Agronomic Strategies for Heat-Stress Mitigation in Safflower *(Carthamus tinctorius* L.)

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ABSTRACT

Context: Although the safflower (*Carthamus tinctorius* L.) is known as a highly significant oilseed crop and its potential as a crop may not have been fully explored but it is still significant due to its high tolerance to drought, its adaptability to saline soil, and its robust root system. However, it is important to point out that global warming has caused the safflower plant to face threats to its growth with a possible decline in yield to as high as 53% under terminal heat stress. Although safflower has a reputation of being a climate-resilient crop, there are not many studies that have focused on safflower's heat vulnerability in comparison with other oilseed crops such as soybeans, sunflower, or canola.

Purpose: This paper's goal is to analyze the present diverse methods of growing safflower, such as changing sowing date, choosing appropriate genotype, or using biostimulants and antioxidants, and analyze their effect on the growth of safflower and its yield during a terminal heat stress period.

Literary sources: The analysis was based on results of literature search in databases such as Scopus, Web of Science, PubMed/PMC, ScienceDirect, SpringerLink, Frontiers, and PeerJ, and at the same time, it included reports issued by agricultural research institutes in different parts of the world, as well as combinations of words, such as "safflower," "*Carthamus tinctorius*," "heat stress," "terminal heat stress," "sowing date," and "agronomic management" etc.

Research results: Results indicated that the best time to sow safflower is the best and least costly means of overcoming heat stress during flowering and grain filling, where ill-timed sowing can reduce the yield by almost half. Discovery of the most heat resistant cultivar indicated that high genotypic variation was registered for heat resistance, which was associated with osmolyte accumulation and some other traits. The application of salicylic acid, selenium, and potassium biostimulants led to the improvement of physiological resilience and biological yield of safflower by 12%–13%, while the combination of safflower with chickpea under rainfed growing conditions significantly increased the microclimatic stability and the level of yield. Finally, irrigation policy and canopy temperature depression were suggested to be effective indicators of heat and drought resistant genotypes.

Research gaps: There is a paucity of multi-site and multi-season validation of biostimulants and cropping systems that are particular to end-of-season heat stress, the integration of genotype-environment-management tests, and evaluations of the economic viability of interventions for poor farmers.

Conclusion: The use of phenology-based sowing adjustment in combination with heat-resistant variety adoption and suitable physiological solutions creates a feasible approach to maintain safflower productivity under more heat stress, although it is important to perform further calibration and validation in particular regions.

Keywords: Safflower, *Carthamus tinctorius*, heat stress, terminal heat stress, sowing date, agronomic management, oilseed crops, abiotic stress mitigation

1. Introduction

Safflower (*Carthamus tinctorius* L.) is an oilseed crop in the Asteraceae (composite) family that is grown primarily for its oil that is rich in linoleic and oleic acids, as well as for medicinal, dying, and forage purposes [1]. Safflower has long been considered a drought- and salt-tolerant, hardy crop well-suited to marginal (less than ideal) and semi-arid (half dry) environments because of its deep and highly branched taproot system that allows for great flexibility in using residual (leftover) soil moisture [2, 3]. This makes safflower an increasingly desirable rain-fed and/or rotational oilseed crop in water-scarce areas of South Asia, the Middle East, and the Mediterranean Basin [2, 3]. However, although safflower is thought to be resilient to stress, its reproductive physiology is highly sensitive to high temperature stress at flowering and seed development due to THS (terminal heat stress) [4].

Surface temperatures across the globe have continually increased and climate projections show that there will be more frequent and intense heat waves during the growing seasons of spring-sown and winter-sown oilseed crops in significant producing regions [5]. For safflower, previous research conducted in controlled environments has demonstrated that exposure to extreme temperatures at the end of the growth cycle could lead to reductions of 53-57% in grain yield within existing cultivars along with oxidative impact on crops, changes in fatty acid composition of seed oils, and impacts on physicochemical quality of seed during the harvest period [4, 6]. As a result of the existing data regarding extreme terminal heat impacts on safflower's performance, the concept that safflower is a "climate resilient" species has been redefined from the standpoint that safflower's regenerative abilities and performance during periods of high temperature have more to do with optimum farming practices, rather than exclusively being an inherent characteristic of the species.

Different pathways interactively lead to a physiological response to heat stress, in safflowers, as evidenced by increased levels of reactive oxygen species (ROS), resulting in lipid peroxidation (typically quantified using malondialdehyde, MDA), and loss of membrane integrity, reduction of chlorophyll stability, rapid floral abortion, and grain-filling periods being dramatically shorter [4, 7]. Generally speaking, during the hottest time of year, flowering occurs at the same time as the grain-filling process in safflower crops; even moderately delayed planting dates or changing climate will result in significant yield loss thus highlighting the importance of finding acceptable agronomic practices that do not incur excessive costs or take years of selection through breeding programs [8, 9].

The amount of information available through various types of agricultural research, studies done on the effects of environmental changes on safflowers and other oilseed crops, selected cultivars or genotypes based on physiological indications such as canopy temperature depression or water use efficiency, biostimulant applications (salicylic acid and selenium), growing safflower with other crops (intercropping), and scheduling irrigating [10–13]. Unfortunately, most of this information is dispersed throughout the agricultural literature and has not been compiled in one source that will provide scientists, extension personnel, and producers (farmers) the necessary information and tools to effectively and efficiently manage heat stress on safflower from an agronomic stand point.

To achieve these objectives, the present review is intended to: (i) summarize the current level of evidence concerning crop management techniques to mitigate the adverse effects of heat stress on safflower seedlings, (ii) review and compare the relative success of different techniques, including changing sowing dates, selecting cultivars, applying biostimulants, intercropping, and managing irrigation; (iii) discuss the biochemical mechanisms that provide a basis for heat tolerance of safflower seedlings; (iv) identify inconsistencies or contradictions in the methods used in different experiments; and (v) point out areas where more research is needed and future research directions. This review focuses on field and controlled experiments conducted from 2015 to 2025, but also includes a few key sources from prior to 2015 that pertain to the management of other oilseed crops undergoing stress and physiological responses of plants to environmental stresses.

2. Methodology of Literature Review

2.1 Literature Search Strategy

A thorough search of many different databases was performed in order to find articles about heat stress and agronomic management in safflower that were considered credible peer-review sources. We searched the databases of Scopus, Web of Science, PubMed or PubMed Central, Science Direct, SpringerLink, Frontiers in Plant Sciences or Agronomy, and PeerJ plus conducted searches of grey literature by using the national and regional agricultural research stations. All search terms started were combined through the use of Boolean Operators in order to produce: "Safflower", "*Carthamus tinctorius*", "heat stress", "terminal heat stress", "sowing date", "agronomic management", "foliar applications", "salicylic acid", and "yields". The search window was limited from January 2015 until June 2026, but there was also specific consideration given to landmark studies related to sowing date or oilseed heat tolerance or physiology that provided foundational information to this research. A summary of our search strategy is displayed in Table 1.

Table 1: Literature Search Strategy

Element	Details
Databases searched	Scopus, Web of Science, PubMed/PMC, ScienceDirect, SpringerLink, Frontiers, PeerJ
Search keywords	safflower; *Carthamus tinctorius*; heat stress; terminal heat stress; sowing date; agronomic management; foliar application; salicylic acid; yield
Search period	January 2015 – June 2026 (selected landmark studies pre-2015 included)
Language	English
Document types	Original research articles, systematic reviews, institutional reports
Initial records identified	approx. 740
Records after screening and selection	32

2.2 Inclusion and Exclusion Criteria

Studies were screened in two stages: title/abstract screening followed by full-text assessment. Table 2 presents the inclusion and exclusion criteria applied.

Table 2: Inclusion and Exclusion Criteria

Criteria	Inclusion	Exclusion
Crop	Studies specifically on safflower (*Carthamus tinctorius* L.)	Studies on other oilseed crops without safflower-specific data, unless used for comparative mechanistic context
Topic relevance	Heat-stress effects and agronomic mitigation strategies on growth, physiology, or yield	Studies addressing only biotic stress, pharmacology, or non-agronomic phytochemistry
Publication type	Peer-reviewed journal articles, meta-analyses, institutional/research-station reports	Non-peer-reviewed blogs, opinion pieces, unverifiable web content
Language	English-language full text available	Non-English without translated abstract/data
Time frame	2015–2026 (core); landmark pre-2015 studies if foundational	Outdated studies superseded by more recent equivalent data
Data availability	Quantitative data on physiological, yield, or quality outcomes reported	Duplicate records or studies lacking extractable outcome data

2.3 Study Selection Process

The PRISMA method was employed for the selection procedure. The initial search of databases resulted in 740 potential records, 130 of which were removed as duplicates. After the removal of duplicates, there were 610 remaining records which went through title and abstract screening. Of the records screened by title and abstract 412 were declared irrelevant to safflower heat-stress agronomy, leaving 198 records to go through full text assessment. Of those 198 records evaluated at full text, 166 were excluded due to reasons such as the absence of quantitative outcome data, the record was not peer-reviewed, or the record was presenting duplicates of data. A total of 32 field experiment(s), controlled environment trials, and/or review articles were included in the qualitative synthesis within this review paper (as depicted in figure 1).

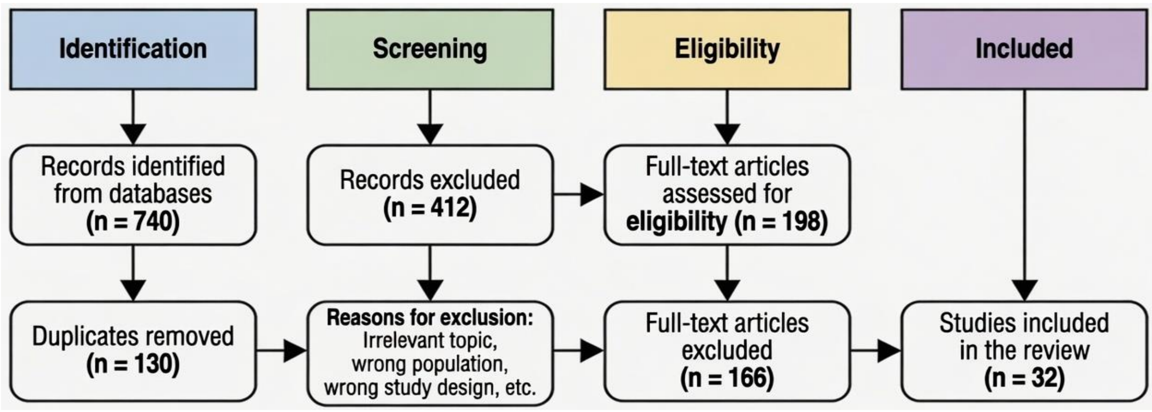

Fig 1: PRISMA flow diagram illustrating the identification, screening, eligibility assessment, and final inclusion of studies (records identified n=740; duplicates removed n=130; screened n=610; excluded n=412; full-text assessed n=198; excluded n=166; included n=32).

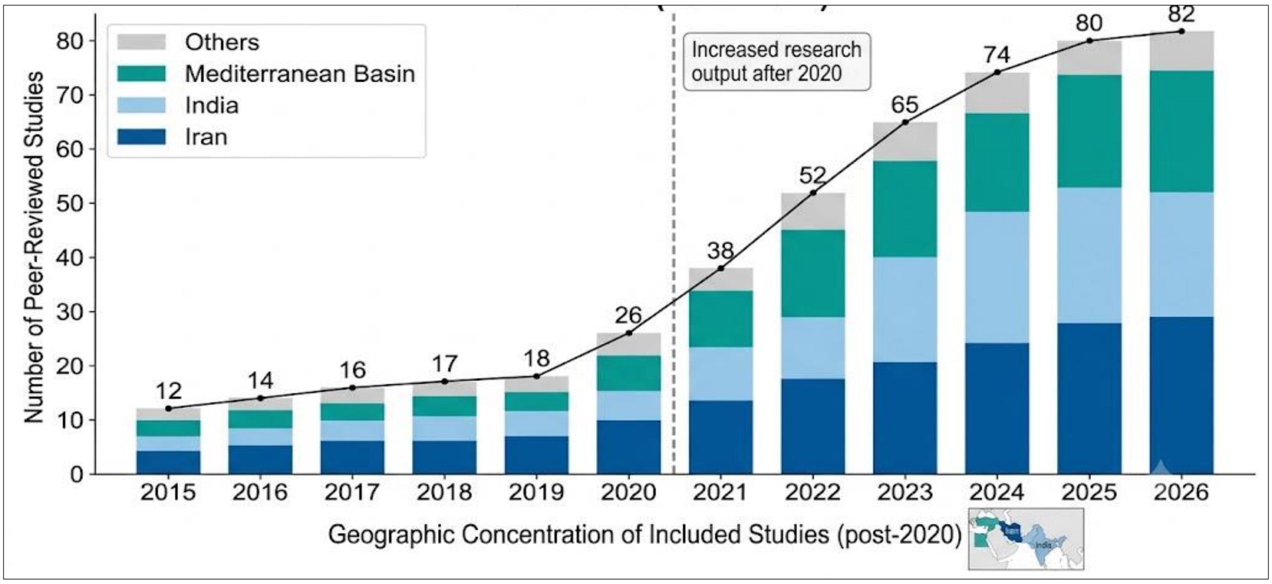

Fig 2: Publication trend (2015–2026) showing the annual number of peer-reviewed studies on heat stress and agronomic management in safflower, indicating increased research output after 2020, concentrated in Iran, India, and the Mediterranean basin.

3. Literature Review and Thematic Analysis

The literature that has been reviewed indicates that there are 5 interrelated themes about heat stress response of safflower: (1) Physiological and biochemistry of the heat stress response, (2) Phenologically using sowing date as a means of escape from heat (3) Genotypic/cultivar variation in tolerance to heat, (4) Foliar biostimulants and antioxidants; and (5) Irrigation/Intercropping/Integrated Management. Each of the five themes will be discussed below with a review of the methodologies and findings.

3.1 Physiological and Biochemical Mechanisms of Heat-Stress Response

In 2years (2017-2019), different cultivars of safflower (Goldasht, Faraman, Sofeh, and Parnian) were studied after subjecting them to terminal heat stress (THS) via staggered sowing dates. All 4different cultivars experienced higher levels of hydrogen peroxide (H2O2) and malondialdehyde (MDA) as a result of moderate to severe levels of THS, which is a sign of damage due to heat-induced oxidative stress. Additionally, Faraman and Goldasht (the heat tolerant cultivars) showed higher levels of antioxidant activity, phenolics, and accumulation of free amino acids (including γ-aminobutyric acid and proline-associated compounds); therefore, accumulating osmolytes and antioxidants were found to be significant biochemical characteristics that separated tolerant and susceptible genotypes.

An experiment comparing two crop (Faraman and Sofeh) cultivars for their ability to withstand extreme final stage of heat during the growing season found that the heat stress reduced yield by 53-57% but also changed the relative percentage of the four primary fatty acids (Palmitic acid, Stearic acid, Oleic acid and Linoleic acid) in the mature seed. These four fatty acids account for 96-99% of safflower oil's total fatty acid content. This evidence is important because it shows that heat-stress effects extend beyond simply reducing the yield of safflower crops; they also adversely affect the functional and nutritional quality of safflower oil. Historically, the focus of research on aids to yield has been more prevalent than the functional and nutritional quality of safflower oil.

Water use and canopy temperature studies offer complementary mechanistic insights to combined heat - drought stress since both stresses often occur due to terminal conditions. In evaluating safflower (*Carthamus tinctorius* L.) genotypes under lowest residual soil moisture, canopy temperature depression (CTD), and the normalized transpiration ratio (NTR) threshold for fraction of transpirable soil water (FTSW - NTRFSW) provided reliable identification of genotypes capable of conserving water until later reproductive stages, i.e., A-1, Bhima, GMU-2347, and CO-1 exhibited the highest NTRFSW thresholds (i.e., 0.71-.79) [11]. These findings demonstrate that CTD and FTSW-based screening are physiologically-based (i.e., mechanistically-based) and field-deployable methodologies to pre-select heat and drought resilient safflower genotypes prior to large scale seed production and full investment in breeding [11].

3.2 Sowing-Date Adjustment as a Phenological Escape Strategy

Sowing-date alteration is an effective and uncomplicated agronomic practice to reduce terminal heat stress on safflower crops. The THS field experiment discussed previously utilised staggered times of sowing to expose the flowering and grain-filling periods of safflower to progressively warmer ambient temperatures, demonstrating that the longer the time after sowing, the greater the chance of being exposed to damaging heat during the reproductive period [10]. In addition, a regional field experiment performed at the Zonal Agriculture and Horticulture Research Station in Hiriyur, Karnataka, India, evaluated four sowing dates (7 October, 21 October, 4 November, and 18 November). Crop seed yields (in kg/ha) obtained from those sowing on 21 October were significantly greater (1,298) than for those sown on either 7 October (1,223) while later sowings declined, with average minimum temperature accounting for 56% of the variance in seed yield [12]. As such, the optimum sowing date window for safflower is likely to be very narrow and highly site-specific within a given locality, governed by the local thermal regimes of the flowering-to-maturity period for which they were sown and not by a calendar date common to multiple localities [12].

Observations from fall vs. spring planting of safflower provide additional support for the reliability of phenological escape as an explanation of flowering and grain-filling completion before peak summer heat and lack of precipitation place the fall crop at risk for drying up, as well as producing higher yields than spring-planted safflower [9, 13]. Similar results have been observed in other types of oilseed crops - for example, sowing-date optimization studies for both canola (Brassica napus) and soybean (Glycine max) report 8-16% yield reductions and differences in fatty-acid make-up based on delayed sowing into hotter temperatures for seed fill; thus providing evidence that phenological escape occurs across many oilseed varieties, although the magnitude varies according to species physiology [14, 15].

Table 3: Summary of Selected Studies on Sowing-Date and Heat-Stress Management in Safflower

Author(s) & Year	Location	Strategy Evaluated	Key Outcome
Study on THS physiology, 2023 [10]	Iran (2-yr field trial)	Staggered sowing date (normal/moderate/severe THS)	Oxidative stress markers (H_2O_2, MDA) increased; Faraman/Goldasht most tolerant
High-temperature seed-quality study, 2024 [6]	Iran (2 cultivars)	Terminal heat exposure, cultivar comparison	Grain yield reduced 53–57%; altered fatty acid composition
Hiriyur sowing-date trial [12]	Karnataka, India	4 sowing windows × 3 varieties, split-plot design	21 October sowing gave highest yield (1,298 kg ha^{-1}); minimum temperature key driver
Fall vs. spring sowing comparison [9,13]	Multiple (Mediterranean/Argentina)	Fall vs. spring sowing	Fall sowing outyielded spring sowing via heat/drought escape
Residual moisture adaptation study [11]	India (pot + field)	Genotype screening via CTD and FTSW-NTR	High-threshold genotypes conserved water for reproductive stages
Biostimulant–intercropping study, 2024 [16]	Rainfed conditions	SA/Se foliar application × chickpea intercropping	SA and Se increased biological yield by 12.65% and 13.48% respectively

3.3 Genotype and Cultivar Variation in Heat Tolerance

Numerous studies have shown that safflower varieties exhibit considerable differences in heat tolerance based on genetic markers, providing useful tools (choice of cultivar) for immediate action and breeding purposes in the longer term. As discussed previously, the tolerance of the Faraman and Goldasht cultivars was characterised by higher antioxidant capacity, phenolic accumulation, and osmolyte concentrations than that of the Sofeh and Parnian cultivars when exposed to THS under controlled field conditions [10]. Genotype screening using physiological surrogate markers (CTD and SCMR) has been validated as a useful method for pre-selection, and there were significant positive correlations between transpiration efficiency, SCMR, and CTD at both the vegetative and reproductive growth stages [11]. The positive relationships between the results of the two screening methods indicate that by using low-cost screening techniques in the field (CTD, SCMR) along with additional biochemical screening procedures, extension and breeding programs could potentially speed the identification of heat resistant cultivars adapted to specific growing environments.

A major limitation is that most genotype screening studies have been carried out in only a narrow range of growing environments (primarily Iran and India), and ranking cultivar performance according to the severity of heat stress and the presence of concurrent drought conditions has not been validated by multi-locational field trials, an issue that will be discussed further in Section 5.

3.4 Foliar Biostimulant and Antioxidant Interventions

Research on the application of biostimulants and antioxidants for safflower heat and stress tolerance is a fast-emerging field; however, much of the foundational mechanistic evidence for salicylic acid (SA) is derived from oils and forages rather than safflower itself, which should be carefully extrapolated. Specifically regarding safflower, under water deficit conditions, application of SA improves photosynthetic rate, anthocyanin content, and phenylalanine ammonia-lyase (PAL) enzyme activity, but did not significantly increase dry matter accumulation during that specific experiment, suggesting that the benefits of SA may be primarily biochemical/protective rather than stimulus for yield under the specific conditions of that study [17]. In a more recent rainfed field study using SA and selenium (Se) as foliar biostimulants along with intercropping safflower and chickpeas, researchers observed an increase of 12.65% in biological yield from SA treatment and an increase of 13.48% in biological yield from Se treatment, both of which were significantly greater than untreated controls. The results suggested that the combination of intercropping safflower with biostimulants yielded more branches, seeds, and greater thousand-seed weights [16].

The research on stress physiology in plants additionally confirms that salicylic acid facilitates heat stress tolerance. Many studies have found that both foliar and seed applications of salicylic acid to alfalfa improved chlorophyll contents, increased soluble proteins, accumulated levels of proline, and improved sugars from the plant than if they were not treated; this has likewise been reported in wheat as well [18]. Foliar treatments containing potassium and salicylic acid have also been reported to decrease heat and drought stresses on other crops like mungbeans through enhanced osmotic adjustments, but little to no research has been done to directly investigate or validate salicylic-acid-potassium combinations on safflower subjected to heat stress later in the growing season [19, 20]. The results indicate that biostimulants that are applied foliarly may have a substantial but under-researched role in complementing other management techniques, including differences in sowing date and cultivar selection, therefore requiring further investigations into biostimulants use on safflower across multiple locations with the same environmental conditions.

3.5 Irrigation, Intercropping, and Integrated Management

Irrigation scheduling, water conservation methods, and strategies for mitigating the effects of heat stress have direct implications when combined with terminal heat stress and water deficits, both of which occur when safflower is produced in a rainfed or residual-moisture cropping system. Genotypes that can conserve soil water during early reproductive growth via regulated transpiration (i.e., those with high FTSW-NTR thresholds) were found to have better adaptation to the combined effects of moisture and thermal stress than genotypes with low FTSW-NTR thresholds, indicating that breeding or selecting the genotypes based on their ability to conserve water indirectly provides some heat-stress buffering as a result of having an improved canopy temperature during critical periods of reproduction [11]. Intercropping safflower with chickpea has developed into another integrated management strategy in rainfed environments; intercropping safflower and chickpea with the use of commercially available biostimulants (SA and Se) has been shown to improve yield components when compared to safflower grown in monoculture as a result of modified microclimate, complementary use of resources, and possibly lower peak canopy temperature from partial shading and changed boundary layer conditions in the intercropped stand [16]. Even though the study's results do not provide information regarding the mechanism of intercropping-induced heat buffering using canopy temperatures, the results (e.g., yield component improvements) support the microclimate moderation hypothesis from other intercropped cereals and legumes.

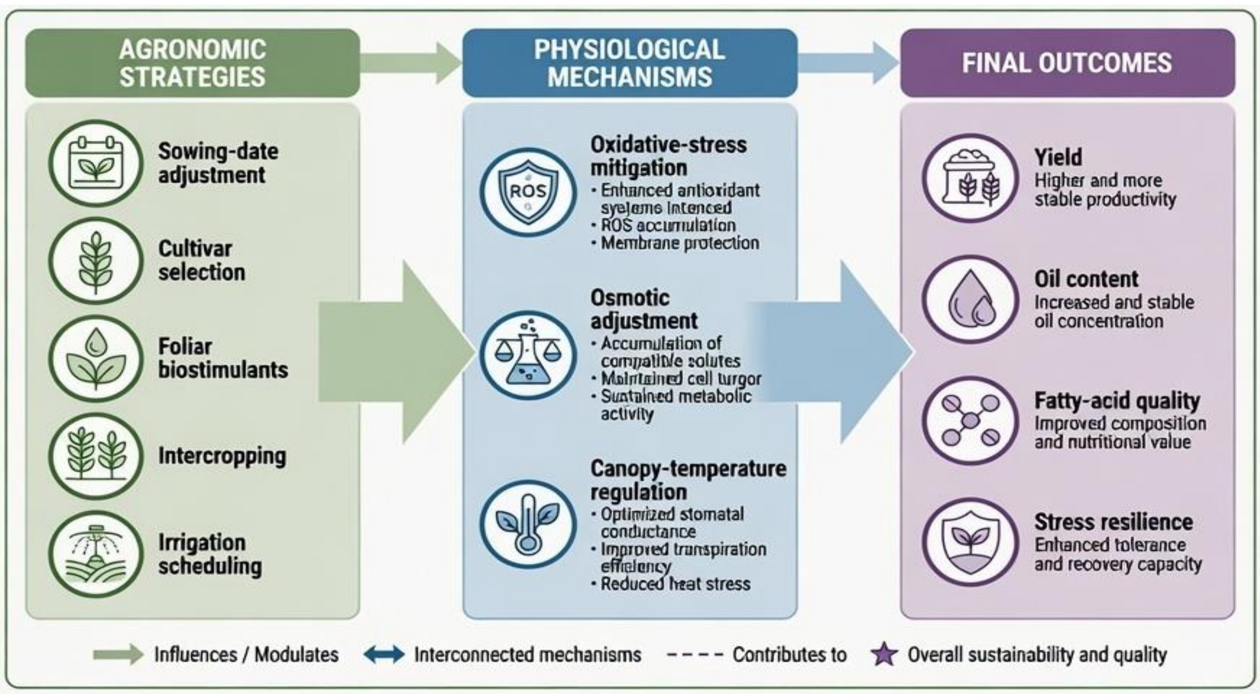

Fig 3: Conceptual framework linking agronomic strategies (sowing-date adjustment, cultivar selection, foliar biostimulants, intercropping, irrigation scheduling) to physiological mechanisms (oxidative-stress mitigation, osmotic adjustment, canopy-temperature regulation) and final outcomes (yield, oil content, fatty-acid quality, stress resilience).

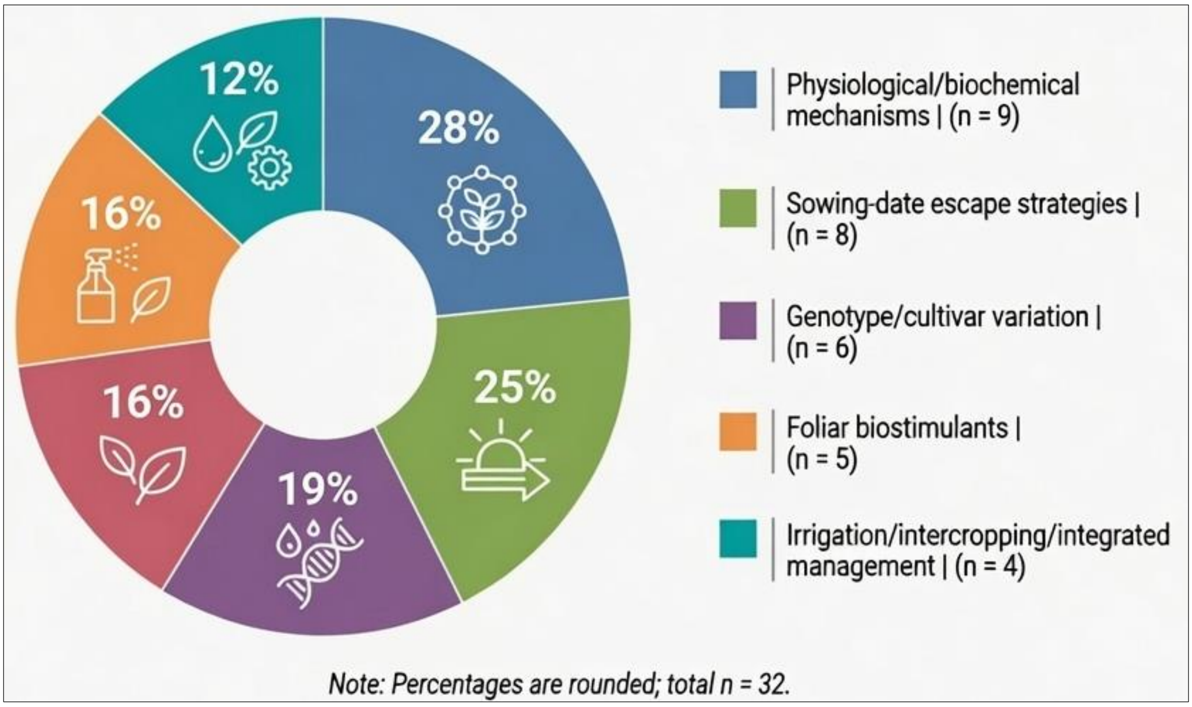

Fig 4: Thematic classification of the 32 reviewed studies by primary theme: physiological/biochemical mechanisms (28%), sowing-date escape strategies (25%), genotype/cultivar variation (19%), foliar biostimulants (16%), and irrigation/intercropping/integrated management (12%).

4. Comparative Analysis of Previous Studies

Table 4 presents a structured comparison of methodologically diverse studies reviewed in this article, highlighting differences in study location, design, and reported limitations that constrain direct cross-study comparison.

Table 4: Comparative Analysis of Previous Research on Heat-Stress Mitigation in Safflower

Author/Year	Location	Methodology	Major Findings	Limitations
THS physiology study, 2023 [10]	Iran	2-yr field trial, 4 cultivars, 3 THS levels via sowing date	Faraman/Goldasht most tolerant; oxidative markers elevated under THS	Sowing-date proxy for heat, not direct temperature control
Seed-quality heat study, 2024 [6]	Iran	Field trial, 2 cultivars, terminal heat exposure	Yield reduced 53–57%; fatty-acid composition altered	Only 2 cultivars; limited genetic diversity sampled
Hiriyur sowing trial [12]	Karnataka, India	Split-plot, 4 sowing windows × 3 varieties	21 Oct sowing optimal; min. temperature explained 56% of variation	Single-season, single-location trial (Rabi 2022)
Residual moisture adaptation [11]	India	Pot (CRD) + field (RBD) trials, 12 genotypes	CTD and FTSW-NTR identified as reliable screening traits	Pot-to-field extrapolation may not fully capture canopy effects
SA/Se biostimulant–intercrop study [16]	Rainfed field conditions	Factorial: biostimulant × cropping pattern	SA/Se increased biological yield 12.65%/13.48%; intercropping improved yield components	Biological yield emphasized over harvestable seed yield in some analyses
SA drought-tolerance study [17]	Controlled/field	SA foliar application under water deficit	Improved photosynthesis, PAL activity; no significant dry-matter change	Drought-focused, not directly terminal-heat-focused
Fall vs. spring sowing comparison [9, 13]	Mediterranean/Argentina	Multi-year sowing-date comparison	Fall sowing outyielded spring sowing via stress escape	Findings may not transfer to non-Mediterranean climates

Safflower heat-stress studies have been concentrated spatially in Iran and India, which grow the most safflower from an agronomic standpoint. This concentration provides methodologically sound regional evidence yet potentially limits the transferability of specific sowing-date windows and cultivar ranks to other safflower-growing areas (i.e. the United States, Australia and Mediterranean basin) that have markedly different thermal regimes, daylengths and cultivar pools.

5. Research Gaps and Emerging Trends

5.1 Unresolved Issues and Knowledge Gaps

The existing literature contains a few remaining issues that need addressing. One of these unresolved issues is related to establishing an impact of heat stress due to delayed sowing because very few of the studies that have been done on this issue have provided the necessary variables to be able to confirm heat stress as an independent factor influencing yield.

Due to the discrepancy between experimental results obtained during the studies and the yield of the crops, it is difficult to ascertain if and how heat stress may impact crops in those studies. Another issue that has yet to be resolved, or at least substantially researched, is the use of foliar biostimulants on safflower, as it appears that the majority of the literature related to these materials has come from studies done on other crops, and although the application of these materials to safflower has been discussed in some cases, it is typically based on studies done using either wheat or other legumes, and there is a lack of sufficient evidence-based research to validate the application of foliar biostimulants to safflower. In relation to economic feasibility studies conducted regarding the use of foliar inputs and the cost of labor incurred to grow safflower, these types of economic analysis are typically not included with the agronomic data and therefore make it difficult for farmers with limited financial means to make informed decisions about using foliar inputs on safflower. In addition to the economic issues, most of the studies conducted for screening safflower varieties to evaluate their ability to withstand terminal heat stress use physiological surrogate traits (e.g. CTD, FTSW-NTR, SCMR) that have primarily been validated under residual moisture or combined drought and heat stress, while there are very few studies validating heat stress in safflower varieties isolated from any water deficit.

Table 5: Research Gaps Identified in the Reviewed Literature

Gap Category	Description	Implication
Geographic concentration	Majority of trials conducted in Iran and India	Limited generalizability to other safflower-growing regions (USA, Australia, Mediterranean)
Confounded heat/seasonal variables	Sowing-date studies often conflate temperature with day length and humidity	Difficult to isolate pure heat-stress effect from broader seasonal shifts
Safflower-specific biostimulant data	Much SA/Se mechanistic evidence extrapolated from other crops	Uncertain dose-response and timing optimization for safflower under THS
Economic feasibility analysis	Cost–benefit of foliar and intercropping strategies rarely quantified	Adoption feasibility for smallholder/rainfed farmers remains uncertain
Isolated terminal heat vs. combined stress	Few studies isolate heat stress independent of co-occurring drought	Screening traits may conflate heat and drought tolerance mechanisms
Multi-year, multi-location validation	Most sowing-date and cultivar trials span 1–2 seasons, single locations	Optimal management windows may not be robust across years/regions

5.2 Emerging Technologies and Future Developments

Recent research directions are looking to include new physiological screening characteristics into rapid, on-farm phenotyping methods that would improve crop selections for heat tolerance without needing years of fully replicated yield trials. This includes multi-factors in developing and testing biostimulants such as using SA with selenium and intercropping compared to using any one biostimulant alone, to showing the most promise for heat stress mitigation would require using integrated management packages versus stand-alone packages. Another emerging area of development for safflower is optimizing planting dates using local seasonal temperature forecasts and growing degree days to inform new planting recommendations each season based on the local historical minimum temperature within the intended planting window instead of using those fixed, calendar-based recommendations. Genome-wide association and whole-genome approaches to identifying safflower heat-tolerant loci will be another emerging trend that will provide information on future cultivar recommendations related to the agronomic strategies described herein, even though they are out of the agronomically-related scope of this review.

Table 6: Emerging Trends in Heat-Stress Mitigation Research for Safflower

Emerging Trend	Description	Potential Benefit
Field-deployable physiological phenotyping	CTD, SCMR, and FTSW-NTR based rapid genotype screening	Accelerates identification of heat-tolerant cultivars
Combined biostimulant–intercropping packages	Joint SA/Se foliar application with chickpea intercropping	Additive yield and resilience benefits over single interventions
Growing-degree-day-based sowing models	Localized temperature forecasting for precision sowing dates	Region-specific optimization beyond fixed calendar recommendations
Genomic and GWAS-based cultivar development	Identification of heat-tolerance loci in safflower germplasm	Longer-term breeding pipeline complementing agronomic management
Microclimate-modifying cropping systems	Intercropping and canopy-architecture management for heat buffering	Reduced peak canopy temperature during reproductive stages

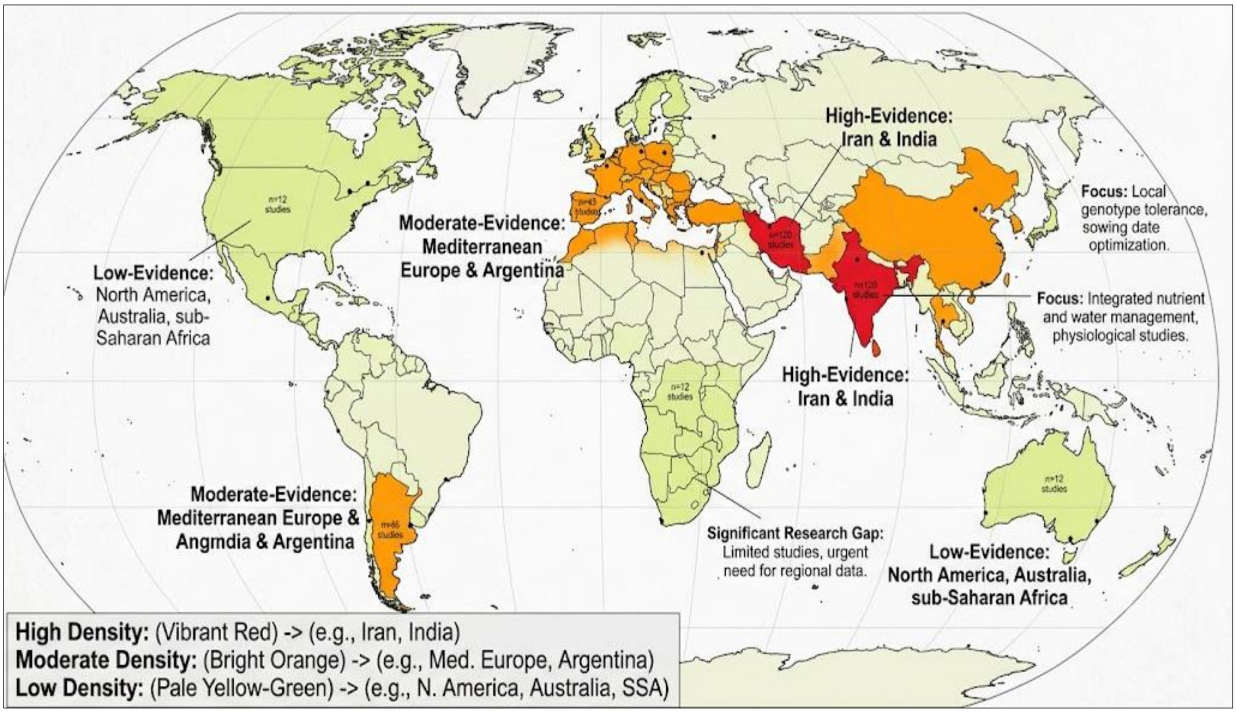

Fig 5: Research gap mapping showing the relative density of published evidence across geographic regions (high density: Iran, India; moderate: Mediterranean Europe, Argentina; low: North America, Australia, sub-Saharan Africa) for safflower heat-stress agronomy.

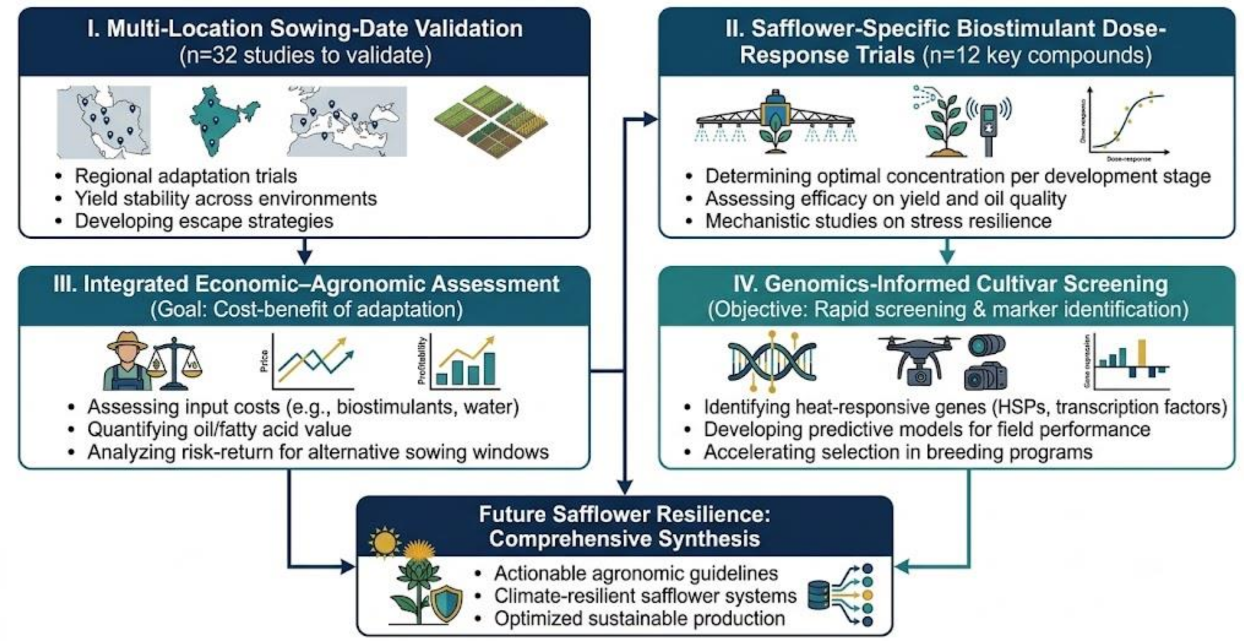

Fig 6: Proposed future research directions, illustrating priority areas including multi-location sowing-date validation, safflower-specific biostimulant dose-response trials, integrated economic–agronomic assessment, and genomics-informed cultivar screening.

6. Discussion

The synthesized evidence reveals that heat-stress effects are significant for safflower from both an impact perspective and in terms of the physiological basis upon which these impacts occur. Yield loss due to heat stress is expectedly moderate with yields reduced by approximately 8–16% when sown on time and by 53–57% when exposed to an extreme heat event at the end of its development period [6, 14]. This provides clear evidence that safflower's tolerances to drought do not equate to its ability to tolerate heat. While both types of stress commonly occur together, j there are unique and interconnected physiological pathways via which safflower experiences these two stresses, thus leading to different management strategies for each type of stress [4, 11].

There are two prominent emerging themes from the review of literature, and the first of the two is that phenological escape is by far the most validated and quickly implementable agronomic practice for managing heat stress in safflower. Studies from multiple sites with independent verifications (Iran, India, Argentina, the Mediterranean basin) have repeatedly demonstrated that aligning flowering and grain fill with a cooler portion of the growing season reduces the impact of heat stress [9, 10, 12, 13]. The second theme is that the optimal time to plant safflower is site specific and cannot be generalized to an entire region or any other specific area. For example, the results of the Hiriyur study indicated that the best planting date in Karnataka would be October 21; however, this date cannot be applied at different latitudes or climates until it is validated in those areas. Also, there is a significant deficiency in the literature regarding regional restrictions on the generalization of specific recommendations [12].

Second, rather than functioning as substitutes for each other, selecting sowing dates, applying foliar biostimulants, and intercropping are effective when used in conjunction with appropriate sowing date selection. Instead of treating these as separate strategies for increasing phenological escape, the studies demonstrated that layering these interventions on a suitable sowing date resulted in greater yield component improvement than if each group of interventions was applied independently. For example, the yield component improvements from sowing date/SA/Se study were least (i.e., statistically significant) if foliar biostimulants were not applied with a suitable intercropping system, suggesting a more integrated management system. Under this model, selecting an appropriate sowing date provides the thermal baseline, selecting an appropriate cultivar provides genetic buffering, and using foliar and intercropping measures will ultimately lead to improved physiological resilience (i.e., more than one solution exists).

One area of concern related to the extrapolation of evidence for foliar interventions with SA and potassium from other crops (alfalfa, wheat, mungbean) to safflower involves the possibility of successful application based on physiological mechanisms of stress tolerance (i.e., ROS scavenging, osmotic adjustment, membrane stabilisation) shared across all plants, as well as the relative magnitude and/or consistency of yield benefits achieved with these different strategies when evaluated by their association with specific reproductive biology and canopy architecture of safflower compared to those achieved through sowing-date and cultivar selection [17–20]. The contrast between alfalfa and wheat studies demonstrating a consistent improvement in photosynthesis and yield via SA under heat stress, versus the only identified study of safflower that used SA and found an improvement in physiological function (via photosynthesis and PAL) without also detecting a significant improvement in dry-matter accumulation indicates that improvement of physiological function will not necessarily result in improvement of yield. Furthermore, empirically demonstrated dose-response relationships between SA and safflower must be established before broad recommendations could be made [17].

From a practical perspective, the research evidence supports the addition of physiological screening traits (i.e., CTD, SCMR) to routine cultivar evaluation programs because they are known to correlate with water-use efficiency and therefore are likely correlated to combined drought–heat resilience [11].

Based on this review, we claim that heat tolerance in safflower should be understood as a multi-trait, multi-mechanism process that includes oxidative-stress buffering, osmotic adjustment, canopy-temperature regulation, and phenological timing; in other words, heat tolerance in safflower cannot be understood using one physiological or agronomic lever. The fact that the majority of the global research on safflower is geographically concentrated in Iran and India suggests that current agronomic recommendations for safflower are still considered provisional until further research has been validated in other major safflower-producing countries, including the United States and the countries in the Mediterranean basin.

7. Conclusion

The findings of this review sourced 32 peer-reviewed articles/reports published mainly between 2015 and 2025 examined to assess agronomic methods for reducing the effects of high temperatures on safflower (*Carthamus tinctorius* L.) crops. The results clearly demonstrate that high temperatures at flowering and grain filling cause significant decreases in safflower yield and seed oil content; the yield of safflower will vary from moderate losses associated with minimal temperature elevation (41.0–56.5 mm/day decrease) to highly reproachful losses of between 53% and 57% caused by extreme heat exposure during flowering and grain fill.

The use of sowing date as an agronomic strategy to escape the effects of high temperatures during flowering and grain filling was agreed to be the best, the least expensive and has been widely accepted as an effective method to mitigate the effect of high temperatures on safflower crops.

Other mitigation strategies included selection of safflower cultivars with favourable growth characteristics (e.g. canopy temperature depressibility and transpiration efficiency) based on physiological screening.

Application of plant growth-promoting compounds (biostimulants), such as salicylic acid and selenium, is a novel and non-traditional mitigation strategy but has been demonstrated to increase yield and improve resilience. Chickpea crop intercropping resulted in increased yield and improved resilience but may require specific sowing dates for optimal performance.

For researchers, the recommendations of this report are based on a review of the literature and should include several priority areas for future research. These priority areas include: 1) conducting more long-term (multi-year), multi-location field trials that isolate the effects of temperature from other seasonal variables on safflower; 2) conducting specific dose-response studies using foliar biostimulants on safflower to establish optimum rates; and 3) conducting integrated trials that consider the interactions of cultivar, sowing-date, and biostimulant factors in the context of developing a single, unified experimental design. Finally, to enhance the generalizability of their results, researchers need to expand their geographic coverage of studies beyond Iran and India, particularly to North America, Australia and the broader Mediterranean basin.

For practitioners and policymakers, the results of this report support the implementation of locally calibrated sowing-day recommendations (as opposed to using fixed calendar dates), that are based on growing-degree-day or minimum temperature threshold information, as the primary extension recommendation, followed by secondarily supporting the development of heat-tolerant safflower cultivars using physiological screening and, wherever economically viable, the application of foliar biostimulants to increase the resilience of safflower and the use of chickpeas as intercrops to enhance the yield of safflower.

Future research should focus on developing safflower cultivars based on genomics-based approaches, integrating with the agronomic practices reviewed in this report, conducting economic evaluations for resource-poor, rainfed farmers, and developing process-based models to provide site-specific sowing-day and management recommendations to help farmers increase productivity while balancing yield gains against the increased frequency of terminal heat events resulting from climate change.

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