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Saffron (*Crocus sativus* L.): The golden spice — management, challenges, and opportunities for sustainable production in the United States

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ABSTRACT

Saffron (*Crocus sativus* L.) is a perennial, stem-less, fall-blooming geophyte in the Iridaceae family. Nicknamed "red gold", saffron is consistently one of the most expensive spices by weight on the global market. Propagating exclusively through corms, its flowering occurs from mid-October to late November in the Northern Hemisphere, displaying violet-colored petals with dark red to reddish-brown stigmas and yellowish brown to yellowish orange styles. Saffron thrives in loose, well-drained, low-density, clay-calcareous soils with adequate organic matter. The major phytochemical components contributing to the distinctive color, taste, and aroma of the stigmas are crocin, picrocrocin, and safranal, respectively. There has been a recent surge in scientific interest in saffron, driven by its potential therapeutic applications against cancer cells, Alzheimer's disease, and cardiovascular disorders. Saffron cultivation does not require significant land or equipment investment, provides employment opportunities, and can serve as an additional income stream for small farms. However, global saffron cultivation is challenged by climate change, rising labor costs, global supply chain disruptions, and product adulteration, emphasizing the need for multi-disciplinary research to understand and maximize the potential of saffron production. Further research into mechanization, biotechnology, and the development and enforcement of authenticity and quality standards will be critical to maintain a sustainable global supply. This review synthesizes current knowledge on saffron, with a focus on its potential in the US and other emerging production regions. It addresses saffron's origin, biology, chemical composition, uses, and market adulteration, while identifying key research gaps and opportunities for expansion. Emphasis is placed on agronomic practices and climate-resilient farming to support informed decision-making and the sustainable development of the saffron industry.

1. Introduction

Saffron (*Crocus sativus* L.), colloquially referred to as "red gold," has historically been one of the world's most expensive spices by weight [1]. It is cultivated extensively in Iran, Azerbaijan, Greece, Italy, Spain, Turkey, Afghanistan, and India, where it has been a staple ingredient for centuries [2]. In 2023, the global saffron market, comprising organic and traditional types, was valued at approximately USD 602.2 million. It is expected to grow at a robust compound annual growth rate (CAGR) of 7.1 % from 2024 to 2030, potentially exceeding a market value of USD 1 billion by the end of the decade [3].

Because of the high market price [4], incorporating saffron into small- and medium-scale crop production could provide significant economic benefits for agricultural communities around the world. Demand for saffron in the US has been steadily increasing in recent decades, both as a culinary ingredient and due to its demonstrated therapeutic effects and benefits for human health [5]. In 2022, the US imported over $20 million in saffron (103,000 kg), up from $5 million (14,000 kg) in 2002 [6]. Despite its high value and market potential, saffron cultivation remains relatively underexplored in the US, offering

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an opportunity for innovative farmers to diversify their cropping systems and enhance on-farm economic viability. Diversified farming systems help mitigate financial, market, and production risks, and the inclusion of saffron as a consistently high-value product could reduce financial risk for farmers while requiring only a small area of land.

Iran is the global leader in saffron production, accounting for more than 80 % of the world's supply. However, ongoing political unrest, climate change, and supply chain disruptions could threaten the world's access to the spice if alternative production zones are not identified. In addition to maintaining a sufficient global supply, reducing reliance on foreign-grown products will strengthen regional food security and improve economic viability for individual farmers. However, knowledge and resources related to saffron production in the US and other emerging production zones are limited. Information on management requirements, market trends, and utilization of saffron, particularly in the US, is essential to expand the industry and capitalize on its economic co-benefits.

This comprehensive review offers a unique synthesis of current knowledge on saffron production, with a particular emphasis on its relevance to the US and other emerging production regions. Unlike previous reviews, this work consolidates critical information on the origin, biology, chemical composition, agronomic management, uses, and adulteration of saffron, while also identifying key research gaps and opportunities for expanded production within the US context. It further explores the potential for organic saffron cultivation—an area not extensively addressed in existing literature. The objective is to develop a comprehensive, evidence-based resource that informs decision-making, guides strategic planning, and supports the sustainable development of the saffron production and industry. This information is especially valuable for small-scale farmers, students, researchers, and industry professionals, providing insights into opportunities and strategies to mitigate potential production, market, and financial risks.

2. Origin

The etymology of the term "saffron" reflects its rich and diverse history across multiple languages [7]. The word "saffron" originates from the French word "safran", which is derived from the Latin word "safranum." Additionally, it has been linked to the Arabic word "Zafaran", which denotes the color "yellow" [1,8]. The center of origin of the saffron plant is debated among scholars, with some attributing its beginnings to Iran [9] and others to Greece [10].

Saffron has a long history of cultivation, with documented use dating back several millennia [7]. One of the earliest textual references appears in the 'Canticle of Canticles' (circa 1100–1000 B.C), in which saffron is mentioned as 'karkom,' potentially linking its origin to the Kashmir region of India [11]. Archaeological evidence from Minoan Crete further supports early crocus cultivation; frescoes dated to 1700-1600 B.C. depict the harvesting of crocus stigmas, suggesting its cultural and possibly medicinal or ritual significance during that period [9,11]. Classical texts also reference saffron or crocus, with mentions found in the works of Aeschylus, Sophocles, Hippocrates, Aristophanes, Theophrastus, Plautus, Varro, Celsus, Pliny the Elder, and Galen, spanning from around 525 B.C. to 200 A.D [12]. There is further evidence to suggest that saffron was utilized for culinary or medicinal purposes in the Mediterranean region during the late Bronze Age [13]. Moreover, during the Akkadian period (2350–2150 B.C.), saffron is believed to have held symbolic and economic significance. The Mesopotamian king Sargon was reportedly born in a place called "Azupiranu," a name interpreted by some scholars to mean 'Saffron city' [11].

Recent genetic studies suggest that the modern saffron crocus (*Crocus sativus*) is a triploid species that originated through the domestication of the wild *Crocus cartwrightianus* [14]. Through advanced genomic sequencing and cytogenetic analyses, these studies have confirmed that the saffron crocus likely originated in the Mediterranean region, particularly in Greece, south of Athens. Independent studies have further corroborated this hypothesis, identifying this area as the native range of the wild crocus species and the likely cradle of saffron cultivation [10].

3. Taxonomy

Saffron is a monocotyledonous flowering plant, characterized by having an embryo with a single cotyledon and parallel-veined leaves [15]. The plant is a perennial stem-less geophyte in the Iridaceae family (Fig. 1) and is one of approximately 80 species worldwide in the *Crocus* genus [16]. Taxonomically, saffron is classified as follows.

Domain: Eukarya
Kingdom: Plantae
Subkingdom: Tracheobionta
Superdivision: Spermatophyta
Division: Magnoliophyta
Class: Liliopsida
Subclass: Liliidae
Order: Asparagales
Family: Iridaceae
Genus: *Crocus*
Species: *sativus*

Plants in the *Crocus* genus are characterized by corms, underground storage organs, enclosed by fibrous reticulated leaf tunics [17] (Fig. 1). *Crocus sativus* is one of few species within the *Crocus* genus that is intentionally cultivated for its culinary value.

4. Morphology

Saffron plants, emerging from corms, typically reach a height of 10–20 cm. The corms, which serve as the plant's underground storage organs, are flat to ovoid or sub-globose depressed shapes, with a horizontal diameter spanning from 0.5 to 6.5 cm and weights between 0.5 and 15 g (Table 1) [1]. Each mother corm produces 1 to 3 medium to large daughter corms from apical buds, with the quantity dependent on the size of the mother corm. Additionally, a medium-sized corm, with 2–3 apical buds, can produce 2 to 3 daughter corms, along with a floral axis and leaves. Many of the roots emerging from the mother corm are thin, fibrous, and 15–20 cm long, though roots may be thicker and shorter near lateral buds. Contractile roots, which can pull the corm deeper into the soil, are thick roots that develop as daughter corms [1,17].

Each corm typically produces a cluster of six to nine grass-like leaves. The leaves are dark green and narrow, typically 40–70 cm long and 2–3 cm wide [17] (Table 2). During emergence, the leaves are upright (orthotopic), but later transition to a horizontal orientation (plagiotopic) during development [1]. In temperate areas of the Northern Hemisphere, leaves generally grow from September to May, after which they dry out.

A saffron plant typically produces a single flower, though up to 4 may emerge from a single plant under ideal conditions. Saffron is a sub-hysteranthous plant, meaning its flowers can emerge either before or after the leaves [1]. The saffron flowers are violet-colored, with dark red to reddish-brown stigmas and yellowish brown to yellowish orange styles [17] (Fig. 1). Each flower contains three stigmas, which are harvested, dried, and marketed as saffron [18].

Saffron flowers consist of a perigonium with six violet tepals, ranging from 20 to 47 mm in length and 11–23 mm in width, a pistil, and an androecium with three stamens characterized by short filaments and yellow anthers containing pollen. On average, each flower weighs between 300 and 500 mg. Fresh stigmas weigh between 25 and 47 mg, while dry stigmas weigh between 6 and 9 mg [1].

Fig. 1. Key stages in saffron (*Crocus sativus* L.) production and processing. (a) Corms—underground storage structures that serve as the propagative material; (b) Saffron plants at flowering stage, displaying erect floral shoots; (c) Fully bloomed saffron flower, characterized by its violet petals and red stigmas; and (d) Freshly harvested stigmas, manually separated from the flowers. Post-harvest, stigmas are subjected to drying using sun, shade, oven, or microwave methods to reduce moisture content and preserve bioactive compounds, color, and aroma. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Physical properties of saffron (*Crocus sativus* L.) corms (Adapted from Ref. [130]).

Properties, Unit	Minimum	Maximum	Mean
Weight (g)	3.85	14.82	7.77
Geometric diameter (mm)	18.34	27.17	22.96
Arithmetic diameter (mm)	18.42	27.49	23.2
Sphericity (dimensionless)	0.83	0.91	0.86
Particle density (g cm^{-3})	1.04	1.22	1.19
Bulk density (g cm^{-3})	0.45	0.51	0.48
Static Coefficient of friction	0.65	0.73	0.7

Table 2
Morphological characteristics of saffron (*Crocus sativus* L.) (Adapted and modified from Ref. [131]).

Parts/organs, Unit	Mean ± SD
Corm (mm)	50 ± 1.0
Neck (mm)	50 ± 1.2
Number of leaves	8.0 ± 1.0
Number of flowers	3.0 ± 1.0
Perigonium length (cm)	4.0 ± 1.0
Stamens: filaments length (mm)	1.0 ± 0.5
Stamens: anthers length (mm)	20 ± 5.0
Stigma length (mm)	24 ± 2.0
Flowering period	Oct–Nov

5. Biology

Saffron is classified as a sterile triploid male monocotyledon (2n = 3x = 24) due to irregular meiosis during gametogenesis, which results in infertile pollen and ovules [11]. Consequently, the species reproduces exclusively through vegetative propagation via underground storage organs known as corms. Corms development occurs during the vegetative growth phase, spanning late autumn through spring, with active growth continuing until leaves senesce in April. Following senescence, the corms enter a dormant phase lasting until approximately July. Flowering typically occurs from mid-October to late November, with phenological timing largely influenced by climatic conditions. Saffron needs sunny spring conditions preceding dormancy for enhancing yield potential in the subsequent autumn, while cooler temperatures in early fall were found to be key drivers of floral induction [19]. In newly established plantings, floral emergence may occur 60–90 days post-planting; however, this period can be extended under conditions of persistent cold and snowfall [17].

6. Phytochemical components of saffron

Saffron contains over 160 volatile and non-volatile compounds [11]; however, three major biologically active compounds—crocin, picrocrocin, and safranal—are primarily responsible for its characteristic color, flavor, and aroma (Fig. 2). Crocin ($C_{44}H_{64}O_{24}$), or 8,8-diapocarotene-8,8-dioic acid, is a vibrant carotenoid pigment that imparts the distinct yellow-orange hue of saffron. It exhibits important antioxidant properties and accounts for approximately 0.5–32.4 % of the dry matter of the saffron stigmas [11]. Picrocrocin ($C_{16}H_{26}O_7$), chemically known as 4-(b-D-glucopyranosyloxy)-2,6,6-trimethyl-1-cyclohexene-1-carboxaldehyde, comprises 0.8–26.6 % of saffron's dry matter. It is a colorless glycoside, imparting the spice with its distinctive flavor and subtle bitterness. Through a natural de-glycosylation process, picrocrocin is converted into safranal ($C_{10}H_{14}O$), a monoterpene aldehyde, responsible for saffron's aroma. Safranal (2,6,6-trimethyl-1,3-cyclohexadiene-1-carboxaldehyde) can constitute up to 70 % of the volatile fraction of saffron [11,16].

In addition to these major constituents, saffron also contains a wide range of other bioactive compounds, including terpenoids (e.g., sesquiterpene, monoterpenoids, diterpenoids, and tetraterpenoids), flavonoids (e.g., kaempferol, Dihydrokaempferol, and Quercetin), alkaloids (e.g., 5-methyl uracil, pyridin-3-ylmethanol, and uracil), steroids (e.g., phytosterols, β-sitosterol, and stigmasterol), and phenylpropanoids (e.g., chlorogenic acid, sinapic acid, p-coumaric acid, caffeic acid, and ferulic acid) [17,20].

7. Saffron cultivation

Saffron is typically cultivated as a perennial crop; however, in certain regions such as Navelli, Italy, it is grown annually. The duration of perennial cultivation varies significantly by region: 3–4 years in Spain, 6–8 years in India and Greece, and up to 12 years in Morocco [17]. Saffron exhibits considerable adaptability to a wide range of environments, particularly those with mild to arid climates, and can tolerate temperatures ranging from −18 °C to 45 °C. It has been successfully cultivated at altitudes up to 2000 m above sea level [21], with several studies indicating increased yields at higher elevations (above 1300 m) due to cooler early autumn temperatures.

Saffron corms are typically planted after August 15 in central Italy (Navelli), during the second half of June in Spain, between mid-July and August in India, from May to September in Greece, between late August and early September in Morroco, and between August to mid-October in the US [13]. On average, 1 ha of saffron cultivation yields 10–15 kg of dried stigmas, although yield may vary widely, from 2 to 30 kg,

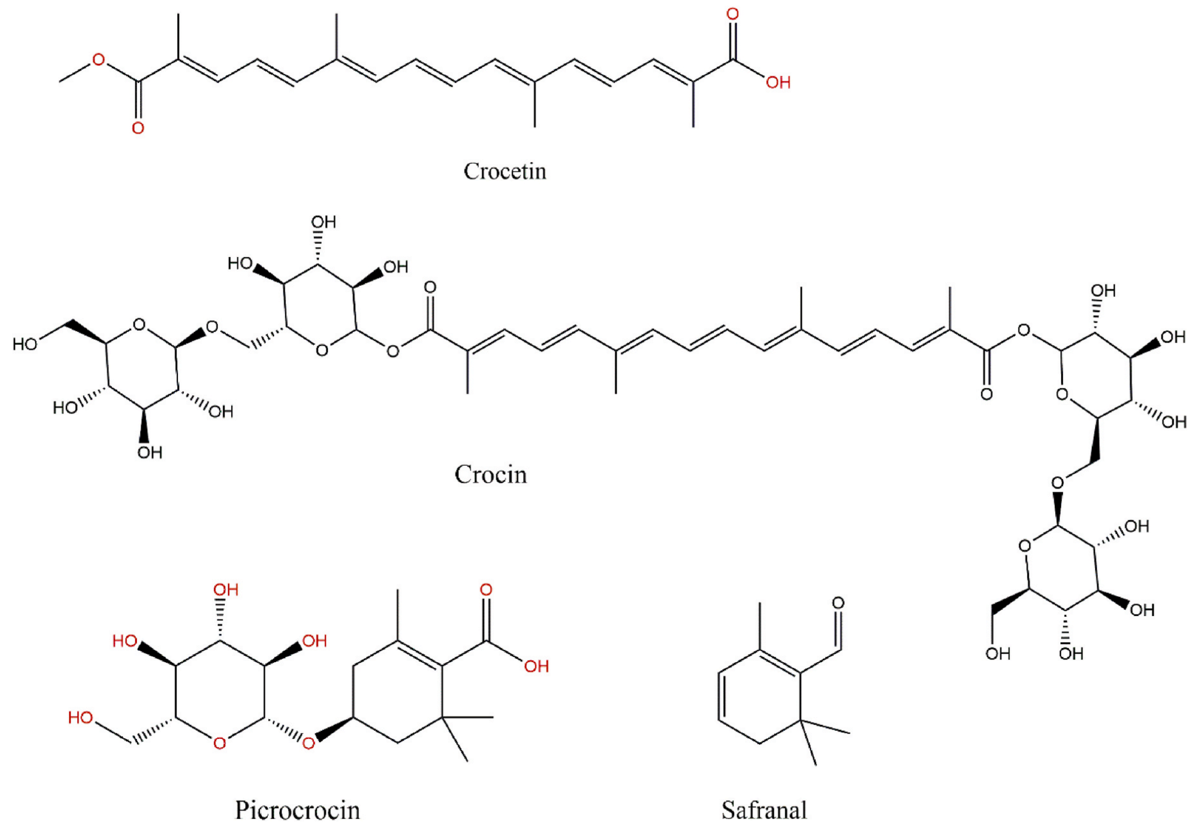

Fig. 2. Structure of saffron's metabolites: Crocetin, Crocin, Picrocrocin, Safranal.

influenced by a myriad of factors such as climate, soil, crop management, and dehydration methods [17]. Esmaeilian et al. [22] studied the effects of plant spacing (5, 10, and 15 cm) and organic manure application (20, 40, and 60 t ha^{-1}) on saffron yield. In the first year, the highest fresh flower yield (74.5 kg ha^{-1}) was observed with 40 t ha^{-1} of cow manure and 5-cm spacing, while in the second year, the highest yield (161.2 kg ha^{-1}) was obtained with 60 t ha^{-1} of manure and 5-cm spacing [22]. The highest dry stigma yield (2.04 and 2.69 kg ha^{-1} in the first and second years, respectively) was observed with the highest planting density (5 cm spacing) and highest manure application rate (60 t ha^{-1}). Notably, the wider spacing (15 cm) resulted in the largest daughter corm weights, averaging 3.18 and 3.23 g in the first and second years, respectively. Plant spacing of approximately 15 cm and a planting depth of 15 cm has been tested in other saffron studies [23]; however, the greatest yields are likely to vary with planting method and size of corm.

Continuous saffron cultivation on the same land is discouraged due to potential declines in soil health and productivity. In regions such as Spain and India, saffron fields are commonly rotated after 10–20 years. To maintain soil health, rotational cropping with corn, linseed, and oats is recommended for 2–3 years before reintroducing saffron [2].

7.1. Soil requirements

Saffron is typically cultivated in loose, well-drained, clay-calcareous soils with adequate organic matter [21]. Soil texture, bulk density, and pH are among the most influential factors affecting saffron yield [24]. Optimal soil conditions for saffron cultivation include high nutrient content, low bulk density, a well-developed and flexible soil structure, efficient drainage, and sufficient water-holding capacity [25]. Coarse-textured soils provide a favorable environment for corm development by reducing mechanical resistance, thereby facilitating sprouting during the initial growth phase and enabling propagation in the later stages of the growth cycle. Proper nourishment of mother corms is critical, as it promotes the development of more and larger daughter corms, ultimately enhancing yield potential in subsequent growing seasons. Additionally, as temperatures rise and soil moisture declines in late winter and early spring, nutrients stored in the mother corm are translocated to the developing daughter corms [19]. Soil pH is another important factor influencing soil biochemical processes and regulating the availability of water and nutrients to plants [24]. A global survey conducted by McGimpsey et al. [26] across 19 saffron-producing fields reported that soil pH values in 16 fields ranged from 6.0 to 7.8, whereas in three fields located in New Zealand, pH ranged from 5.2 to 5.6 [26]. Generally, strongly acidic or highly alkaline soils are considered unsuitable for saffron cultivation. The optimal soil pH for saffron growth appears to lie within a neutral to slightly alkaline range [17,24].

7.2. Crop rotation, cover cropping, and intercropping requirements

Saffron is highly susceptible to weed pressure, disease incidence, and soil nutrient deficiencies. To support soil health and ensure long-term productivity, crop rotation is a key strategy for reducing weed competition and maximizing stigma yield. In Abruzzo, Italy, Tammaro [27] reported that saffron is grown as an annual crop using a six-year crop rotation system that incorporates a variety of species [27]. In contrast, saffron cultivation in Kashmir, India, follows a 15-year rotation cycle, often incorporating maize (*Zea mays*), oats (*Avena sativa*), or linseed (*Linum usitatissimum*) for two to three years to restore soil fertility and mitigate insect and disease pressures [2].

Integrating legumes as intercrops or cover crops has been shown to enhance soil fertility due to their nitrogen-fixing capabilities. For instance, saffron planted at a density of 45 corms per m^2 in combination with faba beans as a cover crop significantly increased both the number of saffron flowers and stigma yield compared to a fallow control [28]. Chickpea (*Cicer arietinum* L.), a drought-tolerant annual legume, has demonstrated potential to improve soil fertility through biological nitrogen fixation in semi-arid conditions [29,30]. Intercropping chickpeas with saffron at 1:1 and 2:2 saffron-chickpea ratios has been found effective in suppressing weeds while contributing to nitrogen availability in semi-arid systems of Zanjan, Iran [30].

Due to saffron's short flowering period and prolonged dormancy during late spring and summer, farmland often remains underutilized for much of the year. Therefore, introducing economically valuable intercrops can improve land-use efficiency and support the financial sustainability of small- and mid-scale saffron farms [30,31]. Intercropping saffron with winter wheat (*Triticum aestivum*) has been shown to maintain saffron-equivalent yields while generating 17 % higher revenue compared to sole saffron cultivation [32]. In Iran, intercropping saffron with black cumin (*Nigella sativa*) maintained an average saffron yield of 7.67 kg ha^{-1} over a six-year period [33]. Additionally, integrating cumin did not significantly alter key saffron parameters, including crocin, picrocrocin, or safranal concentrations [34,35]. Moosavi et al. [36] studied the impact of sowing patterns and plant densities on saffron yield under apple trees (*Malus domestica*) and found that planting saffron in four rows at 20 cm spacing resulted in the highest leaf dry matter, corm number, and corm yield, highlighting the benefits of integrating saffron into orchard systems [36].

In arid and semi-arid regions of the US, oilseed crops such as soybeans (*Glycine max*) and sunflowers (*Helianthus annuus*) may serve as profitable rotational or preceding crops in saffron production systems. However, further research is required to determine their effects on corm yield and the phytochemical profile of saffron [37]. Camelina (*Camelina sativa* L. Crantz), another oilseed crop in the Brassicaceae family [38] with a short life cycle (60–90 days), high oil content, frost resistance, and efficient water use, presents an additional option. Intercropping camelina or wheat with saffron may enhance system-level productivity and soil health, although limited data exist on the impact of these crops on saffron's bioactive compounds.

7.3. Water and irrigation requirements

Saffron is characterized by a relatively low water requirement [39], and its unique morphological traits, such as narrow, thick leaves [40], enable it to thrive in semi-arid and arid regions [41]. Its growth cycle, primarily during the cooler winter months, allows farmers to utilize lower temperatures and, in some regions, more reliable seasonal precipitation. However, the temporal distribution, intensity, and total rainfall during the growing season significantly influence irrigation requirements and scheduling [42]. Inadequate rainfall during critical phenological stages can substantially reduce saffron yield and quality. As such, in most arid and semi-arid regions, supplemental irrigation is essential to ensure synchronized flowering and optimal stigma production. Rainfed cultivation under these conditions may result in shorter flowering periods and delayed flower initiation, adversely affecting uniformity and productivity [43].

Irrigation is essential at several developmental stages: before corm lifting, after corm planting, during the pre-flowering stage, throughout vegetative growth, and in summer to ensure optimal saffron yield and quality. Late summer irrigation is often applied to stimulate uniform floral initiation, while spring irrigation supports corm growth, flower number, and stigma yield [1]. The use of furrow planting has been shown to improve soil moisture retention, enhancing plant establishment and improving yield potential [44,45]. In regions receiving 200–400 mm of annual rainfall, irrigation every 15–24 days during active growth period has been shown to significantly improve yield and uniformity [42]. Traditionally, saffron fields are irrigated up to five times between October and May to support various growth stages [42]. Although some studies suggest that 300 mm of rainfall may suffice for saffron production in certain regions [46], recent research indicates that the frequency of irrigation, rather than the total amount, has a more pronounced effect on yield [24].

Excessive watering can stimulate leaf growth at the expense of reproductive output, thereby reducing flower number and stigma quality [35]. Water scarcity is a critical constraint in many saffron-growing regions, often necessitating the use of marginal-quality water with moderate to high salinity. Saffron is notably sensitive to salinity stress. Some studies have reported a decrease in flower yield when irrigating saffron with water salinity level of 1.7 dS m^{-1}, and complete flowering failure at 4 dS m^{-1} salinity levels. However, other studies have reported successful cultivation at irrigation water salinity levels of 4.1 dS m^{-1} and soil salinity levels of 5.8 dS m^{-1} [47], suggesting that salinity tolerance may vary depending on soil texture, management, rainfall, and other climatic conditions. Notably, salinity-induced stress can be partially mitigated through in-furrow planting and organic amendments such as cow manure, which enhance soil structure and water retention [44]. Indeed, sustainable water management is critical to ensure the long-term viability of saffron production in arid and semi-arid regions [45]. In an experiment assessing irrigation at 45 %, 65 %, and 85 % of the total soil evaporation, maximum yields were achieved with irrigation based on 85 % evaporation [48]. However, economic considerations, including the cost and availability of irrigation water, must be incorporated into irrigation planning. While saffron has a relatively low water requirement, targeted supplemental irrigation remains necessary to ensure agronomic success, optimize yield and quality, and enhance economic viability in water-limited systems.

7.4. Nutrient requirements

Proper application of macro- and micro-nutrients to correct soil nutrient deficiencies will enhance saffron production and quality [49–51].

7.4.1. Macronutrients

7.4.1.1. 1- Nitrogen (N). Nitrogen is critical in enhancing both flower and corm yield in saffron [52]. As a highly mobile element within plant tissues (N is translocated from aboveground vegetative parts, primarily the leaves, to belowground reproductive structures (corms) towards the end of the growing season. Increased soil N availability is positively correlated with enhanced photosynthetic activity and nitrogen uptake, ultimately contributing to greater dry matter accumulation and yield. An eight-year study evaluating the effects of urea, ammonium phosphate, and cow manure on saffron yield found that the application of 100 kg ha^{-1} of urea was most effective in maximizing flower yield, whereas both higher and lower application rates led to reduced yields [53]. Similarly, a study conducted in the Kashmir Himalayas, India, examined the effects of N fertilizer (0, 45, and 90 kg ha^{-1}), farmyard manure (0, 30, and 60 t ha^{-1}), and Azotobacter (0 or 5 kg ha^{-1}) on saffron productivity [54]. The highest yields were achieved with the application of 90 kg ha^{-1} of N fertilizer and 60 t ha^{-1} of manure, resulting in yield increases of 57.57 % and 43.26 %, and corm productivity increases of 79.62 % and 260.97 %, respectively. Overall, most studies indicate that supplemental N improves saffron flower yield and corm development. However, further long-term, region-specific studies are warranted, particularly under the US agroecological conditions, to refine N management strategies for sustainable saffron production.

7.4.1.2. 2- Phosphorus (P). Phosphorus (P) plays a crucial role in both vegetative development and flower induction in saffron [55]. Adequate P fertilization during the first year of cultivation enhances the accumulation of P reserves in daughter corms, which may improve photosynthetic assimilation, promote vegetative development, and support the production of larger daughter corms in subsequent years [56]. In a pot experiment evaluating nutrient uptake and daughter corm production, P was applied at rates of 0, 35, and 70 kg ha^{-1} in combination with

N applied at 0, 50, and 100 kg ha^{-1}. Results indicated that increasing P application increased the fresh weight of saffron corms but decreased the number of corms [56]. Conversely, higher N levels were associated with an increase in corm number but a decrease in corm weight. The weight of both corm and leaf increased over time, while in the second saffron harvest, P and N uptake and concentrations increased in corms but decreased in leaves.

7.4.1.3. 3- Potassium (K). In addition to its significant physiological functions and role in enhancing salinity tolerance, K plays a specific role in improving the quality of agricultural products. In a study evaluating four levels of potassium sulphate fertilizer (0, 50, 75, and 100 kg ha^{-1}), the highest fresh flower weight was observed with application of 100 kg ha^{-1} [57]. Pirasteh-Anosheh et al. [24] examined the yield and yield components of saffron across 13 fields in Iran during the 2020–2021 growing seasons, covering diverse geographic and climatic conditions (hot desert, cold desert, and cold semi-arid) [24]. Based on their findings, they recommended a comprehensive fertilization regimen: (1) application of 50 kg N ha^{-1}, 75 kg P_2O_5 ha^{-1}, and 100 kg K_2SO_4 ha^{-1} per hectare, along with 6 L ha^{-1} of humic acid (12 %) during the initial irrigation, (2) application of 10–15 kg K_2SO_4 ha^{-1} and 50 kg N ha^{-1} after flower harvesting, and (3) application of complete fertilizer (20-20-20) and micronutrients as a foliar treatment from late January to early March in saffron production systems.

7.4.2. Micronutrients

While micronutrients are indispensable for plant growth and development, their required application rates are typically lower than those of macronutrients [58]. Iron (*Fe*) is essential for plant physiological processes [59] and has been shown to enhance fresh flower weight in saffron [60]. The significance of *Fe* in plant nutrition is further underscored by the adaptive mechanism plants employ to acquire it under *Fe*-deficit conditions [60]. Iron deficiency can result in leaf chlorosis and alter *Fe* and other nutrient concentrations in plant tissues. A study investigating the effects of varying levels of *K* and *Zn* fertilizers on saffron showed that higher *K* levels enhanced growth and quality, while Zn enhanced growth but had no significant impact on quality traits; however, the combined application of *K* and *Zn* produced the most pronounced improvement in saffron's growth [61]. Foliar application of *Zn* increased flower number (57.81 %), fresh and dry flower weights (20.62 % and 80.97 %), stigma weights (44.22 % and 65.27 %), crocin (6.88 %), picrocrocin (11.39 %), and safranal (9.66 %) [62]. Applying a 5 % solution of both *Fe* and *Zn* further enhanced saffron traits further; however, *Zn* alone outperformed *Fe* and the combination *Zn* and *Fe* [62]. Additionally, incorporating micronutrients (0.2 % boron, 0.2 % copper, and 20 kg ha^{-1} sulphur) along with recommended macronutrients (N: P205: K_2O at 120:90:80 kg ha^{-1}) and organic amendments (15 tons of manure and 10 quintals of vermicompost) significantly increased saffron yield, particularly under high-density planting systems in Kasmir, India [63].

7.4.3. Organic amendments

Multiple studies have demonstrated the effectiveness of organic amendments, such as arbuscular mycorrhizal fungi, biochar, and compost, in ameliorating plant nutritional status, enhancing growth, and increasing productivity [64]. Organic matter reduces soil swelling and shrinking, improves soil water retention, and enhances mechanical resistance. Up to 80 % of fluctuations in saffron flower yield are attributed to soil nutrient availability [65]; soil organic matter can increase both availability and uptake of nutrients [9,35,52], leading to greater saffron yields [13]. Further, soil organic matter improves soil structural integrity and cation exchange capacity, reducing erosion and nutrient leaching.

Mycorrhizal interactions improve plant growth and productivity primarily through enhanced uptake of both macro- and micronutrients [66], increased nutrient use efficiency, and positive effects on soil health parameters [67]. Arbuscular mycorrhizal symbiosis facilitates P uptake [68,69] and improves N retention by mitigating nitrogen loss from soil [70].

Biochar, a carbon-rich, porous material produced via pyrolysis, has received considerable attention for its potential to enhance soil properties [71,72]. In saffron production systems, biochar enhances nutrient retention, improves fertilizer use efficiency, and promotes crop growth, yield, and productivity [72–74]. Moradi et al. [75] reported that beeswax waste biochar application improved saffron growth and reduced cadmium (Cd) uptake and toxicity in saffron by increasing soil alkalinity, immobilizing Cd, decreasing Cd accumulation in above-ground tissues, and alleviating Cd-induced oxidative stress [75].

Similarly, compost application has been shown to enhance saffron yield by improving soil physical properties and nutrient assimilation [34,72]. Composts contribute to plant growth and biomass accumulation through the gradual release of N and P [76]. Koocheki and Seyyedi [34] observed that application of 25 Mg ha^{-1} composted manure improved saffron yield and *N* and *P* acquisition more effectively than chemical fertilizers (300 kg ha^{-1} N and 100 kg ha^{-1} *P*) or no fertilization.

Integrating mycorrhizal inoculation with chemical fertilizers [69,77] or biochar [78] has been found to enhance plant growth and nutrient uptake. Lone et al. [79] highlighted that mycorrhizal colonization of saffron roots significantly improved mineral absorption, saffron yield, quality, and volatile characteristics, particularly when combined with fertilization. While integrated use of multiple soil amendments appears more effective than individual applications [67], further long-term studies are necessary to validate these findings.

8. Pests and disease

Saffron cultivation worldwide is constrained by a range of biotic stresses, including damage from rodents, insects, fungi, nematodes, viruses, and bacteria. Rodents such as porcupines (*Erethizon dorsatum*), rats (*Nesokia indica*), southern mole vole (*Ellobius fuscocapillus* Blyth), and rabbits (*Oryctolagus cuniculus*) pose significant threat to saffron crops, particularly through corm damage and subsequent yield reduction [80]. Likewise, insect pests, notably the saffron bulb mites (*Rhizoglyphus robini*) and corm thrips (*Thrips tabaci*), are prevalent and contribute to considerable losses through direct feeding and disease transmission [80].

Corm rot, also known as root or neck rot, represents a major disease complex in saffron cultivation and is caused by a diverse group of fungal pathogens, including *Fusarium* spp., *Penicillium* spp., *Botrytis* spp., *Sclerotium rolfsii*., *Pythium* spp., *Rhizopus* spp., *Pseudomonas gladioli, Phoma crocophi*, and *Rhizoctonia* spp. [81]. This disease is especially problematic during humid periods when temperatures exceed 10–12 °C [17]. Integrated disease management approaches, such as soil amendment with neem cake, a natural antifungal agent, and utilizing *Tricoderma viride,* alongside vermicompost, have shown promise in managing corm rot [82]. However, additional research is needed, particularly in the Eastern US, where high humidity levels intensify fungal pressure.

Nematodes also represent a critical challenge in saffron production. Genera such as *Tylenchus, Helicotylenchus*, *Pratylenchus*, *Hirschmaniella*, *Psilenchus*, *Aphelenchoides*, *Ditylenchus*, *Pratylenchus*, *Helicotylenchus*, *Aphelenchus*, *Xiphinema*, *Tylenchus*, *Tylenchorhynchus*, and *Hemicriconemoides* have been associated with saffron corm damage [80]. These parasitic nematodes not only cause direct damage but also predispose the plant to secondary infections by facilitating fungal entry through wounds and lesions. They modulate host plant responses, affect root exudation, and compromise plant immunity [81]. Viral pathogens identified in saffron include bean yellow mosaic virus, turnip mosaic virus, and meadow saffron breaking virus, all of which disrupt normal plant physiological functions. Bacterial pathogens such as *Bacillus croci* and *Burkholderia gladioli* pv gladioli are known to induce soft rot in buds and foliage. Notably, *B. gladioli* can form visible lesions on corms and leaves, substantially reducing the flowering rate [80].

Effective pest and disease management in saffron cultivation requires a combination of preventive and control measures. Key strategies include corm disinfection, refraining from immediate irrigation post-planting, prioritizing fall and winter irrigation over summer irrigation, and incorporating sand to improve drainage into heavy soils to reduce mite infestation. Rodent control can be achieved through the use of baits, traps, and border plowing [80]. For fungal diseases, crop rotation, removal and incineration of infected plant material, and pre-planting corm treatments with antifungal agents such as benomyl or copper-based compounds are recommended [17]. Details on pests, pathogens, and management techniques for saffron are available from Bazoobandi et al. [80] and Gupta et al. [81].

9. Weeds

Saffron cultivation is challenged by a wide range of annual, biennial, and perennial weed species, which vary by geographic location. Common weeds include *Amaranthus retroflexus*, *Bromus danthoniae*, *Bromus scoparius*, *Bromus tectorum, Cardaria draba*, *Chenopodium album*, *Cirsium arvense*, *Crepis saneta*, *Euphorbia helioscopia*, *Heliotropium europaeum, Hordeum murinum*, *Hordeum spontaneum*, *Hordeum vulgare*, *Lepidium virginicum*, *Lithospermum arvense*, *Medicago lupilina*, *Papaver rhoae*, *Poa bulbosa*, *Polygonum aviculare*, *Ranunculus arvensis*, *Salvia moorcroftiana*, *Sophora alepecuroides*, *Taraxacum oficinale*, *Tulipa stellata*, and *Valerianella dentate*, among others [83,84]. In Kasmir India, prevalent weeds include *Euphorbia helioscopia*, *Papaver rhoae*, *Lepidium virginicum*, *Salvia moorcroftiana*, *Chonspora tanella, Galium tricorne*, *Tulipa stellata*, *Erodium cicutarium*, *Lithospermum arvense*, *Ranunculus arvensis*, *Medicago lupilina*, *Filago arvense*, *Poa bulbosa*, *Crepis saneta*, *Descurainea Sophia*, *Polygonum aviculare*, and *Chenopodium album*, among others (Husaini et al., 2010). In Morocco, key weed species include *Convolvulus arvensis*, *Bromus rubens*, *Lolium perenne*, *Hordeum murinum*, *Isatis tinctoria*, *Malva parvif lora*, *Lamium amplexicaule, Cynodon dactylon*, *Aster squamatus*, *Cyperus rotundus*, and *Convolvulus arvensis* [85]. Saffron's short stature and fragile structure reduce its competitiveness, increasing vulnerability to weed infestation [17]. Hand weeding, although effective, is labor-intensive, time-consuming, and economically unsustainable at scale. Herbicides such as atrazine, simazine, metribuzin, ioxynil, and ethafluralin have shown efficacy [83], but pose environmental risks and may lead to herbicide residue accumulation. Their performance also depends on factors such as weed seedbank, species composition, and density. A study from Kashmir, India indicated that metribuzin (560 g a.i. ha^{-1}) applied before sowing, Ioxynil (750 g a.i. ha^{-1}) after harvest in spring, and soil-incorporated ethafluralin (1320 g a.i. ha^{-1}) prior to forking were effective in controlling the weed population [86]. In Turkey, Asil et al. [84]) reported complete (100 %) weed suppression with pre-emergence application of pine sawdust + benfluralin and textile mulch cover while the post-emergence application of 2,4-D amine was least effective (70 % supression). In perennial saffron systems, substantial weed growth typically occurs in spring after flowering. Allowing these weeds to grow until May and subsequently removing them once saffron leaves wither has been suggested as a practical strategy [17]. Integrated weed management approaches including the use of clean corms, regular field scouting, allelopathic cover crops, and crop rotation, are increasingly recommended to reduce herbicide dependency and enhance sustainability [87], but studies on integrated weed management in saffron remains limited.

10. Harvesting, drying, and storage

Saffron flowers should be harvested in the morning when they are fully elongated and beginning to open. Harvesting flowers while still closed or insufficiently elongated can result in underdeveloped stigmas with reduced length, ultimately lowering quality (https://www.uvm.edu/~saffron/). Harvested flowers should be exposed to minimal sunlight, and stigma separation should occur on the same day to maintain quality. If immediate processing is not feasible, temporary storage under refrigeration is recommended. Small-scale growers can minimize quality degradation using readily available materials, such as spreading flowers on a paper towel-lined tray (https://www.uvm.edu/~saffron/).

Harvesting remains predominantly a manual process due to limited mechanization, with labor accounting for approximately 23 % of the total energy input in saffron production [88]. The stigma must be dehydrated to less than 12 % moisture content following the ISO 3632:2011 standards. Dehydration methods significantly affect saffron's chemical composition and quality. Traditional drying techniques include sun-drying, shade-drying, and oven drying at different temperatures. More recent methods, such as microwaving and freeze drying, have demonstrated higher efficiency and improved chemical retention [89].

Each dehydration technique yields saffron with distinct profiles of volatile and non-volatile biochemical compounds. High-quality saffron is characterized by elevated levels of carotene, crocin, safranal, and other antioxidants [90]. Modern methods, such as freeze drying, when combined with optimal harvest and handling practices, preserve these compounds more effectively. In addition to the impact of drying method, saffron quality varies regionally, indicating the influence of ecological factors on secondary metabolite composition [1].

Temperature control during dehydration is critical for the retention and transformation of bioactive compounds. High-temperature oven drying (100 °C for 7–10 min) has been associated with increased safranal and crocin concentrations [91]. In Australian trials, safranal content increased up to 25-fold in samples dried at 86 °C for 20 min, followed by additional drying at 43 °C for a short duration [92]. Similarly, Torki-Harchegani et al. [93] reported that the total crocin content increased with drying temperatures up to 90 °C but declined slightly at higher temperatures. The total safranal content initially decreased slightly as the drying temperature increased from 60 °C to 70 °C, then consistently increased up to 110 °C [93]. Additionally, the picrocrocin content increased with drying temperatures up to 100 °C. Thus, drying at lower temperatures may lead to pigment degradation and quality loss.

Drying induces enzymatic transformations crucial to saffron's bioactivity. Carmona et al. (2006) identified an enzymatic pathway during saffron dehydration that converts zeaxanthin into picrocrocin and crocetin dialdehyde, which can further transform into safranal [94]. Crocetin, a key therapeutic component, is heat-sensitive and prone to degradation at extreme temperatures [90,95]. Traditional shade or sun drying at 20–35 °C may take hours to days, increasing the risk of microbial contamination. Contaminated samples stored for 12 months showed up to 50 % reductions in crocin and picrocrocin levels [96].

Novel drying methods like freeze drying and microwave drying increase the concentrations of bio-active compounds. Freeze drying significantly reduces the loss of volatile and heat-sensitive components compared to sun-drying and enhances quality and shelf life [97,98]; one study found a 500 % increase in safranal content and a 40 % increase in crocin content in freeze-dried samples [99]. However, freeze-drying is time- and energy-consuming, requiring the maintenance of low temperatures (−50 °C or lower) for approximately 50 h. Conversely, microwave drying rapidly reduces moisture while retaining high levels of crocin, safranal, and β-Isophorone [100].

Storage conditions are pivotal in maintaining saffron quality, particularly aromatic compounds. While optimal dehydration preserves the color and aroma of the stigmas, aromatic quality will noticeably decline in long-term storage [101]. Interestingly, aroma intensity may increase during the first six months of storage, despite color loss [102]. Rahimi [103] demonstrated that saffron stored in the dark at ambient temperature (24–26 °C) retained 35 % more crocin than samples stored under light exposure or refrigeration at 4 °C. Thus, storage in dark environments or light-blocking containers is essential to enhance saffron's shelf life and quality. Indeed, saffron quality is influenced by environmental conditions, cultivation approaches, dehydration methods, and storage techniques. While modern dehydration and storage technologies offer considerable advantages, further research is needed to support adoption by small-scale growers in emerging production regions, thereby enhancing profitability and efficiency.

11. Uses

Crocin, picrocrocin, and safranal are the principal bioactive compounds in saffron, contributing to its color, taste, and fragrance, respectively. Crocin is a carotenoid that imparts a vibrant hue, making saffron a sought-after ingredient in the food, textile, and cosmetic industries. Picrocrocin adds a distinct bitter taste, making saffron desirable in culinary creations. Safranal imparts aromatic properties, making saffron valuable in perfumes and aromatherapy.

Saffron also contains significant quantities of anthocyanins, vitamins, amino acids, proteins, starch, mineral matter, and gums, increasing its value for pharmaceutical and cosmetic applications. A growing body of research has explored saffron's potential therapeutic properties [104,105], including its use in the prevention and treatment of various conditions such as cancer, Alzheimer's disease, cardiovascular diseases, gastrointestinal disorders, psychiatric conditions, skin photoaging, and reproductive health issues (Tables 3 and 4). With increasing consumer demand for natural and nutrition-based medicine, capitalizing on the therapeutic properties of saffron offers promising opportunities for market expansion. The nutritional contents in 1tsp of saffron (https://fdc.nal.usda.gov/fdc-app.html#/food-details/170934/nutrients) are available in Table 5.

In addition to its traditional culinary and medicinal application, saffron is increasingly utilized in the production of value-added products such as saffron tea and craft beer. Saffron stigmas can be steeped in hot water or blended with various herbs and spices to produce a tea characterized by its distinct flavor and potential therapeutic benefits. In some formulations, saffron tea is prepared using petals and stamens instead of stigmas. Research has highlighted the health-promoting properties of saffron tea, including neuroprotection against aflatoxin-induced toxicity [106] and potential anti-depressant effects [107]. The incorporation of saffron into craft beverages represents an emerging niche market. For instance, saffron-infused craft beer provides an innovative opportunity for product diversification and consumer outreach. Buiatti et al. [108] studied the formulation of Belgian Blond craft beer infused with saffron, aiming to capitalize on the spice's bitterness, unique aroma, and vivid color to enhance the beer's flavor and appearance [108]. Their study emphasized optimizing the extraction process to maximize flavor and visual appeal while minimizing saffron input.

Table 3
Global studies on the therapeutic use of saffron (*Crocus sativus* L.) in treating human diseases.

Disease	Reference
Diabetes and Alzheimer's	[134–142]
Digestive diseases (Gastritis and Peptic Ulcer, Irritable Bowel Syndrome, Inflammatory Bowel Diseases), Hepatitis, Cancer, Gastric Cancer, Colorectal Cancer, Liver Cancer, Pancreatic Cancer	[143–147]
Neurodegenerative Retinal Disease	[148]
Neurological and psychiatric disorders (cognition, depression, anxiety, sleep disorders, attention-deficit/hyperactivity disorder, obsessive–compulsive disorder, sarcopenia)	[149,150]
Cardiovascular, coronary artery disease	[151,152]
Rheumatic diseases	[153]
Skin Photoaging	[154]
Asthma	[155]
Inflammation	[156]
SARS-CoV-2 (COVID-19)	[157]
Sexual health, reproductive disorders, sexual dysfunction, erectile dysfunction	[158,159]

Table 4
Common uses of saffron (*Crocus sativus* L.) and associated plant parts (Modified from Ref. [16]).

Use	Parts used
Food colorant and flavoring	Stigma
Painting	Dried stigma
Dye and coloring textiles	Saffron flowers
Traditional medicines	Dried Stigma
Cosmetics and perfumes	Whole flower, dried stigma
Herbal tea and soup	Stigmas and petals
Hindu rituals	Stigma
Fertilizers or feed	Petals

Table 5
Nutrients in 1tsp (0.7 g) of saffron (*Crocus sativus* L.).

Nutrients, Unit	Amount
Energy (kcal)	2.17
Water (g)	0.083
Protein (g)	0.08
Total lipid/fat (g)	0.041
Ash (g)	0.038
Carbohydrates (g)	0.458
Total dietary fiber (g)	0.027
Calcium (mg)	0.777
Iron (mg)	0.078
Magnesium (mg)	1.85
Phosphorus (mg)	1.76
Potassium (mg)	12
Sodium (mg)	1.04
Zinc (mg)	0.008
Copper (mg)	0.002
Manganese (mg)	0.199
Selenium (µg)	0.039
Total ascorbic acid/Vitamin C (mg)	0.566
Thiamin (mg)	0.001
Riboflavin (mg)	0.002
Niacin (mg)	0.01
Vitamin B-6 (mg)	0.007
Total Folate (µg)	0.651
Food folate (µg)	0.651
DFE Folate (µg)	0.651
RAE Vitamin A (µg)	0.189
Vitamin A (IU)	3.71
Total saturated fatty acids (g)	0.011
Total monounsaturated fatty acids (g)	0.003
Total polyunsaturated fatty acids (g)	0.014

12. Safety and toxicity of saffron

Consuming saffron in quantities less than 1.5 g is generally considered safe for humans [1,85] with a published LD50 of 20 g kg^{-1}, indicating a relatively low toxicity level [20]. However, surpassing 5 g can lead to toxicity, and consuming around 20 g per day can be fatal [1]. In a review of chemical and biological properties of saffron, Melnyk et al. [109], Schmidt et al. [110], and Shakeri et al. [111] indicated symptoms like nausea, vomiting, diarrhea, and bleeding following the intraperitoneal injection of saffron at doses ranging from 1.2 to 2 g per average body weight in animal studies. However, there are also instances of no adverse effects even with the ingestion of up to 4 g of saffron per day for several days, including among pregnant women. Details on acute, subacute, sub-chronic, chronic, and developmental toxicity, mutagenicity, and genotoxicity of saffron and bioactive ingredients based on different animal and clinical studies are available from Mehri et al. [112].

13. Challenges and opportunities

Despite the significant market potential, various culinary, medicinal, and cosmetic uses, increasing demand, and notable value growth, several challenges hinder large-scale production. Saffron cultivation is highly labor-intensive, requiring manual harvesting and stigma separation. This is a key reason why countries with access to low-cost labor dominate the global market. In the US, limited awareness of saffron and its uses and challenges related to labor availability may affect its future growth. Further, mechanization in saffron farming and processing remains largely underdeveloped globally, impeding efficiency and scalability. Further, saffron adulteration including petals of safflower (*Carthamus tinctorius* L.), petals of calendula (*Calendula officinalis* L.), petals of mountain arnica (*Arnica montana* L.), petals of pomegranate (*Punica granatum* L.), rhizomes of turmeric (*Curcuma longa* L.), seeds of achiote (*Bixa orellana* L.), dried fruits of red pepper (*Capsicum* spp.), and bulbs of red beet (*Beta vulgaris* L.), is a significant challenge to ensuring the authenticity and quality standards of this valuable spice (Table 6). Research on organic farming methods is limited, and field studies within the US are limited (Table 7). The limited availability of corms, coupled with the early stages of in-vitro culture, genome engineering, and microbial biotechnology techniques, further presents significant challenges to scaling up saffron production. More research is needed to evaluate the influence of preceding crops in rotational systems and of the impact of cover crops on saffron flower yield, corm development, and the accumulation of bioactive compounds with potential human health benefits. Moreover, the scarcity of specialized laboratories capable of conducting advanced phytochemical analyses restricts the capacity for comprehensive quality assessment and product development.

Changing climate conditions and the increasing frequency of extreme weather events also threaten saffron cultivation. However, there is a critical lack of modeling studies assessing climate impact and evaluating alternative cultivation methods. Furthermore, limited

Table 6
Common methods of saffron (*Crocus sativus* L.) adulteration and associated practices ([132,133]).

Adulteration methods	Details
No extraneous substances	Mixing with extract or old saffron
Auto adulteration - Adding different parts of saffron plant	Adding stamens, styles or petals cut into strips and dyed
Adding substances to increase mass	Increase in moisture
	Immersion in vegetable oils, syrup, honey, glycerin
	Addition to the above-mentioned syrup, barium sulphate, sodium sulphate, calcium sulphate, calcium carbonate, potassium hydroxide, potassium nitrate, potassium sodium bitartrate, sodium borate, lactose, starch or glucose
Adding similar parts from other plants	Flowers from *Carthamus tinctorius*
	Petals from *Calendula officinalis*
	Petals of mountain arnica (*Arnica montana* L.)
	Petals of hemerocallis (*Hemerocallis* sp.)
	Stigmas from other *Crocus* species, generally shorter and without dyeing properties (*Crocus vernus*, *Crocus speciosus*, etc.)
	Flowers cut in strips from *Papaver rhoeas* L., *Punica granatunm*, *Arnica montana*, and *Scolimus hispanicus*
	Stamens from some carnation species
	Dye from pomegranate fruits or petals (*Punica granatum* L.)
	Dye or fiber from beet (*Beta vulgaris* L.)
	Dye from seeds of achiote (*Bixa orellana* L.)
	Extracts of gardenia fruits (*Gardenia jasminoides* J. Ellis)
	Ground red pepper
	Herbaceous plants are cut into pieces and colored with an azoic colourants
	Root hairs from *Allium porrum*
	Red-dyed silk fibers
	Rhizomes of turmeric (*Curcuma longa* L.)
Adding animal substances	Dried, salted meat fibers
Adding artificial products	Colored gelatine fibers
Adding water-soluble colorants	Tartrazine, erythrosine, ponceau 4R
Adding fat-soluble colorants	Sudan dyes

Table 7
Summary of published studies on saffron (*Crocus sativus* L.) conducted in the United States, highlighting growing media, planting depth and density, research focus, and major experimental findings.

Location	Year	Media	Planting depth and density	Focus	Research findings	Reference
New England	2017–2019	Sandy loam soil, pH = 5.9, OM = 3.6 %	15 cm; 162 corms/m^2, and 120 corms/m^2	Planting density and winter protection methods	No effect of planting density on stigma yield; winter protection decreased saffron yield	[160]
Kentucky	2019–2020	Green roof media, pH = 6.5, OM = 9.8 %	10 cm and 15 cm, 64 corms/m^2	Planting depth and biofungicide treatments effect on saffron production in a green roof system	Shallow planting suitable for annual production, deeper planting for perennial production; in 2019, the higher level of fungicide treatment led to lower fresh flower and dry stigma yield	[161]
Vermont	2019	pH = 6.8, OM = 2.6 %, growing bed tilled, and the topsoil amended with 1.5 m^3 of compost	15 cm and 130 corms/m^2	Impact of dehydration methods on concentrations of crocins, picrocrocin, and safranal using NMR technique	When dried at 100 °C, the saffron contains higher concentrations of safranal and crocins. Picrocrocin undergoes conversion into safranal at elevated temperatures.	[91]
Georgia	2023–2024	Sandy loam, OM = 3 %	15 cm	Production system and planting date	higher flower number in low plastic tunnel compared to the open field; higher number of stigmas under low plastic tunnels, particularly those planted late (early = sept, late October).	[23]

research has explored the potential uses of other plant parts, such as petals and leaves. Addressing these challenges and research gaps necessitates extensive research in innovation and mechanization, particularly under changing climatic conditions. Enhanced collaboration among research institutions, producers, and policymakers—supported by targeted government subsidies—will be essential to advance adaptive strategies and ensure the resilience of saffron production systems.

In 2023, saffron ranked as the 3,437th most traded product globally, with a total trade value of $266M. The leading exporters of saffron in 2023 were Iran ($115M), Spain ($62.1M), and Afghanistan ($56.9M). The top importers were Spain ($45.5M), India ($36.1M), China ($26.7M), and the US ($21.3.M) (Source: https://oec.world/en/profile/hs/saffron) The saffron market is primarily concentrated in the Middle East and South Asia, where favorable climates and traditional practices result in high yields and a tradition of culinary and medicinal usage. Iran plays a pivotal role in meeting global saffron demand by leveraging extensive infrastructure, labor, and expertise in saffron cultivation.

The value of the saffron market in North America is projected to reach approximately $113.24 M by the year 2030 according to Data Bridge Market Research. The significant increase in saffron demand in recent years in the US is largely due to increasing consumer awareness of its medicinal properties (https://www.tridge.com/intelligences/saffron/import). Although lifting trade restrictions on Iranian imports led to an upsurge in saffron imports into the US, domestic growers are investing more in saffron cultivation to meet the growing demand and reduce reliance on imports. States like Vermont, Pennsylvania, and Washington are actively involved in this effort, implementing initiatives to boost domestic saffron production efficiency and sustainability through research, education, and agricultural support programs.

The worldwide organic saffron market in 2023 was valued at $320 million and could reach $530 million by 2032 (https://www.marketresearchfuture.com/reports/organic-saffron-market-3761). In 2023, conventional saffron production made up 63.6 % of the global market; however, increasing consumer awareness concerning the potential health hazards linked to synthetic chemicals in food production has ignited a surge in demand for organic alternatives [113]. Consequently, organic saffron is rapidly emerging as the preferred choice for health-conscious individuals seeking to integrate wholesome, chemical-free ingredients into their diets. Moreover, the rising emphasis on sustainability and ethical consumption practices is propelling consumers and researchers towards organic products and studies that prioritize environmental conservation and ethical farming methodologies [114].

A study recently initiated by the Rodale Institute (https://rodaleinstitute.org/) in the US is expected to deliver valuable insights into organic saffron production. Rodale Institute Southeast Organic Center's project on saffron started in 2023 in Georgia with funding from Southern SARE (https://projects.sare.org/sare_project/os23-166/). This project has been designed to evaluate different production systems and planting dates for saffron production in the Southeast US, identify the best method of processing saffron stigma for small-scale producers, and develop an enterprise budget to document the feasibility of saffron production in the region. This pioneering project, to the best of our knowledge, represents the first comprehensive evaluation of saffron production feasibility in the southern US.

The US harbors several regions with climates and environmental conditions comparable to those in Iran, which are conducive to saffron cultivation; however, research in this area remains limited. Regions with arid summers, mild winters, and well-drained soil are typically optimal for saffron cultivation. Successful saffron cultivation has been evidenced in segments of California, notably within inland valleys and foothills, as well as certain areas of Arizona. Additionally, states such as New Mexico and Washington may also provide conducive environments for saffron production. While saffron output in the US may not rival the scale witnessed in Iran, these regions hold promise for fostering high-quality saffron utilizing appropriate techniques. Furthermore, the adoption of organic farming methodologies can improve the quality of saffron in these potential regions. Avoiding the use of synthetic fertilizers and pesticides allows organic growers to foster a natural equilibrium within the ecosystem, potentially permitting the unique environmental characteristics of each region to manifest in the flavor and quality of the saffron yielded [21,24]. Despite the promising potential of organic saffron farming, the lack of available data necessitates long-term studies.

13.1. Alternative source of income

Given the financial struggles faced by small family farms both in the US and worldwide, it is crucial to find new ways to generate income and adapt farming methods. There is also an increasing urgency for resilient and profitable agricultural options due to the rise in extreme climatic events. The price of saffron has risen since 2010 due to increasing demand [115]. Saffron cultivation does not require much land, does not demand heavy investment in equipment, offers job opportunities for underserved populations, and could serve as an additional income stream for small farms. Typically, saffron production requires 10 % of the total labor during planting, 25 % during cropping, and the majority, 65 %, during harvesting. Economic efficiency studies conducted on saffron production in Iran show an average efficiency range of 80 %–90 %, potentially increasing production by over 10 % without utilizing additional inputs [115]. Implementing standardized good practices has demonstrated potential in improving the quality of saffron in high-density plantations while effectively doubling farmers' income in India [63]. Thus, saffron production could provide significant employment opportunities, generate profit, and serve as a source of alternative income.

13.2. Emerging innovations and mechanization

Emerging methodologies such as soilless cultivation systems (hydroponics, aeroponics, growth chambers, and in-vitro propagation), forced flowering, hormone applications, mechanization, and smart farming techniques are currently undergoing rigorous testing for saffron cultivation [116–119]. Tahiri et al. [120] reviewed different in-vitro propagation methods, including direct and indirect organogenesis and somatic embryogenesis. Temporary Immersion Systems, where cultured explants are periodically immersed in a liquid medium and then exposed to dry phases, are also being explored for in-vitro propagation [121].

Khan et al. [122] introduced an IoT-based system for greenhouse environments to monitor and manage a range of agronomic parameters, including corm size, temperature, humidity, pH, soil moisture, salinity, and water availability. Treccarichi et al. [123] tested three innovative growing techniques for organic saffron production: 1) emergency irrigation twice during the first two weeks after corm planting (4.28 $L\ m^{-2}$); 2) organic nutrition based on amino acids (Aminocomplex extra©), microorganisms belonging to *Frankia* spp., and *Pochonia chlamydosporia* (Maxy root©); and 3) a control treatment with no-emergency irrigation or organic inputs. Results indicated that both emergency irrigation and organic nutrition significantly increased flower and stigma yield compared to the control, with pre-flowering irrigation and organic nutrition identified as key strategies for higher saffron yield in the region. Similarly, researchers are actively exploring mechanization for weeding, planting, and harvesting, and strategies like laser induced breakdown spectroscopy (LIBS), attenuated total reflectance (ATR-FTIR), diffuse reflection Fourier transform infrared spectroscopy (DRIFTS), Raman spectroscopy ^{1}H nuclear magnetic resonance, and electronic noses to detect adulteration [124–126]. In India, farmers are testing mechanization techniques such as weeding and hoeing during June and September, as well as furrow opening for corm plantation in August, aiming to reduce cultivation costs and enhance profitability [63]. Animal-drawn or hand-held equipment are being replaced by power-operated ridgers, tillers, planters, weeders, fumigators, and dryers in different parts of the world. Saeidirad (2020) reviewed different mechanization techniques in saffron for tasks, including digging and sorting corms, bed preparation and breaking crusts, planting, picking, and sorting flowers, among others with an aim to enhance productivity by reducing the labor intensity, expanding cultivation areas, and improving quality [88]. For example, "Saffron All In One" (SAIO) is an innovative design developed to enable four operators to execute vital tasks such as planting, weed removal, and harvesting while lying prone [88]. Despite some promising recent technologies, research in emerging methods is limited, necessitating further studies and data to enhance our understanding and application of these innovative approaches.

13.3. Saffron under changing climate

Saffron cultivation worldwide is becoming increasingly vulnerable to the impacts of climate change and extreme weather events. Fluctuations in temperature and water availability, particularly during critical growth stages like corm sprouting, flower initiation, and flowering, have notable effects on both yield and quality by influencing disease susceptibility, weed proliferation, and pest infestation [64]. Predictive models suggest a decline in saffron yield under scenarios of increased temperatures and decreased precipitation. For example, under the IPCC scenario RCP4.5 (moderate case scenario), saffron yield in Iran's Southern Khorasan province and south of Khorasan Razavi province is projected to decline by 8 % between 2026 and 2050, 12.1 % between 2051 and 2075, and 17 % between 2076 and 2100. Under the RCP8.5 scenario (worst case scenario), the projected declines are more severe, estimated at 11 %, 20.2 %, and 31 % over the same respective periods [127].

Adaptation to climate change in saffron cultivation will require the implementation of multifaceted strategies, as outlined in Table 8. Husaini [128] reviewed the effects of climate change on saffron cultivation in Kashmir and identified biotechnological interventions, such as utilizing plant growth-promoting rhizobacteria, arbuscular mycorrhizal fungi, and genome engineering in improving drought and disease tolerance, enhancing carbon dioxide assimilation, and increasing nutrient uptake in saffron plants [128]. These measures can strengthen the crop's resilience to adverse climatic conditions. Additional strategies may include adjusting planting dates, employing water conservation practices, diversifying agricultural activities, or growing saffron in controlled environments. The latter, in particular, may allow for consistent production while avoiding the impact of rising temperatures [129]. Policy-level interventions such as government subsidies and the development of saffron-specific crop insurance programs can further enhance farmers' adaptive capacity and reduce financial risks [63]. Overall, adapting saffron to the changing climate will require an integrated approach combining agronomic management, policy support, and technological innovation. However, further modeling and field-based research are essential to validate and optimize these adaptation strategies.

Table 8
Select global strategies for adapting saffron (*Crocus sativus* L.) to environmental stresses associated with climate change.

Region	Adaptation strategies	References
Kasmir, India	Plant and microbial biotechnology (gene manipulation, metabolic engineering, microbial symbiotic associations)	[157]
Jammu and Kasmir	Crop insurance policies based on weather and yield	[63]
Taliouine, Morocco	Water conservation, drip irrigation, changing planting dates, changing irrigation periods and frequency, staggering the harvest over time to avoid labor shortages, and use of family workforce	[162]
Iran	Shift from traditional farmlands to greenhouse	[129]
Mashhad, Iran	Saffron-mallow intercropping	[163]
Khorasan province, Iran	Use of organic inputs such as cow manure, reducing chemical fertilizer use	[164]
Hatay, Turkey	Change in planting depth	[165]

14. Conclusions

Reviewing the origin, biology, chemical composition, agronomic management, utilization, processing, storage, and adulteration of saffron highlights significant research gaps and opportunities for advancement. Saffron is increasingly recognized not only as a valuable spice but also for its medicinal and nutraceutical properties, offering promising potential as an alternative income source for farmers in emerging production regions. However, further research is imperative, particularly in areas such as organic farming practices, genome engineering, microbial biotechnology, and farm mechanization to optimize sustainable saffron production systems. Given the high market value and demand for saffron, adulteration remains a widespread issue, underscoring the need for robust, standardized detection and prevention strategies to ensure product authenticity and consumer trust. Additionally, climate change presents a formidable challenge, necessitating adaptation strategies at the local to regional level. While available studies emphasize the importance of adaptive approaches, there is a pressing need for long-term, multidisciplinary research efforts. Enhanced collaboration among researchers, farmers, industry stakeholders, and policymakers will be crucial to addressing the complex challenges associated with saffron cultivation, processing, and commercialization in the face of evolving environmental and market conditions.

CRediT authorship contribution statement

Bharat Sharma Acharya: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Arash Ghalehgolabbehbahani:** Writing – review & editing, Funding acquisition, Formal analysis, Conceptualization. **Said Hamido:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Gladis Zinati:** Writing – review & editing, Resources, Methodology, Investigation. **Arianna Bozzolo:** Writing – review & editing, Methodology, Investigation. **Leigh Archer:** Writing – review & editing, Resources, Methodology, Investigation. **Kristie Wendelberger:** Writing – review & editing, Methodology, Investigation. **Saurav Das:** Writing – review & editing, Visualization, Methodology, Investigation. **Resham Thapa:** Writing – review & editing, Resources, Methodology, Investigation. **Dinesh Panday:** Writing – review & editing, Methodology, Investigation, Conceptualization.

Data availability statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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