



Water Management in Safflower (*Carthamus tinctorius* L.): A Review of Crop Water Requirements, Irrigation Scheduling, Deficit Irrigation, and Salinity Management

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Safflower (*Carthamus tinctorius* L.) is an oilseed crop increasingly valued in arid and semi-arid cropping systems because of its deep taproot, drought-avoidance physiology, and tolerance to moderate soil and water salinity. The scientific literature on safflower water management is reviewed in this article, which summarizes research on crop water requirements, irrigation scheduling, deficit irrigation strategies, irrigation method and timing, pre-season soil-moisture management, and the use of marginal-quality (saline or recycled) irrigation water. Evidence from field trials in India, Iran, Turkey, the United States, and Brazil indicates that safflower requires relatively modest total water input (roughly 300–500 mm depending on climate and soil), but that yield and oil content are highly sensitive to water availability during flowering and seed filling. Deficit irrigation applied during vegetative and rosette stages, combined with full irrigation at flowering and seed development, consistently maximizes water use efficiency (WUE) without proportionally sacrificing yield. Pre-season (pre-sowing) irrigation that recharges deep soil moisture further buffers in-season drought stress by exploiting safflower's extensive rooting system. This review synthesizes practical recommendations for irrigation scheduling, method selection, and salinity management to support sustainable, water-efficient safflower production.

Introduction

Global freshwater scarcity, expanding areas of salt-affected land, and the increasing frequency of drought under climate change have intensified interest in crops that can maintain productivity with limited or lower-quality water. Safflower (*Carthamus tinctorius* L.), a member of the Asteraceae family, is one of the oldest cultivated oilseed crops and has re-emerged as a strategic option for water-limited and marginal agricultural systems (Hussain et al., 2016). It is grown for edible and industrial oil, birdseed, dye, and increasingly as a rotation crop that helps manage saline water tables (Kaffka & Bali, 2002). Unlike many oilseed crops, safflower possesses a deep, branching taproot system that extends below soil up to two to three metres, enabling it to extract stored soil moisture well beyond the reach of most annual crops (Li & Mündel, 1996, as cited in Office of the Gene Technology Regulator [OGTR], 2019). This trait underlies its classification as a drought-avoiding rather than a purely drought-tolerant species, and it has direct implications for how irrigation should be scheduled and how much supplemental water is actually required. At the same time, safflower is susceptible to water stress: yield components — particularly the number of capitula (flower heads) per plant, seed number per head, and thousand-seed weight — are highly responsive to water deficits that occur during flowering and seed filling (Nabipour et al., 2007; Bhattarai et al., 2016). The physiological underpinnings of safflower water use are reviewed, crop water requirements and critical growth stages are quantified, irrigation scheduling and deficit irrigation strategies

reported in the peer-reviewed literature are assessed, and irrigation techniques and salinity management pertinent to sustainable safflower production are discussed.

Botanical and Physiological Basis of Water Use

Safflower's adaptation to water-limited environments is rooted in its morphology and physiology. Its extensive rooting system gives the plant access to water and nutrients unavailable to shallow-rooted crops, allowing it to access residual soil moisture left by a preceding crop or stored from off-season rainfall (Science.gov, n.d.; Bhattarai et al., 2020). Field studies in the Southern High Plains of the United States found that safflower extracted substantially more stored soil moisture — of about 70 mm — when preseason irrigation had recharged the soil profile, compared with about 28 mm of extraction where no preseason irrigation was applied, and that this stored moisture significantly increased evapotranspiration, water use efficiency, and oil yield (Bhattarai et al., 2020). At the physiological level, safflower responds to progressive soil moisture depletion by altering canopy temperature, transpiration efficiency, and stomatal behavior; genotypes vary considerably in these traits, which affects their relative drought tolerance (Singh et al., 2023, as summarized in the residual-moisture-stress literature). Under more acute drought stress, safflower activates biochemical defenses including accumulation of proline, total phenolics, flavonoids, and antioxidant enzymes, alongside declines in chlorophyll and carotenoid content and increased membrane damage (Erdal & Ekmekci, 2023; related biochemical-mechanism studies). Absciscic acid (ABA) signaling and reactive-oxygen-species metabolism have also been implicated in genotypic differences in drought resistance, with more tolerant lines showing elevated ABA and proline levels under stress alongside better maintenance of photosynthetic function. These physiological mechanisms explain why safflower can sustain moderate yields under limited water supply, but also why irrigation timed to the most sensitive growth stages produces a greater yield benefits. Safflower is also classified as a moderately salt-tolerant crop, ranking above many field crops in its ability to sustain yield under saline soil and irrigation water conditions, although yield and consumptive water use both decline as root-zone salinity increases (Kaffka & Bali, 2002; Bali et al., 2001). This combination of deep rooting, drought-responsive physiology, and moderate salt tolerance makes safflower particularly suited to water management strategies built around deficit irrigation and the conjunctive use of marginal-quality water.

Crop Water Requirement and Critical Growth Stages

Total seasonal water requirement in safflower varies with climate, soil depth, and cropping season. In semi-arid tropical post rainy (*rabi*) season on Vertisols in India, safflower has been reported to require approximately 300–320 mm of water over the season, with residual soil moisture contributing an estimated 30–80% of total crop water use depending on soil depth and rainfall distribution (water-use and yield-response studies on rainfed safflower in Vertisols). In irrigated production in northern Utah (USA), measured crop water use ranged from about 8.7 to 19.0 inches (approximately 220–480 mm), with corresponding yields ranging from roughly 1,700 to nearly 3,900 lb/acre, and yields around 4,000 lb/acre required about 19–20 inches of evapotranspiration based on a five-foot soil-water balance (Utah State University [USU] Extension, 2023). These figures illustrate that, while safflower's absolute water requirement is moderate compared with many irrigated oilseed and fiber crops, water available late in the season strongly determines the achievable yield ceiling. The FAO's crop-water guidance for oilseed and industrial crops similarly emphasizes stage-specific sensitivity to water deficits, with irrigation scheduling intended to minimize both under- and over-irrigation relative to crop evapotranspiration and root-zone soil moisture depletion thresholds (Food and Agriculture Organization [FAO]). Applying this general framework to the safflower growth cycle, the crop passes through a sequence of stages with markedly different sensitivity to water stress, summarized as below :

Safflower growth stages and relative sensitivity to water stress

Growth Stage	Approximate Duration	Sensitivity to Water Stress	Effect of Stress on Yield
Germination–Emergence	0–15 days after sowing	Moderate	Poor stand establishment, uneven emergence
Rosette stage	15–40 DAS	Low–Moderate (drought-tolerant window)	Minimal yield penalty; safflower can tolerate deficit here
Stem elongation / branching	40–65 DAS	Moderate	Reduced plant height, branch number, and leaf area index
Flower bud initiation / budding	65–85 DAS	High	Fewer capitula (heads) per plant
Flowering / anthesis	85–105 DAS	Very High (most critical)	Reduced seed set, fewer seeds per head
Seed filling / grain development	105–130 DAS	Very High	Lower 1000-seed weight and oil content
Physiological maturity	130–150 DAS	Low	Irrigation should be withheld to aid dry-down and harvest

Multiple independent field trials converge on flowering and seed filling as the stages during which water deficit causes the greatest yield loss. In a study conducted in Karnataka, India, three irrigations timed at the rosette, flower-initiation, and seed-development stages increased seed yield by 40.2% over an unirrigated control, while two and one well-timed irrigations increased yield by 33.4% and 27.4%, respectively (Parameshnaik et al., 2022). In Iran, cutting off irrigation during the flowering (blooming) period produced the lowest seed and oil yields among several deficit-irrigation treatments, confirming flowering as the most drought-sensitive phase, whereas withholding irrigation during budding or after maturity had comparatively smaller effects (Nabipour et al., 2007). Consistent with this pattern, Brazilian field research found that safflower irrigated only during the vegetative stage produced markedly smaller seeds (about 2.81 g per thousand seeds) than plants irrigated through flowering and grain filling (about 3.85 g per thousand seeds), a difference of roughly 37% in thousand-seed mass.

Irrigation Scheduling Approaches

Traditional irrigation scheduling recommendations for safflower emphasize a heavy pre sowing irrigation followed by infrequent but substantial applications timed to critical growth stages, rather than frequent light irrigations. On heavier-textured soils, two irrigations — one pre sowing and one at flowering — are often sufficient, whereas lighter-textured soils with lower water-holding capacity may require three or more applications across the season. Scheduling irrigation according to an IW/CPE ratio (irrigation water depth to cumulative pan evaporation) of 0.6 to 1.0 has been reported to give favorable results for safflower under Indian growing conditions, balancing yield response against water applied. More physiologically based scheduling tools have also been evaluated. The crop water stress index (CWSI), derived from canopy-air temperature differentials and vapor pressure deficit, has been used to quantify safflower water status in real time and to identify irrigation trigger points. In one study, a threshold CWSI value of approximately 0.63 was identified as the point at which irrigation should commence, while a seasonal CWSI in the range of 0.28–0.33, corresponding to mild water stress at about 75% of field capacity, produced the best combination of relative water content, water use efficiency, and acceptable yield under deficit conditions. These thermal-sensing approaches offer a route toward more precise, real-time deficit-irrigation management than fixed calendar- or growth-stage-based schedules alone. Preseason (pre sowing) irrigation deserves particular emphasis given safflower's deep rooting habit. Because centre-pivot and other high-frequency irrigation systems tend to keep only the upper soil profile wet, they do not fully exploit safflower's capacity to draw water from depth. Field research in the semi-arid Southern High Plains found that preseason irrigation, which recharges the full soil profile before planting, significantly increased evapotranspiration, water use efficiency, and oil yield

relative to fields without preseason irrigation, and reduced the crop's dependence on in-season irrigation applications (Bhattarai et al., 2020). This confirms that, for safflower, the timing of water availability across the full growing season — not simply the total volume applied — is a key determinant of both yield and water productivity.

Deficit Irrigation and Water Use Efficiency

Because irrigation water is increasingly scarce and costly, a substantial body of research has focused on deficit irrigation strategies for safflower that aim to maximize water use efficiency (yield per unit of water applied or consumed) rather than maximizing absolute yield (Bhattarai et al., 2016, drawing on Fereres & Soriano, 2007, and Geerts & Raes, 2009). The underlying principle of deficit irrigation is to allocate limited water to the crop's most drought-sensitive stages while deliberately under-irrigating during more tolerant stages such as the rosette phase, thereby stabilizing yield rather than maximizing it, and freeing saved water for other uses or additional irrigated area (Chartzoulakis & Bertaki, 2015, *deficit-irrigation practices*). Field comparisons of growth-stage-based deficit irrigation regimes in the Southern High Plains found that a reproductive-stage irrigation treatment achieved deeper soil-water extraction and higher water use efficiency than either a full-irrigation or a vegetative-stage-only irrigation treatment, indicating that concentrating available water at reproductive stages allows the crop to use stored and applied water more efficiently overall (Bhattarai et al., 2016). Similarly, in Iranian trials evaluating oil accumulation and harvest timing, deficit irrigation reduced both seed and oil yield relative to full irrigation, but the magnitude of the reduction depended strongly on cultivar, with some genotypes (e.g., Sina) maintaining relatively high oil content and yield across the full range of irrigation treatments (oil-accumulation and harvest-time study). Table below summarizes representative yield and water-use responses reported across several deficit-irrigation studies.

Representative safflower yield and water-use responses under different irrigation regimes

Irrigation Regime (example study)	Seed Yield Response	Water Use Efficiency / Notes
Full irrigation at all stages (I1)	Highest seed and oil yield	Baseline for comparison; highest total water applied
Single supplemental irrigation at critical stage	~27% yield increase over rainfed control	Most water-efficient single application
Two irrigations (rosette + flowering/seed-fill)	~33% yield increase over rainfed control	Good balance of yield gain and water saved
Three irrigations (rosette, flower initiation, seed development)	~40% yield increase over rainfed control	Highest yield among deficit treatments
Mild deficit (~75% of full requirement)	26–28% yield reduction vs. full irrigation	~25% water saved; favorable WUE trade-off
Cut-off at flowering (severe deficit)	Largest yield and oil losses	Flowering is the least tolerant stage to skip

A related line of research has combined deficit irrigation with biological inputs. A recent study evaluated plant growth-promoting bacteria (PGPB) under a gradient of deficit irrigation levels (0%, 25%, 50%, 75%, and 100% of Class-A pan evaporation) using both recycled wastewater and fresh water, reporting yield response factors (k_y) in the range of 0.30–0.39, indicating that safflower yield declines proportionally less than the corresponding water deficit. Such findings reinforce that safflower's yield-response curve to water is relatively flat compared with more water-sensitive row crops, supporting its suitability for regulated deficit-irrigation programs in water-scarce regions.

Irrigation Methods and Practical Management

Because safflower is most commonly grown as a rain fed or supplementally irrigated crop in semi-arid regions, surface (furrow or basin) irrigation combined with a heavy pre sowing application remains the dominant method in traditional production systems, particularly across South Asia. However, as water scarcity intensifies, pressurized methods such as sprinkler and

drip irrigation are being increasingly evaluated for safflower, especially in combination with deficit-irrigation scheduling. Drip irrigation offers the advantage of precise, frequent, low-volume water delivery that can be matched closely to crop evapotranspiration and growth-stage water needs, and evidence from other field and fiber crops indicates that appropriately managed drip systems can substantially improve water productivity, particularly on saline or saline-alkali soils, by controlling the wetting pattern and limiting deep percolation and salt accumulation in the root zone. Timing of irrigation cut-off near maturity is another important practical consideration: continued irrigation after physiological maturity delays dry-down, complicates harvest, and can promote seed-head diseases, so irrigation should generally be terminated once the crop has passed the seed-filling stage.

Salinity and Marginal-Quality Water Management

Safflower's moderate salt tolerance makes it a valuable rotation crop for regions where saline soils or saline shallow groundwater constrain the choice of other crops. Long-term field studies in California's San Joaquin Valley found that safflower could be grown across a range of effective soil salinity (EC_e) from about 1.8 to 7.2 dS/m, using either high-quality irrigation water (EC_i < 1 dS/m) or saline water (EC_i ≈ 6.7 dS/m); increasing root-zone salinity reduced both water use and root growth, and seed yield was not correlated with total consumptive water use across the 400–580 mm range studied (Bali et al., 2001; Kaffka & Bali, 2002). Notably, safflower has historically been used in this region specifically to draw down shallow, saline perched water tables left behind by cotton irrigation, extracting moisture from as deep as 3 meters and achieving some of the highest regional yields under these saline, high-water-table conditions (Kaffka & Bali, 2002). Standard irrigation water-quality guidance (Ayers & Westcot, 1976) places safflower's salinity tolerance thresholds at an irrigation water electrical conductivity (EC_{iw}) of roughly 3.5 dS/m for negligible yield loss, rising through about 4.1, 5.0, and 6.6 dS/m at progressively greater yield-potential reductions — comparable to or somewhat more tolerant than crops such as groundnut and soybean (Texas A&M irrigation water-quality guidance, Ayers & Westcot, 1976). This places safflower among the moderately salt-tolerant field crops suitable for conjunctive use of fresh and marginal-quality irrigation water, an increasingly important option given projected declines in freshwater availability (Hussain et al., 2016). Nonetheless, some caution is warranted: intermediate salinity levels have occasionally been reported to increase yield slightly by favorably altering harvest index, but higher salinity consistently reduces yield, and tolerance varies considerably among safflower genotypes (Bali et al., 2001; salinity-tolerance genotype studies). Where saline or recycled water must be used, practices such as drip irrigation to control the wetting front, leaching fractions to manage salt accumulation, and selection of relatively salt-tolerant cultivars are recommended to sustain long-term productivity.

Integrated Recommendations for Water Management

Based on the reviewed evidence, the following integrated practices are recommended for water-efficient safflower production:

- Apply a heavy pre sowing (preseason) irrigation to fully recharge the soil profile, exploiting safflower's deep taproot to buffer against in-season drought and improve overall water use efficiency and oil yield.
- Prioritize available irrigation water for the flowering and seed-filling stages, which are consistently the most sensitive to water deficit across independent studies; irrigation can be safely reduced or withheld during the rosette stage with minimal yield penalty.
- Where water supply allows two to three irrigations, schedule them at the rosette, flower-initiation, and seed-development stages to capture the largest documented yield gains (27–40% over rainfed controls).
- Under severe water scarcity, adopt regulated deficit irrigation targeting roughly 75% of full crop water requirement, which has been shown to reduce yield by only about a quarter while saving approximately a quarter of irrigation water — a favorable trade-off for water use efficiency.

- Use crop water stress index (CWSI) or soil-moisture monitoring where feasible to trigger irrigation events based on actual plant water status rather than fixed calendar schedules.
- Terminate irrigation at physiological maturity to facilitate dry-down, reduce disease pressure, and avoid wasted water.
- Where saline or recycled water is the only available source, consider safflower as a rotational crop suited to moderate salinity (up to roughly ECiw 4–5 dS/m without severe yield loss), and pair its use with drip irrigation and leaching management to control root-zone salt accumulation.
- Select cultivars with demonstrated drought or salinity tolerance where water quality or quantity is a persistent constraint, since genotypic variation in water use efficiency, membrane stability, and osmotic adjustment is substantial.

Conclusion

Safflower's deep rooting system, drought-responsive physiology, and moderate salinity tolerance make it a distinctive and valuable crop for water-limited and marginal-quality-water agricultural systems. The scientific literature converges on several consistent findings: total seasonal water requirement is moderate (roughly 300–500 mm depending on climate and soil), the rosette stage tolerates water deficit well, and flowering through seed filling is the critical window during which irrigation delivers the greatest yield and oil-content benefits. Deficit irrigation strategies that concentrate available water at these reproductive stages, supported by adequate presowing soil-moisture recharge, consistently achieve the best balance between water savings and yield outcomes. As freshwater resources become scarcer and more variable under climate change, and as more marginal and saline water sources are brought into agricultural use, safflower's combination of drought tolerance and salt tolerance positions it as a strategic crop for sustainable water management in semi-arid and salt-affected cropping systems. Continued research into cultivar-specific water-use traits, precision irrigation scheduling using canopy-temperature and soil-moisture sensing, and optimized conjunctive use of fresh and marginal water will further strengthen safflower's role in water-efficient agriculture.

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