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Saffron (*Crocus sativus* L.): Biology, Cultivation, and Production Dynamics with Special Reference to Temperate Climatic Conditions of Kashmir (India)

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Abstract

The genus *Crocus* (family Iridaceae) comprises approximately 85-100 species distributed across the Mediterranean, Central and Southern Europe, and Western to Central Asia, where they are adapted to temperate climates with distinct seasonal variations. Among them, *Crocus sativus* L. (saffron) is a unique sterile triploid species (2n = 3x = 24) of significant economic importance, widely recognized as the world's most expensive spice. This manuscript provides a comprehensive overview of the taxonomy, origin, cytology, botany, phenology, chemical composition, agro-climatic requirements, cultivation practices, and current challenges associated with saffron. Saffron is believed to have originated through autotriploidy and is propagated exclusively through corms due to its inability to produce viable seeds. Its growth cycle is highly synchronized with seasonal climatic conditions, comprising dormancy, vegetative growth, and flowering phases. The crop thrives in well-drained, calcareous soils under temperate climates, such as those found in the Kashmir valley, which represents the primary saffron-growing region in India. The quality of saffron is determined by key bioactive compounds crocin, picrocrocin, and safranal responsible for its color, taste, and aroma, respectively. Despite its high value, saffron cultivation faces numerous constraints, particularly in Kashmir, including declining productivity, climate variability, inadequate irrigation, soil degradation, disease incidence, and market challenges. Its genetic uniformity and sterility further limit conventional breeding efforts. However, recent advances in molecular markers, biotechnological approaches, improved agronomic practices, and irrigation innovations such as those introduced under the National Saffron Mission have shown potential in enhancing productivity and sustainability. The manuscript highlights the need for an integrated approach combining traditional knowledge with modern scientific interventions to address existing limitations. Emphasis on climate-resilient practices, quality planting material, sustainable soil and water management, and strengthened market linkages will be essential for revitalizing saffron cultivation and ensuring its long-term economic and ecological sustainability.

Key words: *Crocus sativus*, Temperate climate, Cytology, Crocin, Cultivation

The genus *Crocus* (family Iridaceae) comprises approximately 85–100 species with a wide distribution across the Old World, extending from the Mediterranean basin through Central and Southern Europe to Western and Central Asia. The geographical limits of the genus roughly span longitudes 10°W to 80°E and latitudes 30°N to 50°N, encompassing two major phytogeographical regions, namely the Mediterranean and the Irano-Turanian zones [1]. These regions share a characteristic climate marked by cool to cold winters, moderate precipitation concentrated during autumn, winter, and spring, and hot, dry summers with minimal rainfall. Such climatic conditions have played a pivotal role in shaping the ecological adaptations and life cycle strategies of *Crocus* species [2]. Members of the genus are well adapted to these seasonal environmental fluctuations through the development of underground storage organs known as corms. These compact, nutrient-rich structures enable the plants to survive prolonged periods of drought and high temperatures during summer dormancy [3]. During favorable conditions, typically initiated by autumn rainfall or declining temperatures, the corms resume metabolic activity, giving rise to rapid vegetative growth and, in many species, immediate flowering. This phenological adaptation allows crop to complete critical stages of their life cycle such as flowering and initial leaf development before the onset of harsh winter conditions [4-5].

The timing of growth and flowering varies among species, reflecting ecological specialization within the genus. Some species exhibit synanthous development, where leaves and flowers emerge simultaneously, while others are hysteranthous, producing flowers prior to leaf emergence and delaying vegetative growth until spring. This diversity in phenological behavior enhances the adaptability of the genus

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across a range of temperate habitats. Overall, the success and persistence of *Crocus* species in these regions can be attributed to their efficient use of seasonal moisture, physiological tolerance to temperature extremes, and the protective advantage conferred by their subterranean corms, which collectively ensure survival and reproductive success under challenging climatic conditions [6].

Species evolution within the genus *Crocus* is frequently associated with significant chromosomal variability, which contributes to taxonomic ambiguity and complexity in phylogenetic interpretation. Variations in chromosome number, structure, and karyotype organization have been widely reported among *Crocus* species, often resulting from processes such as polyploidy, hybridization, and structural rearrangements. These cytogenetic alterations play a critical role in reproductive isolation and speciation; however, they also complicate species delimitation due to overlapping morphological traits and the potential for interspecific hybridization [7]. Molecular and cytological investigations have further demonstrated that species within the *Crocus sativus* series exhibit high morphological diversity but lack clear phylogenetic boundaries, reflecting the intricate evolutionary history of the genus.

Among the genus, *Crocus sativus* L. (saffron) represents a unique evolutionary entity characterized by its sterile triploid nature ($2n = 3x = 24$). Recent genomic and phylogenetic studies suggest that saffron originated through autotriploidy, most likely from its wild progenitor *Crocus cartwrightianus*, followed by domestication and clonal propagation [8-9]. Due to irregular meiosis, *Crocus sativus* is incapable of producing viable gametes, rendering it completely dependent on vegetative propagation through corms. This mode of reproduction has resulted in extremely limited genetic variability at the DNA level, with several studies describing saffron as a largely monomorphic species despite its wide geographical distribution. Nevertheless, subtle phenotypic variations observed across different regions are often attributed to epigenetic modifications and environmental influences rather than true genetic divergence [10].

The sterility and clonal propagation of saffron have significant implications for its cultivation and improvement. Conventional breeding approaches are largely ineffective, and the accumulation of somatic mutations or epigenetic variation becomes the primary source of variability within the species [11-12]. While this genetic uniformity ensures remarkable phenotypic stability and consistency in quality traits such as color, aroma, and flavor, it also poses challenges in terms of adaptability to biotic and abiotic stresses, making the crop vulnerable to environmental changes and diseases.

Saffron has been cultivated for more than 3,000 years and holds the distinction of being the most expensive spice in the world, often referred to as “red gold.” Its high economic value is primarily attributed to the labor-intensive harvesting process and extremely low yield efficiency worldwide [13]. It is estimated that approximately 75,000–150,000 flowers are required to produce 1 kg of dried saffron stigmas, highlighting the intensive manual effort involved in its production [14]. The stigmas must be carefully handpicked and dried under controlled conditions to preserve their bioactive compounds, further contributing to the high cost of the final product.

In India, saffron cultivation is geographically restricted to the temperate region of Jammu and Kashmir, particularly the Karewa plateaus of Pampore and adjoining areas. The unique agro-climatic conditions of this region characterized by cold winters, mild summers, and well-drained soils are highly conducive to saffron growth and flowering [15]. Beyond its agricultural significance, saffron plays a vital socio-economic role in the region, serving as a major source of livelihood for local farming communities and contributing to cultural heritage and export earnings. However, in recent decades, saffron production in Kashmir has faced a declining trend due to climatic variability, soil degradation, and inadequate crop management practices, necessitating renewed scientific and policy interventions for its sustainable cultivation [16].

Taxonomic classification

Kingdom	:	Plantae
Division	:	Magnoliophyta
Class	:	Liliopsida
Order	:	Asparagales
Family	:	Iridaceae
Genus	:	*Crocus*
Species	:	*Crocus sativus* L.

Cytological characteristics

Saffron (*Crocus sativus* L.) is cytologically distinguished as a sterile triploid species with a chromosome number of $2n = 3x = 24$. This triploid condition results in profound irregularities during meiosis, particularly at metaphase I, where the formation of trivalents and univalents leads to unequal chromosome segregation. Consequently, gametogenesis is highly abnormal, producing non-viable pollen and ovules, and rendering the plant functionally sterile [17-18]. Cytogenetic analyses have consistently demonstrated that the irregular pairing behavior of homologous chromosomes is the principal reason for the absence of sexual reproduction in saffron, thereby necessitating exclusive vegetative propagation through corms. Recent advances in molecular cytogenetics and genome-wide analyses have provided deeper insights into the origin and nature of saffron’s triploidy. High-resolution chromosomal studies and genotyping-by-sequencing (GBS) approaches indicate that *Crocus sativus* most likely originated through autotriploidy, derived from diploid progenitors of *Crocus cartwrightianus*, although hybridization between closely related cytotypes cannot be entirely ruled out [19].

The genus *Crocus* exhibits considerable chromosomal diversity, with wide variation in chromosome numbers, karyotype structures, and genome organization among species. Such cytological heterogeneity plays a crucial role in reproductive isolation, limiting gene flow between taxa and promoting speciation within the genus. However, this diversity also contributes to taxonomic complexity, as morphologically similar species may differ significantly at the chromosomal level, complicating classification and phylogenetic relationships. Despite its chromosomal instability during meiosis, *Crocus sativus* has maintained remarkable cytogenetic uniformity across its global distribution, primarily due to long-term clonal propagation [20]. Modern studies further reveal that while genetic variability at the DNA (deoxyribonucleic acid) level is extremely limited, minor phenotypic variations observed among accessions are often attributed to epigenetic modifications rather than chromosomal differences. Overall, the cytological characteristics of saffron marked by triploidy, meiotic irregularity, and clonal propagation represent a unique evolutionary strategy that ensures phenotypic stability but simultaneously constrains genetic improvement. Understanding these cytogenetic features is essential for developing advanced breeding, conservation, and biotechnological interventions aimed at improving saffron productivity and resilience [21-22].

Fig 1 *Crocus sativus* L. (A) Blooming saffron flowers in field conditions (B) Stigmas (C) Saffron corms

Botany and morphology

Crocus sativus L. (saffron) is a perennial, stemless geophyte belonging to the family Iridaceae, characterized by its unique underground storage organ known as a corm. The plant exhibits a highly specialized morphology and growth habit adapted to temperate climatic conditions, particularly those with pronounced seasonal variation. As a geophytic species, saffron survives adverse environmental conditions, especially summer drought and winter cold, through its corm, which serves as a reservoir of nutrients and energy for subsequent growth cycles [6], [23].

The plant typically attains a height of 10–20 cm and produces narrow, linear, grass-like leaves that arise directly from the corm. These leaves are dark green, often 40–70 cm long and 2–3 mm wide, and possess a characteristic central white stripe caused by an air lacuna. Leaf emergence generally coincides with or follows flowering, depending on environmental conditions, reflecting synanthous or sub-hysteranthous growth behavior [24]. The leaves play a crucial role in photosynthesis during the vegetative phase, contributing to the development of daughter corms.

The corm is the most important vegetative structure in saffron, being ovoid to sub-globose in shape, with a diameter ranging from 0.5 to 6.5 cm and a weight varying between 0.5 and 15 g depending on age and environmental conditions. It is covered by protective fibrous tunics and gives rise to roots, leaves, and flowers. Each mother corm produces one to several daughter corms (cormlets) annually through apical buds, which serve as the primary means of propagation in the absence of sexual reproduction [13], [25]. The size and health of the corm significantly influence flowering potential and yield, with larger corms generally producing more flowers.

The floral morphology of *C. sativus* is highly distinctive and economically significant. Each corm typically produces 1–4 flowers under favorable conditions. The flowers are large, showy, and violet to purple in color, consisting of six petaloid tepals arranged in two whorls. The androecium comprises three stamens with yellow anthers, while the gynoecium consists of a single style that divides into three elongated, vivid red stigmatic lobes. These stigmas represent the commercially valuable part of the plant and are harvested, dried, and marketed as saffron spice [26].

Each flower contains precisely three stigmas, measuring approximately 20–40 mm in length, which are rich in secondary metabolites such as crocin, picrocrocin, and safranal. These compounds are responsible for the characteristic color, taste, and aroma of saffron, respectively [27]. Due to the delicate nature of the flowers, harvesting must be carried out manually and typically during early morning hours to preserve quality. It is estimated that thousands of flowers are required to produce a small quantity of dried saffron, underscoring the crop's labour-intensive nature [14].

Table 1 Physical properties of saffron (*Crocus sativus* L.) corms

Property	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	23.20
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	– (dimensionless)	0.65	0.73	0.70

Source: Acharya *et al*. [28]

The physical properties presented in (Table 1) for saffron (*Crocus sativus* L.) corms are consistent with previously reported findings and clearly reflect their morphological variability and engineering significance. The observed weight range (3.85–14.82 g; mean 7.77 g) aligns with reported values of 0.5–15 g for saffron corms, confirming substantial size heterogeneity that directly influences vegetative propagation and yield potential, with heavier corms producing superior growth and higher stigma yield [28]. Similarly, the dimensional parameters (geometric and arithmetic diameters ≈18–27 mm) and high sphericity (0.83–0.91) corroborate the characterization of saffron corms as ovoid to sub-globose storage organs with near-spherical geometry, which is advantageous for uniform planting and mechanical handling [29]. The density values further validate their structural compactness; particle density exceeding 1 g cm^{-3} indicates solid internal composition typical of storage organs, while lower bulk density reflects inter-corm porosity affecting aeration and storage behavior, an important factor in post-harvest management systems [30]. Additionally, the relatively high coefficient of friction (0.65–0.73) supports the known rough outer tunic and fibrous covering of corms, which increases resistance to flow and must be considered in the design of hoppers, conveyors, and grading equipment [31]. Overall, these physical attributes are not only consistent with established literature but also highlight the dual importance of corm morphology in determining both agronomic performance and the optimization of mechanized handling, storage, and processing systems in saffron cultivation.

Origin and distribution

The origin of saffron (*Crocus sativus* L.) has long been a subject of scientific debate, owing to the absence of a known wild progenitor and its sterile triploid nature. Early hypotheses proposed the Middle East, particularly regions of Iran and Mesopotamia, as the center of origin, while other researchers suggested the island of Crete or broader areas of the Eastern Mediterranean as likely sites of domestication [32]. Recent molecular and phylogenetic studies, however, have provided stronger evidence supporting the hypothesis that saffron originated through autotriploidy from the wild species *Crocus cartwrightianus*, native to Greece, particularly Crete [33-34]. This evolutionary event was likely followed by human selection and vegetative propagation, leading to the domesticated saffron cultivated today.

Archaeological and historical records indicate that saffron cultivation dates back more than 3,000–3,500 years, with its early use documented in ancient civilizations of Mesopotamia, Egypt, and Persia. The crop subsequently spread across Asia, North Africa, and Europe through ancient trade routes, including the Silk Road and maritime trade networks. During the medieval period, saffron gained prominence in Europe, particularly in Spain and Italy, where it became an important commercial crop [24], [35].

The introduction of saffron to the Indian subcontinent, particularly to the Kashmir valley, is believed to have occurred before the 8th century AD. Historical references in the ancient chronicle *Rajatarangini* suggest that saffron was already being cultivated in Kashmir prior to the reign of King Lalitaditya (circa 750 AD) [36]. Some accounts also attribute its introduction to Persian or Central Asian influences, highlighting the role of cultural and trade exchanges in its dissemination. Since then, Kashmir has remained the only region in India where saffron is cultivated commercially, owing to its unique temperate agro-climatic conditions.

At present, saffron cultivation is geographically concentrated in a limited number of countries, primarily within the Mediterranean and West Asian regions. Iran dominates global production, contributing more than 80–90% of the world's total saffron output, followed by countries such as India, Spain, Greece, Morocco, Afghanistan, and Italy [25], [37]. Despite its relatively small production volume, Kashmiri saffron is globally renowned for its superior quality, attributed to higher concentrations of crocin and safranal.

In India, saffron cultivation is confined to the Union Territory of Jammu and Kashmir, particularly the karewa (upland plateau) regions of Pampore, Pulwama, Budgam, and parts of Srinagar. Among these, the Pampore plateau is considered the traditional and most prominent saffron-growing belt, often referred to as the "Saffron Bowl of Kashmir." The region's well-drained calcareous soils, combined with cold winters and dry summers, provide optimal conditions for saffron cultivation. However, in recent decades, the area under cultivation and overall production in Kashmir have shown a declining trend due to factors such as urbanization, climate variability, and inadequate irrigation infrastructure [38-39].

Biology and phenology of saffron

Saffron (*Crocus sativus* L.) exhibits a highly specialized and seasonally synchronized biological cycle that is closely adapted to temperate climates characterized by distinct seasonal variations. As a geophytic species, saffron survives unfavorable environmental conditions through its underground corm, which acts as a storage organ and ensures continuity of growth across seasons. The annual life cycle of saffron can be broadly divided into three main phases: summer dormancy, vegetative growth, and reproductive (flowering) phase.

Dormancy phase (Summer: May–August)

During late spring to summer, saffron enters a period of physiological dormancy following the senescence of aerial plant parts. This phase typically extends from May to August under temperate conditions. The leaves dry out completely, and the plant remains in the form of a dormant corm beneath the soil surface. Metabolic activities are significantly reduced, allowing the plant to withstand high temperatures and soil moisture deficits. This dormancy is essential for the induction of subsequent flowering, as it enables the corm to undergo necessary physiological and biochemical changes required for floral differentiation [23], [25]. Environmental conditions during this phase, particularly temperature and soil aeration, play a crucial role in determining the viability and productivity of the corm in the following season.

Vegetative growth phase (Autumn to Spring)

With the onset of favorable environmental conditions, particularly declining temperatures and increased soil moisture in early autumn, saffron corms break dormancy and initiate vegetative growth. This phase extends from autumn through winter to early spring. Leaves emerge either simultaneously with or shortly after flowering, depending on environmental conditions, and continue to grow actively during the cooler months. Photosynthetic activity during this stage is critical for the accumulation of carbohydrates and nutrients, which are subsequently stored in newly formed daughter corms. Root development also occurs during this period, including the formation of contractile roots that help anchor the corm and adjust its depth in the soil. The duration and efficiency of the vegetative phase directly influence corm multiplication and size, which are key determinants of future yield [24]. Favourable climatic conditions, particularly adequate soil moisture and moderate temperatures, enhance biomass accumulation and corm development.

Flowering phase (October–November)

The reproductive phase of saffron is marked by flowering, which typically occurs during October to November in temperate regions such as Kashmir. Flower initiation begins during the late dormancy phase but is triggered by a combination of environmental cues, primarily temperature and soil moisture. Cooler temperatures in early autumn (around 15–20°C) have been shown to promote floral induction, while excessive rainfall or high temperatures during this period can adversely affect flowering [23], [40]. Each corm produces one to several flowers, depending on its size and physiological status. The flowering period is relatively short, usually lasting 2–3 weeks, and requires precise timing for harvesting to ensure optimal quality of stigmas. The synchronization of flowering is an important agronomic trait, particularly for efficient harvesting and processing.

Environmental regulation of phenology

The phenological development of saffron is strongly regulated by environmental factors, with temperature and soil moisture being the most critical. Studies have demonstrated that lower temperatures during the pre-flowering stage enhance floral primordia development, while adequate soil moisture facilitates bud emergence and flower expansion [23]. Conversely, water stress or unseasonal rainfall during flowering can lead to reduced flower number and quality. Spring conditions also play a vital role in determining future yield. Sunny and moderately warm conditions during spring favor photosynthesis and the accumulation of reserves in daughter corms, thereby enhancing their size and flowering potential in the subsequent season [25]. Thus, the entire biological cycle of saffron is intricately linked to seasonal climatic patterns, making it particularly sensitive to climate variability.

Chemical composition and quality of saffron

The quality and commercial value of saffron (*Crocus sativus* L.) are primarily determined by its unique chemical composition, particularly the presence and concentration of three major bioactive compounds: crocin, picrocrocin, and safranal. These compounds are responsible for the characteristic color, taste, and aroma of saffron, respectively, and serve as key indicators in international quality evaluation systems. The biosynthesis, stability, and concentration of these constituents are influenced by genetic factors, agro-climatic conditions, harvesting practices, and post-harvest processing methods [25], [41].

Crocin (Coloring strength)

Crocin is a water-soluble carotenoid pigment responsible for the intense yellow to orange coloration imparted by saffron. Chemically, crocin consists of crocetin esters conjugated with sugar moieties, which enhance its solubility in water. It is considered the most important quality parameter in saffron, as it determines its coloring strength, which is widely used in culinary and industrial applications. Higher crocin content is associated with superior saffron quality and is influenced by factors such as genotype, environmental conditions, and drying techniques [27], [42]. In addition to its coloring properties, crocin has been reported to possess significant antioxidant, anticancer, and neuroprotective activities [43].

Picrocrocin (Taste)

Picrocrocin is a monoterpene glycoside that imparts the characteristic bitter taste to saffron. It is considered a precursor of safranal and plays a crucial role in flavor development. During the drying process, picrocrocin undergoes enzymatic or thermal degradation to produce safranal, thereby linking taste and aroma formation. The concentration of picrocrocin is often used as an indicator of freshness and proper processing, as excessive degradation may result in reduced taste quality [41].

Safranal (Aroma)

Safranal is a volatile compound responsible for the distinctive aroma of saffron. It is formed primarily during the drying and storage processes through the degradation of picrocrocin. The concentration of safranal depends largely on post-harvest handling, particularly drying temperature and duration. Controlled drying conditions are essential to optimize safranal formation without compromising other quality attributes. Safranal also exhibits various pharmacological properties, including antidepressant and anticonvulsant effects [42], [44].

Other chemical constituents

In addition to the three main compounds, saffron contains a wide range of other bioactive constituents, including flavonoids, anthocyanins, vitamins (such as riboflavin and thiamine), amino acids, and minerals. These compounds contribute to the nutritional and medicinal value of saffron. The presence of crocetin, kaempferol, and other phenolic compounds enhances its antioxidant capacity, making saffron a valuable ingredient in pharmaceutical and nutraceutical applications [25].

Quality standards and evaluation

The quality of saffron is internationally standardized based on its chemical composition using spectrophotometric methods. The International Organization for Standardization (ISO 3632) has established guidelines for grading saffron based on three parameters: coloring strength (crocin content), bitterness (picrocrocin content), and aroma (safranal content). Saffron is classified into different categories (Category I, II, III, etc.) depending on the absorbance values of these compounds. In India, saffron quality is regulated by the Bureau of Indian Standards (BIS), which aligns with ISO specifications while incorporating regional quality parameters. Kashmiri saffron, in particular, is recognized for its superior quality, often exhibiting higher crocin and safranal content compared to saffron from other regions, attributed to its unique agro-climatic conditions [46], [45]. Improper handling and storage may lead to degradation of bioactive compounds and increased risk of adulteration, which remains a major concern in the global saffron market [47].

Agro-climatic requirements

Climate

Saffron (*Crocus sativus* L.) is a temperate crop that thrives under specific climatic conditions characterized by distinct seasonal variations. The Kashmir valley, located in the northwestern Himalayas, provides an ideal agro-climatic environment for saffron cultivation due to its unique combination of temperature regimes, precipitation patterns, and altitude. Traditionally, saffron in Kashmir is cultivated on elevated plateaus known as *karewas*, which offer well-drained soils and favorable microclimatic conditions [48].

The climate of Kashmir is marked by cold winters, with temperatures often ranging from −5°C to 10°C, and mild to moderately warm summers, where temperatures typically vary between 20°C and 30°C. These seasonal temperature fluctuations are crucial for regulating the physiological processes of saffron. The cold winter period facilitates proper vernalization and supports the vegetative growth phase, while the warm summer conditions promote corm maturation and induce dormancy. This dormancy phase is essential for the differentiation of floral primordia, which ultimately determines flowering intensity in the subsequent autumn [23], [40].

Another critical climatic factor is the distribution of rainfall, particularly during the flowering period (October–November). Saffron requires relatively dry conditions during flowering, as excessive rainfall or high humidity can adversely affect flower emergence, reduce stigma quality, and increase susceptibility to fungal diseases. In contrast, moderate soil moisture during the pre-flowering phase is beneficial for bud initiation and uniform flowering [25]. The typical precipitation pattern of Kashmir, with most rainfall occurring during winter and spring and relatively dry conditions in autumn, has historically been well-suited for saffron cultivation.

Temperature plays a decisive role in floral induction. Studies have shown that cooler temperatures during early autumn (approximately 15–20°C) are optimal for the initiation and development of flower buds. Deviations from this range, particularly prolonged high temperatures or unseasonal rainfall events, can delay or suppress flowering, ultimately affecting yield and quality [23], [49]. Furthermore, adequate sunshine during the spring season is essential for photosynthetic activity, which supports the accumulation of carbohydrates in daughter corms, thereby influencing productivity in the following year.

Despite these favorable conditions, saffron cultivation in Kashmir has been increasingly challenged by climate variability and change. Erratic rainfall patterns, including untimely precipitation during flowering, prolonged dry spells, and rising temperatures, have significantly impacted saffron productivity in recent decades. Reports indicate a marked decline in yield attributed to reduced soil moisture availability during critical growth stages and increased incidence of corm rot diseases under fluctuating environmental conditions [38-39]. Additionally, changing snowfall patterns and reduced winter chilling may disrupt the dormancy cycle, further affecting crop performance.

Recent studies have emphasized that climate change poses a serious threat to the sustainability of saffron cultivation in the Kashmir valley. Increasing temperature trends, coupled with unpredictable precipitation, are altering the delicate balance required for optimal growth and flowering. As a result, adaptive measures such as supplemental irrigation, improved drainage systems, and climate-resilient agronomic practices are being recommended to mitigate these impacts [50-51].

Soil

Soil plays a critical role in the successful cultivation of saffron (*Crocus sativus* L.), as the crop is highly sensitive to waterlogging, soil compaction, and nutrient imbalances. Optimal growth and productivity are achieved in well-drained soils, particularly sandy-loam to clay-calcareous types, which provide a favorable balance between aeration, moisture retention, and nutrient availability. Saffron thrives best in soils with a neutral to slightly alkaline pH (6.5–8.0), as such conditions facilitate optimal nutrient uptake and corm development [25], [40]. The underground corm, being the principal propagative and storage organ, requires soils that are loose, friable, and well-aerated to support proper root penetration and corm enlargement. Excessively heavy clay soils tend to retain water and may lead to poor aeration, increasing the risk of corm rot and fungal infections. Conversely, overly sandy soils, while well-drained, may lack sufficient nutrient-holding capacity and require adequate organic matter supplementation to sustain productivity [24]. Therefore, soils with a balanced texture such as sandy-loam are considered ideal for saffron cultivation.

In the context of Kashmir, saffron is predominantly cultivated on Karewa soils, which are lacustrine deposits found on elevated plateaus in the valley, particularly in regions such as Pampore, Pulwama, and Budgam. These soils are typically calcareous, well-drained, and moderately fertile, with a silty-loam to clay-loam texture. One of the most advantageous characteristics of Karewa soils is their excellent drainage capacity, which prevents water stagnation around the corms an essential requirement for saffron cultivation [39]. The elevated topography of Karewas further enhances drainage and reduces the risk of waterlogging during periods of precipitation. Additionally, Karewa soils possess moderate levels of essential nutrients, including calcium and potassium, which are beneficial for corm growth and flower development. However, long-term continuous cultivation without adequate soil management has led to a gradual decline in soil fertility in some saffron-growing areas of Kashmir. Depletion of organic matter, micronutrient deficiencies, and soil compaction have been identified as key constraints affecting productivity [38], [52].

Organic matter plays a vital role in maintaining soil health and enhancing saffron yield. The incorporation of farmyard manure (FYM), compost, or vermicompost improves soil structure, increases water-holding capacity, and promotes microbial activity, all of which contribute to better corm development and higher flower yield. Studies have shown that the application of organic amendments at rates of 20–60 t ha^{-1} significantly improves soil physicochemical properties and enhances saffron productivity [53-54].

Soil depth is another important factor influencing saffron cultivation. A minimum soil depth of 20–30 cm is generally required to allow adequate space for corm development and root growth. Shallow soils restrict corm expansion and may lead to reduced yield. Furthermore, proper soil tilth and periodic loosening are necessary to prevent compaction and ensure efficient root respiration. In recent years, soil degradation and changing land-use patterns in Kashmir have posed significant challenges to saffron cultivation. Increased urbanization, improper irrigation practices, and erosion have adversely affected soil quality in traditional saffron belts. Consequently, there is a growing emphasis on sustainable soil management practices, including integrated nutrient management (INM), crop rotation, and conservation agriculture, to restore soil fertility and ensure long-term productivity [51-52].

Cultivation practices

Saffron (*Crocus sativus* L.) cultivation involves a series of carefully managed agronomic practices that directly influence yield, quality, and sustainability of production. In the temperate conditions of Kashmir, traditional practices have evolved over centuries; however, recent research emphasizes the need for improved and scientific approaches to enhance productivity and profitability.

Propagation

Saffron is a sterile triploid species (2n = 3x = 24) and does not produce viable seeds; hence, it is propagated exclusively through vegetative means using underground corms. Each mother corm produces several daughter corms during the growing season, which serve as planting material for subsequent cycles. Corm size is a critical determinant of yield potential. Larger corms, particularly those weighing more than 10 g, exhibit higher vigor, produce more flowers, and generate a greater number of daughter corms compared to smaller ones. Studies have demonstrated a positive correlation between corm size and flower yield, making the selection of healthy, disease-free, and large-sized corms essential for successful cultivation [40], [25]. However, continuous vegetative propagation may lead to the accumulation of pathogens, necessitating periodic replacement and selection of high-quality planting material [39].

Planting

Proper planting practices are crucial for ensuring optimal plant establishment and yield.

Time of planting

In Kashmir, saffron corms are typically planted during July–August, coinciding with the onset of favorable soil temperature and moisture conditions required for root initiation and subsequent flowering.

Planting depth

Corms are generally planted at a depth of 10–15 cm, which provides protection against temperature fluctuations, desiccation, and mechanical damage while facilitating proper root and shoot development.

Spacing

A spacing of 10–15 cm between corms is recommended to ensure adequate aeration, nutrient availability, and space for daughter corm development.

Optimal planting geometry and depth are essential for maximizing flower production and maintaining soil health. Deviations from recommended practices may result in overcrowding, reduced corm size, and lower yields [54].

Nutrient management

Saffron responds well to organic nutrient management, as excessive use of chemical fertilizers may adversely affect soil health and corm quality. The incorporation of organic manures such as farmyard manure (FYM), compost, and vermicompost is widely recommended. Application of organic manure at rates of 20–60 t ha^{-1} has been shown to significantly improve soil structure, enhance microbial activity, and increase nutrient availability, thereby leading to higher flower yield and better stigma quality [53]. Organic amendments also improve water-holding capacity and reduce soil compaction, which are critical for corm development. Integrated nutrient management (INM), combining organic inputs with minimal inorganic fertilizers, is increasingly being advocated to sustain long-term productivity and soil fertility [52].

Irrigation

Traditionally, saffron cultivation in Kashmir has been rainfed, relying on natural precipitation. However, due to changing climatic conditions and erratic rainfall patterns, moisture stress during critical growth stages has become a major constraint. Supplemental irrigation, particularly during pre-flowering (September–October) and vegetative growth phases, has been found to significantly enhance flower yield and corm multiplication. Modern irrigation systems, such as sprinkler irrigation, introduced under initiatives like the National Saffron Mission, have shown promising results in improving productivity and water-use efficiency [36], [51]. Care must be taken to avoid over-irrigation, as waterlogging can lead to corm rot and other fungal diseases.

Harvesting and post-harvest processing

Harvesting of saffron is a highly labour-intensive and delicate process that requires precision and timing. Flowers are typically harvested early in the morning, immediately after blooming, to preserve the quality of stigmas and prevent degradation of volatile compounds. Each flower contains three stigmas, which are manually separated and subjected to drying. Proper drying is critical for maintaining the chemical composition and quality of saffron. Traditional drying methods involve shade drying or low-temperature heating, while modern techniques use controlled environments to optimize moisture removal and preserve bioactive compounds [25]. It is estimated that approximately 75,000 flowers are required to produce 1 kg of dried saffron, highlighting the labour-intensive nature of the crop [14]. Post-harvest handling, including storage in airtight containers away from light and moisture, is essential to maintain quality and prevent degradation.

Yield and productivity

The productivity of saffron in the temperate agro-climatic conditions of Kashmir Valley remains considerably lower than the global average, despite the region being historically recognized for producing premium-quality saffron characterized by superior aroma, colour, and crocin content. The average saffron yield in Kashmir generally ranges between 2-5 kg ha^{-1}, whereas several saffron-producing countries such as Iran, Spain, and Greece report average productivity levels of 10-15 kg ha^{-1} under improved cultivation and management systems. This substantial yield gap reflects the combined influence of biological, environmental, and management-related constraints that limit saffron productivity in the region.

Low productivity in Kashmir is primarily associated with the traditional cultivation practices followed by farmers, degradation of saffron-growing soils, inadequate nutrient management, moisture stress during critical growth stages, and declining corm vigour over time. Since saffron is a sterile triploid crop propagated exclusively through corms, the quality and health of planting material directly determine flowering intensity and stigma yield. Small-sized or diseased corms produce fewer daughter corms and reduced floral initiation, ultimately lowering productivity. Larger corms possessing higher carbohydrate reserves generally exhibit better vegetative growth, higher flower emergence, and increased stigma production. Therefore, corm size acts as one of the most critical determinants of saffron yield.

Soil fertility status also exerts a significant influence on saffron productivity. Saffron performs best in well-drained, sandy-loam soils rich in organic matter and essential nutrients. However, continuous cultivation without balanced nutrient replenishment has resulted in nutrient depletion and declining soil health in many saffron-growing areas of Kashmir. Deficiencies of nitrogen, phosphorus, potassium, and micronutrients adversely affect corm development, flowering behaviour, and daughter corm multiplication. The incorporation of farmyard manure, vermicompost, and integrated nutrient management practices has been reported to improve soil structure, microbial activity, and nutrient availability, thereby enhancing yield potential.

Climate variability has emerged as another major factor affecting saffron productivity in Kashmir Valley. Saffron cultivation is highly sensitive to fluctuations in temperature and precipitation patterns. Adequate rainfall or irrigation during the pre-flowering stage is essential for proper floral initiation and flower emergence. However, irregular precipitation, prolonged dry spells, reduced snowfall, and increasing temperature trends associated with climate change have negatively influenced flowering synchronization and stigma development in recent years. Excessive rainfall during flowering can further damage flowers and reduce stigma quality, while drought stress limits corm growth and daughter corm formation. Thus, changing climatic conditions pose a serious threat to the sustainability and productivity of saffron cultivation in the region.

Management practices adopted by farmers significantly influence yield outcomes. Traditional methods of cultivation, including improper spacing, shallow planting depth, inadequate weed management, and delayed corm replacement, contribute to poor productivity levels. In many saffron fields, corms are retained for prolonged periods without rejuvenation, resulting in overcrowding, increased disease incidence, and reduced flowering efficiency. Adoption of scientific cultivation practices such as the use of healthy large-sized corms, optimum planting density, timely irrigation, nutrient supplementation, and integrated disease management can substantially improve saffron productivity. Moreover, mechanization constraints and labour-intensive harvesting operations further affect efficient crop management and economic returns.

The comparatively lower yield of saffron in Kashmir, therefore, should not be viewed solely as a consequence of environmental limitations but rather as the cumulative outcome of multiple interacting factors involving planting material, soil health, climatic uncertainty, and farm management practices. Addressing these constraints through improved agronomic interventions, climate-resilient cultivation strategies, and dissemination of scientific production technologies is essential for enhancing saffron productivity and sustaining the economic viability of saffron cultivation in Kashmir Valley.

Constraints in Kashmir saffron cultivation

Saffron (*Crocus sativus* L.) cultivation in the Kashmir valley, despite its historical significance and premium quality, has been facing a steady decline over the past few decades. This decline is attributed to a combination of agronomic, environmental, socio-economic, and infrastructural constraints. Understanding these challenges is essential for developing effective strategies to sustain and enhance saffron production in the region.

Declining area and productivity

One of the most pressing concerns in Kashmir saffron cultivation is the continuous decline in cultivated area and yield. Reports indicate that both the area under saffron cultivation and productivity have decreased significantly since the late 20th Century. This decline has been linked to land-use changes, including urbanization and conversion of traditional saffron fields (*karewas*) into residential and commercial areas. Additionally, reduced soil fertility, poor crop management practices, and lack of technological interventions have contributed to lower yields [38-39]. The average productivity in Kashmir remains considerably lower compared to other saffron-producing countries such as Iran and Spain.

Climate change and erratic rainfall

Climate variability has emerged as a major constraint affecting saffron cultivation in Kashmir. The crop is highly sensitive to environmental conditions, particularly temperature and precipitation patterns. In recent years, erratic rainfall, prolonged dry spells, and unseasonal precipitation during the flowering period have adversely affected flower initiation, stigma quality, and overall yield. Reduced snowfall and rising temperatures have also disrupted the natural dormancy cycle of corms, leading to poor flowering and reduced productivity [50-51]. Climate change has thus become a critical threat to the sustainability of saffron cultivation in this temperate region.

Poor irrigation facilities

Traditionally, saffron in Kashmir has been cultivated under rainfed conditions, relying heavily on natural precipitation. However, changing climatic patterns and reduced rainfall have highlighted the limitations of this system. Inadequate irrigation infrastructure is a major constraint, particularly during critical growth stages such as pre-flowering and vegetative phases. Moisture stress during these stages can significantly reduce flower yield and corm development. Although initiatives such as the National Saffron Mission have introduced sprinkler irrigation systems in some areas, their adoption remains limited due to infrastructural and economic constraints [36], [52].

Diseases and pests

Saffron cultivation in Kashmir is also affected by various diseases and pests, which contribute to yield losses and reduced corm quality. Among diseases, corm rot, caused by fungal pathogens such as *Fusarium oxysporum*, *Rhizoctonia crocorum*, and *Penicillium* spp., is particularly destructive. These pathogens thrive under conditions of poor drainage and excessive soil moisture, leading to significant corm mortality. Additionally, pests such as rodents and nematodes damage corms and roots, further affecting plant growth and productivity [55-56]. The lack of effective disease management practices and limited availability of disease-free planting material exacerbate these problems.

High labour cost and labour-intensive operations

Saffron cultivation is inherently labour-intensive, particularly during harvesting and post-harvest processing. The delicate flowers must be handpicked early in the morning, and the stigmas are manually separated and dried. This process requires significant labour input, making production costly. In recent years, rising labour costs and labour shortages have become major challenges, discouraging farmers from continuing saffron cultivation. Mechanization is limited due to the delicate nature of the crop, further increasing dependence on manual labour [40].

Lack of quality planting material and technological gaps

Another significant constraint is the lack of high-quality, disease-free corms for propagation. Since saffron is vegetatively propagated, the accumulation of pathogens over successive generations leads to degeneration of planting material. Furthermore, there is limited adoption of improved agronomic practices, including nutrient management, spacing, and modern drying techniques, which affects both yield and quality [39].

Market and economic constraints

Saffron farmers in Kashmir also face market-related challenges, including price fluctuations, lack of organized marketing systems, and competition from cheaper imported saffron. Adulteration and lack of proper branding further reduce the economic returns to farmers. Although Kashmiri saffron has recently received Geographical Indication (GI) status, its full potential in enhancing farmer income has yet to be realized [52]. The decline in saffron production in Kashmir is a multifaceted issue driven by environmental, agronomic, and socio-economic factors. Addressing these constraints requires an integrated approach involving climate-resilient practices, improved irrigation infrastructure, disease management, availability of quality planting material, and better market support [57]. Sustainable interventions are essential to revive and strengthen saffron cultivation in this historically important region.

Recent advances and future prospects

Saffron (*Crocus sativus* L.), despite its high economic value and global demand, faces several biological and agronomic limitations, primarily due to its sterility and narrow genetic base. In recent years, significant advances have been made in the areas of molecular biology, agronomy, irrigation management, and sustainable farming practices to enhance saffron productivity and quality, particularly in traditional growing regions such as Kashmir. These innovations provide promising avenues for overcoming existing constraints and ensuring the long-term sustainability of saffron cultivation.

Molecular markers and genetic studies

The application of molecular marker techniques, such as Random Amplified Polymorphic DNA (RAPD), Inter Simple Sequence Repeat (ISSR), and Simple Sequence Repeat (SSR), has revolutionized the study of genetic diversity and population structure in saffron. Due to its vegetative mode of propagation and sterility, *C. sativus* exhibits limited genetic variability, making conventional breeding approaches challenging. Molecular markers have been extensively used to assess genetic uniformity, detect somaclonal variations, and identify minor polymorphisms among saffron accessions from different geographical regions. Studies using ISSR and SSR markers have revealed subtle genetic variations that can be exploited for germplasm characterization and conservation [58-59]. Additionally, Amplified Fragment Length Polymorphism (AFLP) and Sequence-Related Amplified Polymorphism (SRAP) markers have provided insights into phylogenetic relationships and evolutionary origins of saffron [33], [60]. These molecular tools are also valuable for authentication of saffron, helping to combat adulteration and ensure product quality in international markets [47].

Improved agronomic practices

Recent research has emphasized the optimization of agronomic practices, including planting density, corm size selection, nutrient management, and crop rotation, to improve saffron yield and quality. The adoption of scientific cultivation methods, such as optimal spacing, use of organic amendments, and integrated nutrient management, has shown significant improvements in flower and stigma yield [54]. Crop rotation with cereals and legumes has been recommended to improve soil fertility and reduce disease incidence. Furthermore, the use of biofertilizers and beneficial microorganisms has demonstrated potential in enhancing nutrient uptake and plant growth.

Irrigation innovations: National Saffron Mission

One of the most significant interventions in saffron cultivation in Kashmir has been the introduction of sprinkler irrigation systems under the National Saffron Mission (NSM). Traditionally rainfed, saffron cultivation has suffered due to erratic rainfall and prolonged dry spells. The adoption of sprinkler irrigation has improved soil moisture availability during critical growth stages, particularly pre-flowering and vegetative phases, resulting in enhanced flower yield and corm multiplication. Reports indicate that fields equipped with sprinkler systems have shown marked improvements in productivity and crop reliability compared to rainfed conditions [36], [52]. This initiative represents a major step toward climate-resilient saffron farming in the region.

Organic and precision farming approaches

With increasing emphasis on sustainability and environmental conservation, organic farming practices are gaining importance in saffron cultivation. The use of farmyard manure, compost, and vermicompost not only improves soil health but also enhances the quality of saffron by increasing the concentration of bioactive compounds such as crocin and safranal. In addition, precision agriculture techniques, including soil testing, site-specific nutrient management, and controlled irrigation, are being explored to optimize resource use and maximize productivity. The integration of Geographic Information Systems (GIS) and remote sensing technologies can further aid in monitoring crop health and environmental conditions, enabling data-driven decision-making [61].

Biotechnological interventions

Biotechnology offers promising solutions to overcome the inherent limitations of saffron, particularly its sterility and lack of genetic variability. Techniques such as tissue culture, in vitro propagation, and somatic embryogenesis have been developed to produce disease-free and uniform planting material. Micropropagation techniques enable rapid multiplication of corms under controlled conditions, reducing the risk of pathogen transmission and improving planting material quality [62]. Additionally, genetic transformation and genome editing tools hold potential for introducing desirable traits such as disease resistance, stress tolerance, and improved metabolite production. Although still in the experimental stage, omics approaches (genomics, transcriptomics, and metabolomics) are being increasingly used to understand the molecular mechanisms underlying saffron growth, development, and secondary metabolite biosynthesis. These approaches may pave the way for future genetic improvement programs despite the reproductive limitations of the species [58].

Future prospects

The future sustainability and economic viability of saffron cultivation, particularly under the temperate conditions of Kashmir Valley, largely depend upon the successful integration of traditional cultivation wisdom with modern scientific and technological interventions. In recent years, saffron production has been increasingly challenged by climate variability, declining soil fertility, erratic precipitation patterns, disease incidence, and shrinking productivity, thereby necessitating the adoption of climate-resilient and resource-efficient production systems. Development of climate-smart cultivation practices, including regulated irrigation scheduling, moisture conservation techniques, protected cultivation approaches, and adaptive agronomic management, can help mitigate the adverse impacts of changing climatic conditions on flowering behaviour and corm development. Equally important is the large-scale production and timely distribution of disease-free, genetically superior, and high-quality corms, as healthy planting material directly determines floral productivity, daughter corm multiplication, and long-term field sustainability. Scientific corm selection, tissue culture techniques, and nursery-based propagation systems may significantly improve planting material quality and reduce the spread of corm-borne pathogens. Expansion of irrigation infrastructure, particularly through sprinkler and drip irrigation systems under initiatives such as the National Saffron Mission, represents another critical intervention for enhancing productivity in rainfed saffron-growing areas of Kashmir, where moisture stress during pre-flowering stages frequently limits yield potential [63]. Furthermore, the adoption of precision farming technologies, integrated nutrient management, organic cultivation practices, and digital monitoring systems can improve input-use efficiency, maintain soil health, and enhance saffron quality while minimizing environmental degradation. Organic saffron production, in particular, holds substantial export potential owing to the increasing global demand for residue-free, high-value spices and nutraceutical products. Strengthening value chains, improving post-harvest processing, branding, geographical indication (GI)-based marketing, and establishing stronger market linkages between growers, cooperatives, exporters, and international buyers are also essential for improving farmer income and ensuring fair price realization [64-65]. In addition, institutional support, farmer training programmes, extension services, and policy-driven investments in research and infrastructure development will play a crucial role in revitalizing the saffron sector in Kashmir. Therefore, the future prospects of saffron cultivation lie in a holistic and integrated approach combining scientific innovation, sustainable resource management, market-oriented production systems, and preservation of the unique traditional heritage associated with Kashmiri saffron cultivation. Furthermore, continued research in molecular biology and biotechnology is essential to unlock the genetic potential of saffron and address its inherent limitations. Policy support, farmer training, and technological dissemination will play a crucial role in revitalizing saffron cultivation and enhancing its global competitiveness.

CONCLUSION

The genus *Crocus*, and particularly *Crocus sativus* L., represents a remarkable example of evolutionary adaptation, cytogenetic uniqueness, and economic importance. Its successful establishment across the Mediterranean and Irano-Turanian regions is largely attributed to its specialized life cycle, ecological flexibility, and the protective role of the underground corm, which enables survival under harsh seasonal conditions. The genus is characterized by significant chromosomal diversity, contributing both to its evolutionary success and to taxonomic complexity. Saffron, as a sterile triploid species, occupies a distinct position within the genus due to its exclusive vegetative propagation, genetic uniformity, and dependence on human cultivation. While this clonal nature ensures consistency in quality traits such as color, aroma, and flavor, it simultaneously limits genetic improvement and adaptability. The crop's high economic value, driven by its unique chemical composition and labor-intensive production, has sustained its global demand for centuries. In the context of India, saffron cultivation in the Kashmir valley holds immense agricultural, socio-economic, and cultural significance. However, the sector is currently challenged by declining productivity, climate variability, soil degradation, and infrastructural limitations. These constraints underscore the urgent need for scientifically informed and sustainable interventions. Recent advances in molecular biology, agronomy, irrigation, and biotechnology offer promising opportunities to overcome these challenges. The integration of improved cultivation practices, climate-resilient strategies, high-quality planting material, and modern technological tools can significantly enhance productivity and sustainability. Moreover, strengthening market systems and policy support will be critical for ensuring the long-term viability of saffron cultivation. A multidisciplinary approach combining traditional knowledge with modern scientific innovations is essential to unlock the full potential of saffron. Sustained research, effective resource management, and strategic interventions will not only help preserve this valuable crop but also ensure its continued contribution to the economy and livelihoods of farming communities, particularly in regions like Kashmir where it remains an integral part of heritage and identity.

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