm. This indicates that crop water requirement was fully met in deep Vertisols. Technical WP and economic WP of safflower in deep soils ranged from 0.37 to 0.39 kg m^{-3} and \$0.20 to \$0.23 m^{-3}, respectively (Table 10). Simulation results showed that deep Vertisols hold a huge opportunity for sustainable crop intensification that can be harnessed by cultivating postrainy season crops like safflower, even under rainfed conditions.

Simulated safflower yield under medium soils ranged from 637 to 663 kg ha^{-1} with net income ranging from \$265 to \$285 ha^{-1} (Table 10). The crop experienced water stress for an average of 30 days and equivalent to about 50–100 mm deficit. Moreover, technical WP and economic WP were 0.27–0.28 kg m^{-3} and \$0.11–0.12 m^{-3}. Crop yields and net income in normal and wet years were slightly better versus deficit years, but this difference was insignificant among years (shown by *t*-test).

Safflower yield under shallow soils was poor. Simulated seed yield ranged from 110 to 176 kg ha^{-1}. Out of 10 years, remunerative yields were obtained in only 2 years with a high risk of crop failure (Table 10). Safflower in shallow soils can only be remunerative through land and water management practices and by providing essential supplemental irrigation at critical growth stages.

4 | DISUSSION

4.1 | Water requirement in a safflower production system

Field-scale water budgeting in the postrainy season can provide insights into specific water requirements for safflower growth. Two major components influence water availability in a given landscape in the postrainy season: (i) residual moisture in different soil layers and (ii) postrainy season rainfall. Results from this study showed that deep and medium soils store about 175–265 mm of available residual soil moisture, of which 120–150 mm is stored in the 0- to 0.45-m layer. This is equivalent to 55%–85% of the crop's total water requirement. The remaining requirement is met from postrainy season rainfall in a rainfed ecology, which is uncertain. With negligible postrainy season rainfall, there is a high probability of remunerative yield from a crop grown in deep soils, whereas in medium soils, such a condition poses the risk of declining yields. Remunerative crop yields are highly unlikely in shallow Vertisols due to poor residual moisture.

TABLE 10 Yield, net income, and water productivity under different land management scenarios derived for spiny cultivars from model simulations.[a]

Soil depth	Parameters	Deficit years	Normal/surplus years
Shallow	Average seed yield (kg ha^{-1})	176	110
	Net income ($ ha^{-1})	NR	NR
	Number of years of remunerative cultivation	1 (out of 4)	1 (out of 6)
	Average moisture at sowing (mm)	55	70
	Rainfall during crop period (mm)	130	135
	Consumptive water use, ET (mm)	150	200
	Crop water stress (days)	56	55
	Technical WP$_{ET}$ (kg m^{-3})	0.12	0.05
	Economic WP ($ m^{-3})	–	–
Medium	Average seed yield (kg ha^{-1})	637	663
	Net income ($ ha^{-1})	265	285
	Number of years of remunerative cultivation	3 (out of 4)	6 (out of 6)
	Average moisture at sowing (mm)	130	150
	Consumptive water use, ET (mm)	230	235
	Crop water stress (days)	30	30
	Technical WP$_{ET}$ (kg m^{-3})	0.27	0.28
	Economic WP ($ m^{-3})	0.11	0.12
Deep	Average seed yield (kg ha^{-1})	1090	1215
	Net income ($ ha^{-1})[b]	605	700
	Number of years of remunerative cultivation	4 (out of 4)	6 (out of 6)
	Average moisture at sowing (mm)	205	265
	Consumptive water use, ET (mm)	300	310
	Crop water stress (days)	6	5
	Technical WP$_{ET}$ (kg m^{-3})	0.37	0.39
	Economic WP ($ m^{-3})	0.20	0.23

Abbreviations: ET, evapotranspiration; NR, non-remunerative; WP, water productivity.

[a] Seed price is $0.75 kg^{-1} and cost of cultivation is $215 ha^{-1}.

[b] 1 USD = 53.4018 INR (conversion rate, base year 2012).

Further, results suggest total water consumption during the crop season was 24%, 30%, 34%, and 11% at 0–30, 31–60, 61–90, and 91–120 days, respectively. This indicates that the second and third months of crop growth are crucial, demanding as much as 65% of the total water requirement. In addition, yield response for spiny and non-spiny cultivars is different, which varied from 10% to 50% despite having same crop management practices and soil moisture regimes in respective soils. It is appropriate to characterize and parameterize spiny and non-spiny cultivars separately in future field and modeling studies due to their inherent differences in genetically influenced attributes.

4.2 | Opportunity for sustainable crop intensification in vertisols

Agricultural systems, in particular rainfed agriculture in the semiarid tropics, are highly vulnerable to climatic and socioeconomic shocks. In semiarid agroecosystems, rainfall variability causes water stress (Barron et al., 2003; Rao et al., 2006; N. Singh & Ranade, 2009), leading to poor yields or complete crop failure. This study showed that safflower requires nearly 300–320 mm of water in the postrainy season. It is possible to cultivate safflower in Vertisols (deep black soil), as nearly 80% of the required water can be met from in situ moisture as the plant can extract water from deep soil layers (up to 1.5–2.0 m) and the rest from postrainy season rainfall. Timely sowing, zero-tillage, and other intercultural operations are essential, as soil moisture from the topsoil layers should be utilized efficiently, especially at the time of sowing. If moisture from the top layer gets depleted, it is less likely to lead to crop establishment despite abundant soil moisture being available in the lower layers. Landscape-based resource conservation interventions such as broad bed and furrow, mulching, and zero-tillage help in enhancing infiltration rate, enable more rainfall harvesting, and reduce non-productive evaporation losses. In situ and ex situ land management practices can harvest an additional 50–100 mm rainfall that can meet the deficit in crop water requirement compared to traditional practices (Anantha et al., 2021; Garg et al., 2021).

Increasing population pressure and rising food demand, including oilseed crops, underline the need to enhance cropping intensity in irrigated areas and also in rainfed regions. Contrary to the belief that rainfed areas can produce only one crop with marginal yield, there is a huge untapped potential in rainfed agriculture. Recent studies on landscape rejuvenation report that the introduction of resource conservation technologies in fragile ecosystems has transformed entire degraded landscapes and facilitated crop intensification (Anantha et al., 2022; Garg et al., 2022b, Garg et al., 2022a; R. Singh et al., 2014; R. Singh et al., 2022). Safflower has immense potential in rice-fallow areas of Eastern India and in similar agroecological zones of Bangladesh, Pakistan, Sri Lanka, Nepal, and Myanmar if landscape-based resource conservation practices are introduced. These interventions can enhance residual soil moisture availability and facilitate improved surface and groundwater availability, which are crucial for supplemental irrigation during the crop's critical growth stages.

5 | CONCLUSION

Safflower yield varied with soil moisture availability in plots at different soil depths. The experimental site experienced wet, normal, and deficit years during 2009/2010, 2010/2011, and 2011/2012, respectively. The highest safflower yield (1800 kg ha^{-1}) was obtained in plots with deep soil during 2009/2010, while minimum yield (125 kg ha^{-1}) was recorded in shallow soil during 2011/2012. A strong linear relationship was found between consumptive water use (ET) and crop yield. Moreover, spiny cultivars produced 10%–50% more seed than non-spiny cultivars.

Total water requirement in safflower during the postrainy season was estimated at 300–320 mm under semiarid tropical conditions. About 60%–70% of the required water requirement was met through residual soil moisture in deep and medium soils, and the rest came from postrainy season rainfall. Safflower yield potential and net income from spiny cultivars grown in deep soils were estimated at 1000–1200 kg ha^{-1} and \$600–708 ha^{-1}, respectively. The safflower crop may suffer from water scarcity during deficit years without postrainy season rainfall. Limited yield potential was observed in safflower under shallow soils.

The predictive simulations developed in this research may help agronomists and land managers investigate potential complementary cropping scenarios using deep-rooted safflower.

AUTHOR CONTRIBUTIONS

Padmavathi Ponakala: Conceptualization; data curation; writing—original draft. **Kaushal K. Garg**: Conceptualization; formal analysis; writing—original draft. **K. H. Anantha**: Writing—review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data can be made available with a reasonable request to authors.

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