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Saffron (Crocus sativus L.) Cultivation and Properties: A Review

Khadija Lachguer*, Imane Boudadi, Mohamed Lachheb, Ikram Beraouz, Soumaya El Merzougui, Mohamed Ben El Caid, Khalid Lagram, Mohammed Amine Serghini

Laboratory of Biotechnologies and Valorization of Natural Resources, Department of Biology, Faculty of Sciences, Ibn Zohr University, Agadir, Morocco

*Corresponding author's email: lachguerkhadija@gmail.com

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ABSTRACT

Saffron, derived from the flower of *Crocus sativus* L., is one of the most valuable and sought-after spices in the world. This review provides a comprehensive and novel overview of saffron horticultural practices, with a special focus on the innovative potential of its various byproducts. It encompasses the entire cultivation process, including harvesting, postharvest handling, storage, and the challenges faced in its marketing. Moreover, this review brings attention to the often overlooked saffron byproducts (petals, stamens, leaves, corms), which recent studies have shown to contain valuable bioactive compounds. These compounds exhibit significant potential for diverse applications across the food, pharmaceutical, cosmetic, and textile industries. By emphasizing the novel aspects of fully utilizing saffron byproducts, this review contributes to enhancing the value of the saffron production chain and opens new avenues for sustainable agricultural practices.

Introduction

The use of spices has been recognized globally for decades, valued for their flavor, aroma, and pigments (Zheng et al., 2016). Primarily, spices serve as preservatives, seasonings, and colorants, and they are also employed in dyeing and traditional medicine (Yildirim et al., 2020). Among these, saffron (*Crocus sativus* L.) stands out as one of the most intriguing and sought-after condiments. It consists of the dried stigmas of a plant belonging to the Iridaceae family (Mzabri et al., 2021).

Saffron is renowned as one of the most expensive and fascinating spices in the world, a status attributed to its medicinal properties, distinctive flavor, low yield, and the labor-intensive processes of planting, maintenance, harvesting, and stigma separation, which must be done manually. Often referred to as "red gold," it resembles a handcrafted item (Siddique et al., 2020; Leone et al., 2018). This niche spice has been esteemed for various applications since ancient times, serving as a condiment in royal kitchens, a tonic and antidepressant in traditional medicine, a dye for the elegant garments of the affluent, an ink for ancient inscriptions, and as an ingredient in perfumes and cosmetics (Yousefi and Shafagh, 2019).

Chemical analyses have identified over 150 organic compounds in saffron, including carbohydrates, lipids, and polypeptides. Among these, three major bioactive components—safranal, crocin, and picrocrocin—are chiefly responsible for the plant's pharmacological effects (Khorasany and Hosseinzadeh, 2016).

Recently, saffron has garnered attention for its promising pharmacological potential, exhibiting a broad spectrum of properties, including antioxidant, antimicrobial, anti-inflammatory, cytotoxic, anticarcinogenic, neuroprotective, cardioprotective, antidepressant, antihyperglycemic, and antitumor effects (Shokrpour, 2019; Abdel-Rahman et al., 2020; Butnariu et al., 2022; Moshfegh et al., 2022; Kazemi et al., 2023; Mykhailenko et al., 2022).

Saffron cultivation represents an additional source of income, enabling diversification of production and offering an attractive alternative crop for low-input farming systems, such as organic farming (Gresta et al., 2008). It helps enhance the incomes of small producers, reduces unemployment, and mitigates rural depopulation. However, its cultivation areas have declined in Europe due to the labor-intensive nature of production, a situation that benefits countries like Morocco, where saffron farming relies primarily on family labor (Aboudrare et al., 2014).

Research efforts have focused on improving saffron yields and quality through the selection of efficient corm accessions (Ben El Caid et al., 2020), and the optimization of cultural practices, including nutrient management (Ghanbari et al., 2019) and the use of biostimulants (Caser et al., 2019). To enhance the value of saffron crops and increase profitability, studies have investigated the valorization of saffron byproducts, particularly the tepals. These byproducts have shown potential as natural dyes and have been found to possess a range of beneficial properties, including antibacterial, antitussive, antispasmodic, hepatoprotective, immunomodulatory, renoprotective, antidepressant, antinociceptive, antidiabetic, antihypertensive, and antioxidant effects (Hosseini et al., 2018; Lachguer et al., 2021; Khan et al., 2020; Maestre-Hernández et al., 2023; Mottaghipisheh et al., 2020; Kazemi et al., 2023; Mykhailenko et al., 2022).

While various reviews on different aspects of saffron are available in the literature, this paper aims to present a comprehensive overview of saffron, incorporating recent studies to define its history, botany, geographical origins, and specific characteristics. It will summarize its agronomic aspects and report on the uses and biological evaluations conducted on saffron and its byproducts.

Methodology

Relevant literature was sourced using electronic databases, including Google Scholar, Web of Science, Scopus, and PubMed. A variety of search terms were employed, such as “saffron,” “*Crocus sativus* L.,” “saffron byproducts,” “petal,” “stamen,” “use,” “phytochemistry,” and “biological activities.” Bibliographic resources pertaining to the various aspects of *Crocus sativus* L. in both French and English were included in this review. Additionally, we incorporated insights from a decade of research conducted in our laboratory, which focused on the valorization of saffron byproducts, as well as studies in phytochemistry, molecular biology, micropropagation, and agronomy.

Generalities about Crocus sativus L.

History and genetic origin

Crocus sativus L. is an ancient spice with a botanical origin that remains unclear despite its long history of cultivation, dating back to at least 3,500 years ago during the Sumerian and Babylonian eras (Ravindran, 2024). Studies indicate that saffron may have originated along the Mediterranean shores of Asia Minor and in the valley between the Tigris and Euphrates rivers (Wenger, 2022). Other potential origins include Southeast Asia, Central Asia, or India, while some researchers suggest Persia (Iran), ancient Greece, or Crete as possible starting points (Zohary et al., 2012).

Negbi (1999) demonstrated that saffron was selected and domesticated in Crete during the Late Bronze Age. From there, it spread to India, China, and Middle Eastern countries, eventually reaching the Mediterranean basin through the Arabs, likely being introduced to Morocco in the 9th century. Recent research by Schmidt et al. (2019) clarified the genetic origin of saffron through comparative chromosome analysis (in situ hybridization, FISH) across different species within the *Crocus* genus. Their findings indicated that *Crocus sativus* descends from *Crocus cartwrightianus*.

Supporting this lineage, Nemati et al. (2018) conducted a phylogenetic study that utilized single nucleotide polymorphism (SNP) analysis and genotyping by sequencing (GBS), revealing a high allelic similarity between *C. sativus* and *C. cartwrightianus*. Further analysis by Nemati et al. (2019), which included single-copy nuclear loci, GBS data, chloroplast genomes, and genome size, confirmed that saffron originated from the autoploidization of two distinct genotypes of wild *C. cartwrightianus* found in southern Athens, Greece.

Distribution and economic importance of

saffron

Saffron is cultivated in many countries worldwide, with global production estimated at 430 t in 2019. The market price can reach up to \$10,000 kg^{-1}, depending on quality (Cid-Pérez et al., 2021; Kafi et al., 2018). It is widely cultivated in Iran, India, Greece, Morocco, Afghanistan, Spain and Italy, with Iran producing around 90% of the world's saffron. Morocco is the fourth-largest producer, with over 1,800 ha and a production exceeding 10 t in 2020 (Lachheb, 2023). Traditional production sites are located in Taliouine and Taznakht, with efforts to expand to other regions (Lachguer et al., 2022). In recent years, saffron production has declined in European countries such as Spain, Greece, and Italy, as well as in India (Kashmir). Despite being the leading producer, Iran's yield decreased from 5.1 kg ha^{-1} in 1982 to 3.5 kg ha^{-1} in 2017, possibly due to soil quality deterioration, poor-quality corms, diseases, pests, poor post-harvest management, and climate change (Cardone et al., 2020).

The global saffron trade was valued at \$247 million in 202, with a projected annual growth rate (CAGR) of 12% by 2025 (Kumari et al., 2021). The top exporters are Iran (42.1%), Spain (19%), Afghanistan (16.2%), and Greece (4.22%), while the top importers are China (14.4%), Spain (12.7%), Saudi Arabia (10.5%), and India (8.87 %) (https://oec.world/en/, 2021).

Botanical traits

Saffron (*Crocus sativus* L.) is a monocotyledonous, hysteranthous, herbaceous perennial plant that typically reaches a height of 25 to 40 cm (Kumar et al., 2009). Its high adaptability facilitates widespread cultivation in the Mediterranean region and western Asia (Leone et al., 2018). The species grows between longitudes 10 °W and 80 °E and latitudes 30–50 °N (Cardone et al., 2020).

The genus *Crocus* is classified based on morphological characteristics, as detailed in the book *The Crocus*, edited by Mathew (1999). Taxonomically, saffron belongs to the family Iridaceae, within the superdivision Spermatophyta, division Magnoliophyta, class Liliopsida, subclass Liliidae, and order Liliales. The corm, a short, thick underground stem, is composed of parenchyma cells rich in starch and covered with fibrous tunics (Molina et al., 2004).

Corms vary in shape and size, typically measuring 0.5 to 6.5 cm in diameter and weighing between 0.5 and 70 g. Mature corms have 1 to 3 dominant apical buds that germinate in the following season to produce floral axes and daughter corms (Renau-Morata et al., 2013). Saffron has two types of roots (Fig. 1): thin, fibrous roots responsible for water and nutrient absorption, and contractile, thick roots that help maintain soil depth (Khalesi et al., 2004).

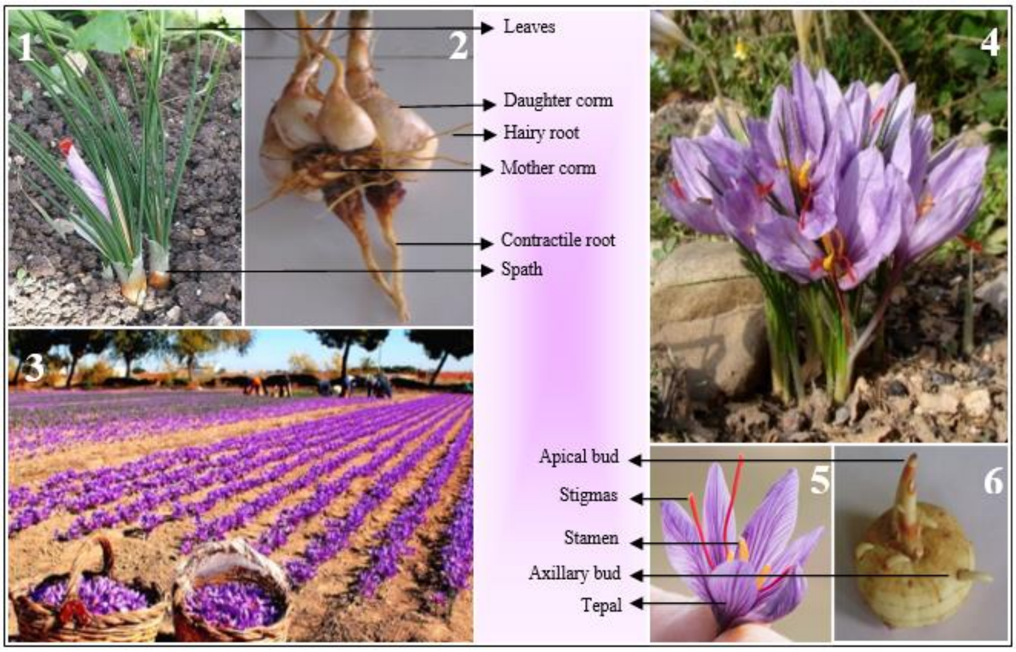

Fig. 1. Saffron leaves (1), Saffron corms and roots (2), saffron farming (3), Saffron plant (4), saffron flower (5) and saffron corm (6).

The flower has six purple tepals that are usually 2 to 4.7 cm in length and 1.1 to 2.3 cm in width. It has a 9- to 10 cm-long yellow-green style, and a red stigma with three filaments, which are the plant's consumable part. The androecium contains three sterile stamens with two-lobed yellow anthers (Mzabri et al., 2021). The leaves are narrow, linear, and dark green, reaching lengths of 20 to 60 cm, with a whitish inner band and a ribbed opposite side, which helps reduce water loss by limiting evapotranspiration. The number of leaves bud^{-1} varies from 5 to 11, growing vertically in early autumn and drying out by late spring (Renau-Morata et al., 2012).

Management techniques

Most crop management techniques, including planting, weeding, flower picking, and stigma separation, are conducted manually around the world. This labor-intensive process makes saffron cultivation both laborious and expensive. Saffron can be grown as either a perennial or an annual crop, with cultivation periods varying by country: up to four years in Spain, up to eight years in Greece and India, and up to twelve years in Morocco (Ait-Oubahou and El-Otmani, 1999).

As the crop ages (typically after 4 to 5 years), the yield of stigmas and corms tends to decline due to competition for water and mineral nutrients, as well as increased susceptibility to fungal attacks resulting from overpopulation (Ramezani et al., 2022).

Soil preparation

Soil preparation is crucial before planting saffron to achieve a friable texture. The soil should be plowed to a depth of approximately 30 cm, followed by cover cropping and leveling, ensuring it is free of weeds. Raised beds, measuring 1.5 m in width and 15 cm in height, with 30 cm paths, can facilitate maintenance. Saffron thrives in neutral to slightly alkaline, loose, and well-drained soils (Gresta et al., 2009).

High-quality saffron and optimal yields can be attained through corm cultivation in controlled environments, such as plastic tunnels, greenhouses, and growth chambers utilizing hydroponic systems (Askari-Khorasgani and Pessarakli, 2019). Various studies have optimized parameters including nutrient solution composition, fertilizers, corm size, planting density, and substrates like perlite, vermiculite, and peat moss.

Forcing methods have also been explored to extend the flowering period and increase production by controlling temperature, humidity, and light. While hydroponic systems can enhance yield and shorten the growing period, some studies have reported lower yields in hydroponics (4 kg ha^{-1}) compared to soil cultivation (7 kg ha^{-1}) (Schroeder et al., 2020; Mollafilabi et al., 2013; Nardi et al., 2022).

Plantation

In perennial crops, the planting depth is greater than in annuals, typically ranging from 10 to 20 cm for perennials and 8 to 10 cm for annuals. In sandy soils, planting depth can reach up to 30 cm (Gresta et al., 2008). The use of large, disease-free corms (greater than 2.5 cm) has a positive impact on saffron yield.

Sowing is performed manually, with the timing varying by region and climate. In Morocco, traditional planting occurs in raised beds measuring 2 × 2 m, with rows spaced 20 cm apart and clusters of 2-3 bulbs planted 10-15 cm apart. While high planting density can initially enhance performance, it may lead to reduced long-term yields due to overcrowding and the accumulation of harmful substances in the soil (Ramezani, 2022).

Rotation crop

Crop rotation is essential for maintaining soil health, restoring fertility, improving soil structure, and controlling pests and diseases (Kafi et al., 2018). The preceding crop should be disease-free, preferably a legume, while avoiding crops like alfalfa, potatoes, and sugar beets that share diseases with saffron (Mollafilabi, 2001). The recommended rotation period is between 3 to 8 years. Additionally, saffron can be cultivated between rows of almond trees, vines, other fruit trees, or ornamental plants such as roses (Kafi et al., 2018).

Irrigation

Saffron is well-suitable for arid and semi-arid regions due to its drought resistance and ability to remain dormant for five months without irrigation. Irrigation typically begins from October to November and stops after mid-May to avoid the risk of fungal attacks (Kafi et al., 2018). In Iran, up to 3000 m^3 of flood irrigation is used annually, whereas in Morocco, 350 to 500 m^3 ha^{-1} is applied weekly during autumn and biweekly in winter and early spring, totaling 7000 m^3 ha^{-1} year^{-1}. Common irrigation systems include surface, sprinkler, and drip irrigation. The frequency varies by soil type, growth stage, and climate, with recommendations ranging from 4 to 10 irrigations annually. Saffron has also high salinity tolerance (Nehvi and Salwee, 2010;

Cardone et al., 2020; Mzabri et al., 2017; Kafi et al., 2018).

Fertilization

Saffron has low nutrient requirements, and excessive use of fertilizers, particularly nitrogen, can promote vegetative growth at the expense of yield. In India, a combination of 5–10–15 kg of NPK is applied along with manure (Kafi et al., 2018). In Iran, the application of 46 kg of nitrogen in the form of urea is common (Rezaian and Forouhar, 2004). Globally, most farmers apply between 20 to 30 t ha^{-1} of organic matter (Koocheki, 2004).

Foliar fertilizer application with urea sprayed in winter has reportedly stimulated flowering and increased crocin levels, although it may also reduce the levels of picrocrocin and safranal (Rabani-Foroutagheh et al., 2014). Biostimulants are also advantageous for saffron cultivation. Mycorrhizal fungi such as *Rhizophagus intraradices* and *Funneliformis mosseae*, whether applied alone or in combination with fertilizers, as well as rhizobacteria like *Bacillus subtilis* FZB24 and vermicompost, have been found to positively impact both the quantity and quality of saffron (Caser et al., 2019; Ghanbari et al., 2019; Husaini, 2014).

Weed control

Weed control is crucial in saffron production as weeds compete with saffron for water, nutrients, and light, negatively impacts corm growth and yield (Rimani et al., 2019; Ramesh et al., 2017). Common saffron weeds include *Cardaria draba, Bromus tectorum, Poa bulbosa, Hordeum spontaneum, Amaranthus retroflexus* and *Cirsium arvense* (Soufizadeh et al., 2007). In Morocco, 210 weeds from 34 botanical families have been identified in saffron-producing areas, with Asteraceae, Poaceae, Fabaceae, Brassicaceae and Caryophyllaceae being dominant. Key species include *Convolvulus arvensis*, *Bromus rubens, Lolium perenne* and *Hordeum murinum* (Rimani et al., 2019). Weeding can be done manually or with herbicides such as Simazine (Gesatop 50%) or Atrazina (Gesaprim 50%) at 10 kg ha^{-1}. During summer rest, general herbicides such as Roundup (Glyphosate) or Buster (2,4-D, 2,4-DP) can be applied. Physical control methods such as using plastic mulch or sawdust, are also effective alternative (Gresta et al., 2008).

Harvesting

Harvesting saffron involves the collection of flowers and the meticulous separation of stigmas, a labor-intensive process that requires precision. The harvest period typically spans from October to November and lasts 2 to 3 weeks, depending on the region. Given the ephemeral nature of the flower, harvesting begins the day it blooms, ideally early in the morning before sunrise, to ensure saffron quality and facilitate easier separation (Kafi et al., 2018).

The flowers grow a few centimeters above the ground and are often surrounded by leaves, necessitating hand harvesting, usually performed by family members. Stigmas are gently plucked using fingertips or small scissors, although some countries have introduced mechanical methods. After harvesting, stigmas are separated from the flowers and protected from light and contamination before drying. Mechanization may involve tools such as a vertical air column, an oscillating separator, or a wind tunnel (Emadi, 2009; Babaie et al., 2012).

Manually picking 1,000 flowers takes approximately 45 to 55 min, with an additional 100 to 130 min required for pruning. One kg of flowers yields about 72 g of fresh saffron, which dries to approximately 12 g. Consequently, producing 1 kg of dried saffron demands between 370 to 470 h of labor (Golmohammadi, 2014).

Saffron yields can range from 2 to 28 kg ha^{-1}, influenced by environmental, biological, and anthropogenic factors such as cultivation duration, edaphic and climatic conditions, corm size and origin, as well as cultural practices including planting density, irrigation, and fertilization (Cardone et al., 2019; Ben El Caid et al., 2020; Ghanbari et al., 2019).

Corms are typically replanted every 1 to 12 years, depending on the country. Before replanting, corms are washed, classified, selected, and disinfected with fungicides such as copper oxychloride or prochloraz. For optimal flowering, corms should be stored at 23–27 °C for 3–5 months or at 25 °C for over 55 d, followed by forcing at 17 °C (Molina et al., 2004, 2005).

Drying

The drying process is a crucial step in saffron production, as it preserves and enhances the spice's flavor, aroma, and color, during which the stigmas lose nearly 80% of their weight (Campo et al., 2010). Various saffron drying techniques are employed worldwide, including sun drying, shade drying, the use of dryers, forced air drying, low-temperature oven drying with oil moistening, and roasting over hot ashes in silk sieves (Kumar et al., 2009; Anastasaki et al., 2010). Research indicates that drying saffron in an electric oven at 60 °C yields the best quality results (Atyane et al., 2017). Once fully dried, saffron should be stored in tightly closed glass containers, protected from light, heat, and humidity, ideally at low temperatures around 4 °C (Atyane et al., 2017).

Pests and diseases

Saffron cultivation encounters various pest and disease challenges that can significantly impact its growth, yield, and quality. Among the primary fungal threats are *Rhizoctonia violacea*, *Pythium irregular*, *Fusarium solani*, *Phoma crocophila*, *Macrophomina phaseolina*, and *Penicillium cyclopium*, which cause corm rot, particularly in humid conditions. Effective strategies to mitigate these fungal threats include breeding resistant genotypes, in vitro culture, grading and sorting corms before planting, crop rotation, and the application of fungicides such as Benomil or copper solutions (Gresta et al., 2008; Gupta et al., 2021; Gupta et al., 2011).

Nematodes further exacerbate fungal infections by causing root lesions that weaken plants and facilitate pathogen entry (Khan and Sharma, 2020). In Morocco, nematodes such as *Aphelenchoides*, *Pratylenchus*, and *Helicotylenchus* significantly reduce saffron yield (Benjlil et al., 2020). In Kashmir, the main nematode genera identified in saffron include *Tylenchus*, *Helicotylenchus*, and *Pratylenchus* (Sheikh et al., 2017).

Saffron is also susceptible to various viruses, including the yellow bean mosaic virus, cucumber mosaic virus, tobacco rattle virus, tobacco necrosis virus, and tomato tan disease virus (Parizad et al., 2016; Parizad et al., 2018). Additionally, rodents such as moles, rats, and rabbits pose a threat by feeding on corms and leaves, while cantharidin beetles and crows can damage the flowers. Rodent control can be achieved using poison baits, smoke gas devices, or poison gas-releasing tablets (Ghorbani and Koocheki, 2017).

Saffron quality

The quality of saffron is primarily determined by the concentration of its three major secondary metabolites: crocin, picrocrocin, and safranal, which are responsible for its color, flavor, and aroma, respectively (Zhang et al., 2019). Several factors influence saffron quality, including climatic conditions (temperature and precipitation), soil quality, altitude, the origin of corms, genetic traits, harvest and post-harvest practices, the degree of flower openness at harvest time, drying methods (including temperature and duration), and storage conditions (Atyane et al., 2017; Cardone et al., 2019; Lage and Cantrell, 2009; Erden et al., 2016; Carmona et al., 2005; Campo et al., 2010; Avila-Sosa et al., 2022).

To obtain high-quality saffron, short drying at high temperatures is recommended by Carmona et al. (2005). Drying at 60 °C for 55 min is suggested to yield the highest content of crocin and picrocrocin, while drying at 55 °C for 1 h 30 min is recommended for a high safranal content (Cossignani et al., 2014). Microwave drying is considered ideal for preserving molecules compared to other methods but has been shown to result in lower antioxidant activity in the stigmas (Tong et al., 2015). Other authors have concluded that freeze-drying produces higher levels of crocin and safranal (Acar et al., 2011). Storage time also affects saffron quality. Freshly dried spice has high crocin and picrocrocin contents, while safranal, a volatile compound, increases with storage time (Sereshti, 2018). High humidity and storage degrade crocin and picrocrocin but allows the development of saffron aroma (Avila-Sosa et al., 2022). Additionally, crocin and picrocrocin decrease more significantly with shade drying than with oven drying (Chaouiqi et al., 2018). Color intensity (crocin) is the most important parameter related to saffron quality, as it helps establish the market price (Avila-Sosa et al., 2022). The coloring strength decreases by about 30-40 units year^{-1}, with the shelf life of saffron being three to four years under good conditions (Campo et al., 2010). Therefore, crocin and picrocrocin are the most affected parameters in saffron categorization.

Saffron quality is assessed according to the ISO 3632:2010-2011 standard, which classifies saffron into three categories: Category I (high quality), Category II (medium quality), and Category III (low quality). The classification considers factors such as the presence of flower residues, foreign materials, moisture content, volatile components, ash content, coloring power, bitterness, and aroma (ISO-3632-2, 2010).

Quality assessment involves quantifying the aqueous extract of the stigmas (1%) using spectrophotometry. Specific measurements include crocin at 440 nm, picrocrocin at 257 nm, and safranal at 330 nm (Sabatino et al., 2011).

Adulteration

Saffron, being a high-value product, is particularly susceptible to adulteration, a practice that has been recorded since the Middle Ages in Europe, where those caught falsifying it could face severe penalties, including death (Gresta et al., 2008). Adulteration may involve the addition of vegetable or synthetic substances, whether organic or inorganic. Common adulterants include byproducts of saffron such as styles and stamens, as well as other herbs like safflower, turmeric, calendula, annatto, arnica, poppy, capsicum, onion skins, maize stigmas, beet, and pomegranate. Additionally, synthetic dyes such as Tartrazine, Methyl orange, Quinoline, Ponceau 2R, Erythrosine, and Eosin are sometimes used (Carmona and Alonso, 2004). Saffron may also be mixed with oil, honey, glycerin, potassium or ammonium nitrate, dried meat fibers, or red silk fibers, and the geographical origin of saffron production can be misrepresented as a form of fraud (Rubert et al., 2016).

To combat adulteration, various detection methods have been explored. These include laser-induced breakdown spectroscopy (LIBS), attenuated total reflectance (ATR-FTIR), diffuse reflection Fourier transform infrared spectroscopy (DRIFTS), Raman spectroscopy with principal component analysis (PCA), chemometric methods, and 1H NMR metabolite fingerprinting (Varliklioz et al., 2017; Petrakis et al., 2015; Petrakis and Polissiou, 2017). Furthermore, some researchers have proposed the use of an electronic nose system, which has shown promise in effectively distinguishing between pure and adulterated saffron (Heidarbeigi et al., 2015).

Chemical composition

The saffron stigma contains over 150 compounds, both volatile and non-volatile, including primary metabolites such as carbohydrates, minerals, lipids, vitamins, amino acids, and proteins, as well as secondary metabolites like carotenoids, monoterpenes, and flavonoids, primarily anthocyanins (Maggi et al., 2020). The color of saffron is attributed to crocin, an 8,8-diapocarotene-8,8-dioic acid, which is the most abundant component, constituting 6–16% of the dry matter and having the chemical formula $C_{44}H_{64}O_{24}$ (Gregory et al., 2005). Crocin is the key pigment in saffron, accounting for approximately 80% of its compounds; it dissolves rapidly in water to form an orange solution, making it widely used as a food coloring (Shahi et al., 2016). Crocetin, the aglycone of crocin, is a carotenoid known as 8,8-diapo-8,8-carotenoid acid, with the chemical formula $C_{20}H_{24}O_4$ (Kothari et al., 2021). The distinctive taste of saffron primarily arises from picrocrocin, or 4-(β-D-glucopyranosyloxy)-2,6,6-trimethyl-1-cyclohexene-1-carboxaldehyde, which is the second most abundant component, comprising 1–13% of the dry matter and having the chemical formula $C_{16}H_{26}O_7$ (Samarghandian and Borji, 2014). Picrocrocin is a monoterpene glycoside responsible for saffron's bitter flavor and serves as a precursor to safranal (Shahi et al., 2016).

The primary volatile compound contributing to saffron's aroma is safranal, or 2,6,6-trimethyl-1,3-cyclohexadiene-1-carboxaldehyde. This compound is present in very low quantities (0.001 to 0.006% of dry matter) and has the chemical formula $C_{10}H_{14}O$ (Carmona et al., 2006). Safranal is formed from the enzymatic action of β-glucosidase on picrocrocin after drying and storage, and it is absent in fresh stigmas (Maggi et al., 2010). Its concentration can comprise up to 70% of the total volatile fraction (Kothari et al., 2021).

Saffron tepals, which are the primary byproduct of saffron processing, are generated in large quantities, yielding approximately 92.6 g of petals for every 100 g of flowers. The production of 1 kg of stigmas results in about 350 kg of petals, requiring the harvest of 150,000–200,000 flowers, thus making these byproducts economically viable for valorization (Sánchez-Vioque et al., 2012). The tepals are rich in protein, fiber, lipids, and essential minerals such as potassium, calcium, and phosphorus, rendering them suitable for use as animal feed (Shahi et al., 2016). They are also a source of phenolic and biologically active compounds, including flavonoids (e.g., kaempferol, rutin, quercetin, luteolin, hesperidin, and other bioflavonoids), carotenoids (crocin and crocetin), tannins, and anthocyanins (delphinidin, petunidin, and malvidin) (Kanakis et al., 2006).

Due to their lower cost and substantial production compared to the stigma, saffron petals present a promising resource for various applications, some of which are discussed in this review. Saffron stamens, while containing high levels of protein, ash, soluble sugars, and long-chain unsaturated fatty acids, have lower concentrations of polyphenols, flavonoids, and polysaccharides compared to the tepals (Zara et al., 2021). They also contain valuable microelements and antioxidant compounds (Chichiriccò et al., 2019). The beneficial properties and applications of saffron (stigma) and its byproducts in medicine, perfumes, cosmetics, and the food industry have been extensively documented in the literature.

Marketing

The organization of marketing channels is increasingly recognized as a critical area of research in marketing, with existing studies highlighting the challenges faced by saffron market channels (Hamid et al., 2017). In many developing countries, saffron exports struggle to find adequate markets due to the absence of effective marketing strategies, which are essential for boosting sales and securing sustainable competitive advantages.

Key challenges include the tendency to sell and export saffron in bulk without processing, which diminishes its added value. Additional weaknesses in the saffron sector are linked to non-compliance with international standards, outdated distribution systems, and the lack of organizations capable of supervising farmers throughout the production-to-marketing process. Furthermore, there are ineffective marketing organizations, limited funding for scientific research on saffron valorization and its byproducts, issues with fraud, increased competition from countries like China and Afghanistan, and a lack of robust e-commerce infrastructure (Mohammadi and Reed, 2020).

In Morocco and several other countries, farmers often sell their products through intermediaries, leading to significant losses due to insufficient knowledge regarding market supply, demand, and financial instability (Aboudrare et al., 2014). Addressing these challenges requires the establishment of cooperative groups and unions aimed at developing the saffron sector and improving producers' living conditions. Strategies should include reducing the number of intermediaries, creating a direct marketing network for saffron, establishing legal barriers to prevent bulk exports, and ensuring government oversight of farmers. Additionally, there is a need to create standards and certifications to identify saffron and prevent fraud, as well as to control the saffron market and product processing. Increasing investment, better addressing consumer preferences, and encouraging scientific research are also vital (Mohammadi and Reed, 2020).

Saffron prices fluctuate significantly based on the year, end use, and market conditions. These price variations not only affect growers but also have a broader impact on the local economies of saffron-producing regions (Shahnoushi et al., 2020). For instance, in the Taliouine-Taznakht region of Morocco, a 77% increase in saffron prices led to substantial improvements in production technology, such as the adoption of drip irrigation systems, which significantly boosted flower yield and increased income, particularly for women workers (Filipski et al., 2017). Therefore, educating marketers on pricing structures and dynamic marketing strategies is crucial for effectively promoting saffron and attracting potential international buyers.

Properties and uses of saffron

Biological activities of saffron and its byproducts

The biological properties of different parts (stigma, tepal, leaves, corm, and stamen) of *Crocus sativus* L. have been investigated. Table 1 displays noteworthy findings from the most pertinent pharmacological studies.

Oxidative stress refers to diseases caused by reactive oxygen species (ROS), called free radicals. It is defined as a disturbance in the balance between oxidants (free radicals) and antioxidant defenses, favoring oxidants, which leads to pathogenic potential implicated in several diseases, including cancer, cardiovascular diseases, diabetes, and neurodegenerative disorders (Butnariu et al., 2022). The medicinal effects of saffron are related to its strong antioxidant capacity, primarily attributed to crocin, crocetin, safranal, and flavonoid compounds such as kaempferol (Ashktorab et al., 2019). The antioxidant activity of saffron stigmas from seven different production areas was studied using various essays (DPPH, %OH, O_2% radical-scavenging, and reducing power). The results showed that total polysaccharides content ranged from 52.65 to 67.18 mg g^{-1}, and total crocin content varied from 80.59 to 230.36 mg g^{-1}, with both extracts exhibiting excellent antioxidant activity using all methods (Zhang et al., 2019). The antioxidant potential of saffron stigmas and callus have also been studied by Parray et al. (2015). Saffron byproducts could also serve as a potential source of natural antioxidants. Aqueous and organic extracts of petals were evaluated by different *in vitro* assays, specifically, diethyl ether, n-Butanol, and ethyl acetate fractions (Lachguer et al., 2022). Further studies evaluated the antioxidant activity of tepals, styles, leaves, spaths, tunics, and stamens, revealing a significant potential for antioxidant activity (Maestre-Hernández et al., 2023; Lahmass et al., 2017; Lahmass et al., 2018).

Saffron demonstrates several beneficial properties for the human immune system, particularly in enhancing the body’s response to infections caused by bacteria and fungi. Safranal and crocin are notably responsible for the bactericidal effects observed during food contamination by pathogens like *Salmonella* (Pintado et al., 2011).

Table 1. Biological activities of saffron byproducts.

Extraction method	Metabolites	Biological activity	Results	Reference
Extraction by agitation Ethyl acetate extract (petals)	Polyphenols: >111.91 µmoles µmoles EG 100 g^{-1} DW Flavonoids: >109.25 µmoles EG 100 g^{-1} DW	Antioxidant	**Antioxidant activity** ABTS test > 8.42 µmoles Trolox 100 g^{-1} DW)	(Maestre-Hernández et al., 2023)
Soxhlet extraction Methanolic extract (petals)	-	Antibacterial	*Staphylococcus aureus*: MIC 6,25 mg mL^{-1}, MBC 12,5 mg mL^{-1}, *Bacillus cereus*: MIC 12,25 mg mL^{-1} MBC 25 mg mL^{-1} *Escherichia coli*: MIC 50 mg mL-1 MBC 100 mg mL^{-1}, Pseudomonas aeruginosa: MIC 100 mg mL^{-1} MBC 200 mg mL^{-1}	(Sales and Pashazadeh, 2020)
Extraction hydro-ethanolic 1:1 (petals)	Kaempferol-3-O-sophoroside/glucoside Quercetin-3-O- sophoroside	Antidepressant	Kaempferol, a flavonoid of the tepals and stamen was reported to have antidepressant activity	(Mottaghipisheh et al., 2020)
Maceration Methanolic extract (petals)	kaempferol and crocin	Anti-cardiovascular	Methanolic extract: weak negative inotropic and chronotropic intrinsic activities and a significant intrinsic activity on smooth muscle with a potency on the ileum EC_{50} = 0.66 mg mL^{-1} better than on the aorta EC_{50} = 1.45 mg mL^{-1}. Kaempferol and crocin: selective negative inotropic activity. Kaempferol decreased the contraction induced by KCl (80 mM) in guinea pig aortic and ileal strips. Crocin had no effect. They decreased intracellular ROS formation and increased cell viability.	(Zeka et al., 2020)
Maceration (petals, leaves, corms) ethanol/water (80%, v/v)	-	Analgesic Anti-inflammatory Anti-coagulant Antidepressant	Analgesic effect Latency activity = 64.06% (petals), 29.07% (leaves), 22.40% (corms). Percentage edema inhibition of 70.50% (petals), 53.29% (leaves), 47.47% (corms). Coagulation time: 86.5 s (petals), 66.83 s (leaves), 42.83 s (corms). Potential antidepressant: Immobility time ≤ 76.66 s (petals), 106.83 s (leaves), 96.50 s (corms).	(Khan et al., 2020)
Maceration Aqueous extract (petals)	-	Anti-dyslipidemia Anti-cardiovascular	Extract decreased the serum lipid levels of patients (triglycerides, total cholesterol and low-density lipoproteins) in the intervention group (113.81 ± 12.93, 56.52 ± 4.68 and 48.28 ± 3.70).	(Kazemi et al., 2023)
Maceration (leaves) Ethanol/water 80/20 (v/v)	-	Anti-diabetic	Prevention of body weight loss. Protection against increased water intake, urine elimination, blood glucose, plasma triglycerides, cholesterol, urea, creatinine, AST and ALT levels in diabetic rats treated.	(Ouahhoud et al., 2019)
Maceration (leaves) Hydro-ethanolic 80%	-	Nephroprotective	Extract exhibit good recovery potential for nephrotoxicity induced by gentamicin. = renoprotective effect.	(Ouahhoud et al., 2022)
Ultrasonication (stamen) 70% ethanol	Flavonoids	Hepatoprotective	Kaempferol-3-O-sophoroside exhibits a protective of t-BHP-induced cell injury through the regulation of the expression of antioxidant, antiapoptotic, and anti-inflammatory gene.	(Ye et al., 2021)
Infusion (stamen)	-	Neuroprotective Anti-inflammatory	Improvement Patient health questionnaires 9 (PHQ-9) scale and Brain derived neurotrophic factors (BDNF). Reduction the inflammatory markers C-reactive protein (CRP) and Tryptophan (TRP) level in plasma. Increased the availability of TRP in brain.	(Ahmad et al., 2022)
-	-	Anti-hypertensive	Extract attenuated the pressor effect induced by AngII, and increased MAP and SBP induced by LNAME. Higher effect on L-NAME than that of AngII BRS improvement Anti-hypertensive effects that are probably mediated by an inhibitory effect on AngII, increasing nitric oxide production, or improving baroreflex sensitivity.	(Mohebbati et al., 2021)
80% ethanol extract (corms)	Phenolic compounds: 18.9 mg g^{-1} GAE Flavonoids: 8.8 mg g^{-1} RE	Hepatoprotective	Extracts decreased liver enzyme levels and improved oxidative stress status in hepatotoxic rats. This effect was notable in case of acetaminophen-induced hepatotoxicity.	(Moossavi et al., 2016)

ALT: Alanine amino Transferase; AngII: angiotensin II; AST: Aspartate amino Transferase; DPPH: 2,2-diphényl 1-picrylhydrazyle; GAE: Gallic acid equivalent; L-NAME: NG-nitro-L-arginine methyl ester; MAP: Mean Arterial Pressure; MBC: Minimum bactericidal concentration; MIC: Minimum inhibitory concentration; QE: Quercetin equivalent; RE: Rutin Equivalent; SBP: Systolic Blood Pressure.

Research has shown that saffron stigma and tepal possess antioxidant, antibacterial, and anti-biofilm properties, as evidenced by assays such as DPPH and ORAC, tested against methicillin-resistant *Staphylococcus aureus* strains (Bellachioma et al., 2022). Additionally, saffron petals can serve as a natural dye and exhibit antibacterial activity against *Staphylococcus aureus*, *Escherichia coli*, and *Pseudomonas aeruginosa* when applied to wool fabric (Shahmoradi et al., 2014).

In a study investigating the antibacterial effects of saffron stigmas and callus extracts on four pathogenic bacterial strains (*S. aureus*, *E. coli*, *P. aeruginosa*, and *S. flexneri*), both extracts displayed significant antibacterial action, with the stigma proving most effective against all tested strains (Parray et al., 2015). Ethyl acetate extracts from various saffron parts have shown efficacy against *Micrococcus luteus*, *Staphylococcus epidermidis*, *Staphylococcus aureus*, *E. coli*, as well as the fungi *Candida albicans*, *Aspergillus niger*, and *Cladosporium* species. Moreover, ethanolic and methanolic extracts of saffron have demonstrated appropriate anti-Brucella activity (Hosseinzadeh and Nassiri-Asl, 2013).

The methanolic extract of saffron petals exhibits a stronger inhibitory effect on Gram-positive bacteria compared to Gram-negative ones, with minimum inhibitory concentrations (MIC) and minimum bactericidal concentrations (MBC) ranging from 6.25-100 mg mL^{-1} and 12.5-200 mg mL^{-1}, respectively (Sales and Pashazadeh, 2020). Lachguer et al. (2022) found that diethyl ether and ethyl acetate extracts were particularly effective against *S. aureus*, outperforming their effects against *Listeria monocytogenes*, *E. coli*, and *Klebsiella pneumoniae*. These extracts also demonstrated antifungal activity against key species responsible for post-harvest molds and crop yield losses, with *Botrytis cinerea* showing greater susceptibility than *Fusarium solani*, *Penicillium expansum*, and *Penicillium digitatum*.

Additionally, the liposoluble fraction of saffron flower stamens contains high levels of linoleic, linolenic, and palmitic fatty acids, exhibiting strong antimicrobial effects both in vitro and within food matrices against common food-borne pathogens like *S. aureus* and *E. coli* (Zara et al., 2021). Saffron corms also contain antifungal compounds that remain effective at high temperatures, with the outer part of the bulb showing enhanced antifungal activity against *Fusarium oxysporum*, attributed to a mixture of triterpenoid saponins (Rubio-Moraga et al., 2013).

Saffron has shown significant anti-inflammatory effectiveness in various experimental models. Hosseinzadeh and Younesi (2002) studied the impact of aqueous and ethanolic extracts of saffron stigmas on the pain threshold in mice, finding that higher doses significantly alleviated chronic inflammation caused by formalin-induced edema in rat paws. In a carrageenan-induced hind paw edema test, the ethanolic extract of saffron stigmas exhibited the most pronounced inhibition of inflammation, recording a 77.33% reduction at the fourth hour, followed by petals (70.50%), leaves (53.29%), and corms (47.47%) (Khan et al., 2020). Saffron petals also play a role in managing conditions like polycystic ovary syndrome (PCOS) by improving ovarian steroid dysregulation and reducing inflammatory markers. Key bioactive compounds found in saffron tepal, including anthocyanins, kaempferol, and quercetin, have been shown to inhibit the production of inflammatory factors and pro-inflammatory cytokines, showcasing strong antioxidant properties (Moshfegh et al., 2022).

Further investigations into the potential nutraceutical benefits of saffron extracts, derived from corms, leaves, petals, and stigmas, indicate that all parts possess significant pharmacological activities, suggesting their use as potential therapeutic agents for anti-inflammatory, analgesic, anticoagulant, and antidepressant purposes (Khan et al., 2020).

Numerous studies have also explored the neuroprotective effects of *Crocus sativus L.*, particularly regarding neurodegenerative conditions like Parkinson's and Alzheimer's diseases (Hatziagapiou et al., 2019). Research supports the notion that saffron’s mechanisms of action may counteract neurodegenerative processes. The aqueous extract of saffron stigmas has been found to combat retinal neurodegeneration, potentially due to the presence of specific crocins along with other active components (Maggi et al., 2020). Additionally, studies suggest that saffron may mitigate neural damage through mechanisms such as reducing oxidative stress, down-regulating apoptotic proteins, and exerting vascular protective effects by lowering levels of nitric oxide and brain natriuretic peptide (Abdel-Rahman et al., 2020).

Depression, a common psychological issue, is often linked to prolonged stress and serotonin deficiency, which is exacerbated by tryptophan depletion. Recent research has explored the combined effects of chamomile and saffron stamen as a complementary therapy for individuals with mild to moderate depression. The study found significant improvements in depressive symptoms among participants (Ahmad et al., 2022).

Saffron’s tepal and stamen are particularly rich in flavonol glucosides, such as quercetin-3-O-sophoroside, kaempferol-3-O-sophoroside, and kaempferol-3-O-glucoside, which suggest potential antidepressant properties (Mottaghipisheh et al., 2020). Furthermore, ethanolic extracts from saffron petals and stigmas have demonstrated notable antidepressant effects, with reported immobility times of ≤76.66 seconds in behavioral tests. In contrast, extracts from saffron corms and leaves exhibited moderate to mild antidepressant activity (Khan et al., 2020). These findings underscore saffron's potential as a natural therapeutic option for managing depression.

Cardiovascular diseases are the major causes of mortality worldwide and pose significant challenges for clinical treatment. Saffron may be used as a potent phytomedicine for treating and preventing of dyslipidemia and cardiovascular disorders. Research has showed that saffron petal can reduced blood serum lipid profiles, as well as urea and creatinine in patients with dyslipidemia (Kazemi et al., 2023). The methanolic petal extract showed weak negative inotropic and chronotropic intrinsic activities and a significant intrinsic activity on smooth muscle, with potency on the ileum $EC_{50} = 0.66$ mg mL^{-1}, better than on the aorta. This by-product is rich in bioactive compounds such as kaempferol and crocin, which have subsequently been shown to affect multiple targets, potentially providing benefits in the early stages of chronic diseases such as atherosclerosis or hypertension (Zeka et al., 2020).

Recent studies highlighted the health benefits of saffron in relation to cardiovascular health and diabetes management. Treatment with saffron petals has been shown to reduce mean plasma malondialdehyde levels, enhance antioxidant levels, and lower lipid profiles and inflammatory markers. These effects stem from saffron's antioxidant properties, which help decrease lipid peroxidation and inflammation, making it a potential preventive agent against cardiovascular diseases, especially those linked to high cholesterol (Mohamadpour et al., 2020).

Saffron stigma, stamen, and petal may also exhibit antihypertensive effects, potentially improving blood pressure in elderly individuals with hypertension by influencing factors that regulate vascular endothelial resistance (Farrokhfall et al., 2019; Mohebbati et al., 2021; Hooshmand-Moghadam et al., 2021). In the context of diabetes, which is characterized by elevated blood sugar levels due to inadequate insulin secretion or poor cellular response, hydro-ethanolic extracts of saffron tepals and stigmas have demonstrated protective effects in diabetic rats. These extracts significantly prevented weight loss and controlled increases in water intake, urine output, blood glucose, and plasma triglycerides, cholesterol, urea, creatinine, and liver enzymes (AST and ALT) (Ouahhoud et al., 2019). Additionally, saffron petals, rich in polyphenols, have shown notable antidiabetic activity through their α-glucosidase inhibitory effects (Wali et al., 2020). These findings suggest that saffron may be a valuable natural remedy for managing both cardiovascular health and diabetes.

Cancer is characterized by the uncontrolled proliferation of abnormal cells that form malignant tumors, which can invade surrounding healthy tissue. These cells can grow in any tissue and are challenging to treat effectively. A study tested aqueous saffron stigma extract on the A549 lung cancer cell line at concentrations ranging from 100 to 800 µg mL^{-1}. Saffron inhibited A549 cell proliferation, induced morphological changes, reduced the number of viable cells, and promoted apoptosis. The IC_{50} values were 380 µg mL^{-1} after 48 h and 170 µg mL^{-1} after 72 h (Samarghandian et al., 2013). Moradzadeh et al. (2018, 2019) explored the antileukemic properties of saffron, finding that it can slow cancer cell growth by inhibiting nucleic acid synthesis, stimulating the antioxidant system, and promoting the differentiation of promyelocytic leukemia cells at concentrations below 10 µM. Further research revealed that saffron petals extracts (Hexane, dichloromethane, and ethanol) decreased cell viability in MDA-MB-231 cells using the MTT method, demonstrating significant toxicity (Wali et al., 2020). The ethanolic extract of saffron leaves reduced the viability of melanoma (IGR39) and triple-negative breast cancer (MDA-MB-231) cells, with $EC_{50} = 410 \pm 100$ and 330 ± 40 µg mL^{-1}, respectively (Mykhailenko et al., 2022).

Other researchers have reported the pharmacological actions of saffron regarding different parts of the gastrointestinal system. Harchegani et al. (2019) evaluated the hepatoprotective properties of aqueous extracts of saffron. The results of this work indicated that saffron decreased the activity of liver enzymes and malondialdehyde values in hepatotoxic rats, with a significant enhancement in serum total antioxidant capacity. Crocin exhibit an hepatoprotective effect in experimental acute liver injury induced by CCI_4 (Aras et al., 2022). Saffron petals and stamens also demonstrated a hepatoprotective effect, with Kaempferol-3-O-sophoroside showing protection against t-BHP-induced cell injury through the regulation of antioxidant, antiapoptotic, and anti-inflammatory gene expression (Ye et al., 2021). Ethanolic extracts decreased liver enzyme levels and improved oxidative stress status in hepatotoxic rats, with notable effects in case of acetaminophen-induced hepatotoxicity (Moossavi et al., 2016). Furthermore, safranal produced gastro-protective effects against indomethacin-induced gastric ulcers (Tamaddonfard et al., 2019). Petal extract also exhibited ulcer healing activity in acetic acid induced gastric ulcers in rats (Mohammadifard et al., 2021).

Numerous clinical studies have examined the effects and mechanisms of action of saffron as a possible therapy for eye diseases. The results demonstrated that oral saffron was effective in the treatment of mild/moderate age-related macular degeneration and had a positive impact on visual function (Broadhead et al., 2019). Other various therapeutic effects of saffron, such as antinociceptive, anticonvulsant, anticoagulant, hypnotic, antihistamine, antityrosinase, anti-asthmatic, analgesic, nephroprotective, and sexual dysfunction, have been studied (Hosseinzadeh and Younesi, 2002; Sariri et al., 2011; Leone et al., 2018; Khan et al., 2020; Ouahhoud et al., 2022). The safety limits for saffron consumption are based on toxicological evaluations of saffron and its main compounds. In general, consuming less than 1.5 g of saffron stigmas is not toxic to humans. However, doses above 5 g are considered toxic, and a daily intake of around 20 g can be fatal (Mzabri et al., 2019).

Cosmetology, perfumery, food, agriculture, and dyeing uses of saffron and its byproducts

Saffron is experiencing a resurgence in the cosmetics industry, thanks to its rich history of use for beauty and skin health. Historically, figures like Cleopatra utilized saffron in their beauty regimens, while traditional practices in Iran and Greece recognized its benefits for improving complexion and treating various skin conditions. In Hindu culture, saffron is symbolically significant, often used by women as a bindi, representing good fortune and awareness (Yildirim et al., 2020).

Today, both saffron stigmas and petals are valued for their bioactive compounds, including crocin and kaempferol, which make them promising ingredients for cosmetic formulations. Research suggests that saffron may outperform traditional sunscreen agents like homosalate and act as a natural UV absorber. It also shows potential in skin lightening by inhibiting tyrosinase activity, thereby reducing melanin production (Mzabri et al., 2019).

Beyond these effects, saffron possesses anti-aging properties, helping to treat acne and reduce erythema. Its antioxidants combat skin inflammation, and clinical studies indicate that formulations containing 3% saffron extract can effectively manage melanoma, demonstrating superior efficacy compared to placebo (Cardone et al., 2020). Furthermore, daily use of creams incorporating saffron extract and avocado oil has been shown to be safe and effective for facial skin rejuvenation, improving elasticity and reducing signs of aging while decreasing transepidermal water loss (Naeimifar et al., 2020).

Since the Parthian dynasty, saffron has been celebrated in perfumery for its woody, sweet, and exotic character. It serves as a natural pigment in both cosmetics and food, with its intense red-orange color primarily derived from compounds like crocin and crocetin. In cosmetics, saffron is often utilized as a coloring agent in products such as lipsticks and eyeshadows, while in the culinary world, it enhances dishes and beverages by imparting a rich golden-yellow hue and a delicate, aromatic flavor (Pandita, 2021). Additionally, saffron petals can be used for garnishing and embellishing various dishes. Research has demonstrated saffron's antibacterial properties against foodborne pathogens like salmonella, as well as its ability to enhance the antioxidant activity of foods and improve their textural and sensory qualities, such as in pasta (Armellini et al., 2018). When added to yogurt, saffron not only intensifies color but also reduces fat content (Gaglio et al., 2019).

In agriculture, saffron functions as a biostimulant, offering a natural alternative to chemical inputs. Khoulati et al. (2023) explored the use of aqueous extracts from saffron byproducts, stigmas, tepals, and stamens, as foliar treatments on eggplant plants in greenhouse conditions. Their findings indicated that saffron stigma extract significantly improved plant height and various biochemical parameters, including levels of polyphenols, flavonoids, anthocyanins, flavanols, condensed tannins, lycopene, carotenoids, and °Brix content. A concentration of 0.6 g L^{-1} yielded the most substantial benefits, enhancing plant growth and exhibiting antifungal effects against *Phytophthora infestans*. This suggests that saffron extract could serve as a viable biological alternative to enhance agricultural quality and sustainability while reducing reliance on chemical products. The allelopathic effects of safranal on lettuce and weeds were investigated by Mardani et al. (2019), who found that safranal significantly reduced chlorophyll content and fresh weight in sensitive weed species, with an effective concentration (EC50) of 6.12 µg cm^{-3}.

For centuries, natural dyes have been used to color food and textiles, and their demand is rising as consumers seek safe, environmentally friendly alternatives to synthetic dyes. Saffron, known for its distinctive golden-yellow hue, is widely utilized for this purpose. Recent studies have investigated transforming saffron flower waste into eco-friendly dyes for sustainable wool and cotton textile coloration. Extracts from petals and stamens exhibit thermal and pH stability, with optimal dyeing achieved at a concentration of 6% for direct dyeing and 2% with a mordant at pH 3, with temperatures of 90 °C for wool and 98 °C for cotton over one hour. This method produces a color range from brown to green, showing good fastness to washing, rubbing, and light (Lachguer et al., 2021, 2023).

Additional studies have demonstrated that sonication of saffron stamens at 50 °C for 30 min effectively extracts dye, with pre-mordanting using copper salts enhancing color intensity and resistance to washing and light. This dye also shows promising dyeability on nylon fabrics, along with antibacterial and antioxidant properties comparable to commonly used natural dyes (Sadeghi-Kiakhani et al., 2023). Valorizing saffron byproducts as secondary raw materials through various technologies can enhance the sustainability and profitability of saffron production by utilizing high-value biomass. This approach opens new market opportunities, fosters industry growth, strengthens connections between industrial sectors and local communities, and creates employment through innovative recycling initiatives (Cardone et al., 2020).

Conclusions

This review presented a comprehensive discourse of saffron significance in cultivation and diverse applications. Renowned for its unique agronomic and eco-physiological traits, saffron exhibits an annual growth cycle but is cultivated perennially through vegetative propagation. Its phenological phases can be unpredictable, with flowers sometimes appearing before, during, or after leaf development. While saffron requires minimal water and has a low harvest index, its sterility poses challenges for conventional breeding methods aimed at genetic improvement. To enhance saffron production, various cultivation techniques can be employed. These include selecting high-quality corms, using mulch, improving soil properties with biofertilizers, establishing mycorrhizal associations, planning precise irrigation during critical stages, and utilizing micropropagation. Additionally, genetic and biological studies that aim to extend leaf appearance beyond flowering could facilitate mechanization and reduce labor dependency, representing a significant advancement in the industry.

Saffron occupies a privileged position as a valuable medicinal food product, contributing to the sustainable development of its producing regions. Beyond its well-known role as a spice, saffron's dried stigmas are also utilized in the pharmaceutical, textile, and cosmetic industries. Its pharmacological properties have gained recent recognition in the Codex, leading to the development of several pharmaceutical preparations that include saffron stigmas. However, the delicate nature of saffron cultivation, coupled with low yields from manual harvesting and frequent instances of falsification, results in high costs, making it inaccessible to many consumers. Additionally, while floral waste, such as tepals and stamens, represents a significant portion of the harvest, its commercial value is much lower than that of the stigmas.

An emerging concept of waste recovery has garnered attention among researchers over the past decade. Extensive scientific data now highlight the importance of saffron bio-waste, which contains various bioactive compounds with considerable potential for the food, pharmaceutical, aromatic, and nutraceutical industries. By valuing these bio-residues, farmers could obtain fairer prices, enabling them to manage their expenses more effectively. Further research into the biological effects of saffron and its waste products is essential. Well-designed in vitro and in vivo studies in humans will enhance our understanding of saffron's potential and open up new avenues for its use.

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Conflict of Interest

The authors indicate no conflict of interest in this work.

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