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Advanced Techniques in Cultivation of Saffron and Their Potential Impact on Yield: A Narrative Review

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Abstract

Saffron (Crocus sativus L.) is a high-value spice traditionally cultivated in arid and semi-arid regions. With the increasing demand for this premium product, innovations in cultivation methods are vital for enhancing production efficiency and sustainability. This paper reviews innovative approaches to saffron farming, focusing on controlled-environment cultivation techniques such as hydroponics and aeroponics, as well as advanced irrigation, breeding, and mechanization methods that address water scarcity, soil limitations, and productivity. A narrative review methodology was employed to systematically collect, summarize, and synthesize findings from existing research, providing a comprehensive overview of technological advancements in saffron production. Controlled environmental systems, including hydroponics and aeroponics, offer promising solutions for enhancing saffron yield and quality. Advanced irrigation practices, such as drip irrigation and customized scheduling, improve water use efficiency. Techniques like in vitro cultivation, forced flowering, and nonconventional breeding enhance year-round production and plant resilience. The adoption of organic and smart farming practices further promotes sustainability and efficiency. Mechanization has streamlined saffron harvesting, thereby reducing labour costs and improved profitability. The integration of advanced cultivation techniques, irrigation management, and mechanization is transforming saffron production. These innovations, along with sustainable practices, hold significant potential to address the challenges of water scarcity and soil limitations, ensuring future improvements in saffron farming. Further research is needed to optimize these methods for large-scale adoption.

Key words: Saffron Cultivation, Advanced Cultivation Techniques, Precision Agriculture, Yield Improvement, Sustainability

د زعفرانو د کرلو پرمختللي تخنیکونه او د حاصلاتو پر زیاتوالي یې احتمالي اغېز: یوه روایتي بیاکتنه

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لنډیز

زعفران (*Crocus sativus* L.) د لوړ اقتصادي ارزښت لرونکې مصاله ده چې په دودیز ډول د وچو او نیمه وچو سیمو په اقلیم کې کرل کیږي. دې محصول ته د نړیوالې تقاضا د ډیروالي په شرایطو کې، د کرنې پرمختللي تخنیکونه د تولید د اغېزمنتیا او پایداري د لوړولو لپاره حیاتي

ارزښت لري. دغه مطالعه د زعفرانو د کرنې نوې لارې چارې په ځانګړي ډول د کنټرول شوي چاپېریال کرنې سیستمونه (هایډروپونیک او ایروپونیک)، پرمختللي اوبو لګولو تخنیکونه، اصلاحاتي پروګرامونه او میکانیزه کول د اوبو کم مصرف، د خاورې د محدودیتونو او د تولید د ټیټوالي ستونزې څېړي. د دغه مطالعې د ترتیب لپاره د روایتي بیاکتنې کړنلاره کارول شوې تر څو د زعفرانو د تولید د ټکنالوژیکي پرمختګونو جامع ارزونې له پاره د شته څېړنو شواهد په منظم ډول راټول، تجزیه او یوځای کړي. کنټرول شوي چاپېریالي سیستمونه لکه هایډروپونیک او ایروپونیک د زعفرانو د حاصلاتو او کیفیت د لوړولو لپاره اغېزمنې لارې چارې وړاندې کوي. د دغه کره کتنې په پایله کې څرګنده شوه چې د پرمختللي اوبو لګونې میتودونه (څاڅکي اوبه لګونه او ځانګړی مهالویش) د اوبو د کارونې مؤثریت ډېروي. د انساجو کرل، جبري ګل هڅونه او غیر دودیزې إصلاحي لارې چارې د کال په اوږدو کې د تولید د زیاتوالي او د نبات د زغم د لوړولو لامل کېږي. د عضوي او هوښیارې کرنې ټکنالوژۍ پلي کول د تولید دوامدارۍ او اغېزمنتیا ته وده ورکوي. میکانیزه کول د حاصلاتو د راټولولو بهیر آسانوي، د کاري لګښتونو کموالی رامنځته کوي او د اقتصادي ګټې کچه لوړوي. د پرمختللو کرنیزو تخنیکونو، د اوبو لګولو مدیریت او میکانیزه کولو ادغام د زعفرانو د تولید سیستم بدلوي. دغه نوښتونه، د دوامدارو لارو چارو سره یوځای، د اوبو د کموالي او د خاورې د محدودیتونو د ننګونو په حل کې اغېزمن رول لري او د زعفرانو د کرنې راتلونکی پرمختګ تضمینوي. د دغو تخنیکونو د پراخې پلي کېدنې لپاره نوره څېړنه اړینه ده.
کلیدي ټکي: د زعفرانو کرکیله، پرمختللي کرنیز تخنیکونه، ځیرکه کرنه، د حاصلاتو لوړونه، پایداري

Introduction

Saffron (Crocus sativus L.), a perennial plant belonging to the Iridaceae family, has long been a symbol of culinary and medicinal excellence due to its vibrant colour, unique flavour, and various health benefits. The plant is primarily cultivated for its stigmas, which are handpicked and dried to produce the precious saffron spice (Gresta et al., 2008a). Over the years, saffron has found its way into food, pharmaceutical, and cosmetic industries, driving a surge in global demand (Molina et al., 2005a). Despite its widespread appeal, saffron cultivation remains a labour-intensive and resource-heavy process, hindered by challenges such as water scarcity, soil degradation, and susceptibility to pests and diseases (Koocheki et al., 2014a). These challenges are compounded by the limited access to advanced agricultural technologies and the growing pressure for higher yields in the face of increasing global competition.

Saffron has long been recognized as one of the world's most valuable spices, with its cultivation sustained for centuries through traditional farming practices that rely on locally available resources (Ali et al., 2020). Despite this rich heritage, saffron production globally faces persistent challenges such as limited access to modern farming technologies, inefficient cultivation practices, and environmental constraints that restrict productivity (Sharifi et al., 2022). Afghanistan, often highlighted as a producer of some of the highest-quality saffron, serves as a valuable case study within this global context, where traditional practices coexist with emerging efforts toward modernization. Similarly, expanding interest in nontraditional regions such as New Zealand, the United States, and Chile (Fernandez, 2004a) underscores the importance of adapting advanced cultivation techniques. Integrating these innovations presents significant opportunities to enhance yield, improve quality, and address the inherent limitations of conventional saffron production systems worldwide.

Saffron's ability to thrive in marginal lands and its compatibility with low-input cropping systems make it an attractive option for sustainable agriculture. Yet, despite its potential, the future of saffron cultivation remains uncertain due to several key obstacles, including the lack of access to quality planting material, mismanagement of agricultural inputs, and inadequate mechanization. For instance, the world's largest producer, Iran, accounted for over 90% of global saffron production in 2018, yet has faced declining yields since the early 2000s, signalling the urgent need for innovation in cultivation practices. These challenges highlight the necessity for a holistic approach to improving saffron production, one that incorporates genetic advancements, better crop management, and modern technologies (Gresta et al., 2008b).

This narrative review delves into the latest advancements in saffron cultivation techniques and examines their potential impact on increasing yields and improving sustainability. By exploring both the scientific and practical aspects of these innovations, the study aims to provide a comprehensive understanding of how modern agricultural practices can enhance saffron farming worldwide. It emphasizes the growing importance of adopting advanced methods to overcome traditional limitations and meet rising global demand. Ultimately, the review also considers the broader socio-economic implications of these techniques for saffron-producing regions across diverse agro-climatic conditions.

Methodology

This narrative review was conducted through a systematic literature search to identify, analyze, and synthesize existing research on innovations in saffron cultivation and irrigation management. Multiple academic databases and sources were consulted, including Google Scholar, Scopus, Web of Science, ScienceDirect, and SpringerLink, to ensure comprehensive coverage of peer-reviewed literature. The search strategy employed a combination of predefined keywords and Boolean operators. Core search terms included "saffron cultivation," "saffron yield improvement," "innovations in saffron farming," "irrigation management in saffron," "smart farming technologies," and "precision agriculture saffron," with operators such as AND, OR, and NOT applied to refine the scope of retrieval.

Eligibility criteria were established to maintain the quality and relevance of the evidence base. Publications were considered if they were peer-reviewed journal articles, books, or conference proceedings published in English after 2000, and if they directly addressed saffron production, irrigation methods, or smart farming systems. Studies that were non-scientific, lacked methodological rigor, or were inaccessible in full text were excluded. Following an initial screening of titles and abstracts, eligible studies were retrieved for full-text review. Data were then extracted, categorized, and synthesized under two principal themes: (i) innovations in saffron cultivation and (ii) irrigation management and smart farming systems. This systematic approach ensured both methodological rigor and alignment with scholarly standards for narrative reviews.

Results and Discussion

Advancement in Saffron Cultivation

Until the 1980s, Spain dominated the global saffron trade, producing 52% of the world's saffron. By the late 1990s, Iran became the leading producer, followed by Kashmir, Greece, and Spain (Husaini et al., 2010). Despite expanded cultivation in Iran, yields have been declining. Saffron yield is influenced by agronomic, biological, and environmental factors, such as corm storage, climate, sowing time, crop management, and pest control (Molina et al., 2004a). Yields range from 2.5 kg ha-1 in Kashmir to 29 kg ha-1 in Navelli under optimal conditions. Factors like mismanagement, lack of mechanization, poor irrigation, and small farm sizes hinder yield improvement (Koocheki et al., 2017b). Water scarcity is a major issue in saffron cultivation, with an average water footprint of 4659 m^3/kg in (Bazrafshan et al., 2019). Water use efficiency is critical, especially in arid regions like Gonabad, Iran, where traditional Qanat irrigation systems have supported saffron farming for over 2500 years (FAO, 2018). Innovations in water management and farming techniques, such as controlled environment agriculture and hydroponics, are needed to improve water use efficiency (Mollafilabi et al., 2013a).

To ensure saffron's future, it's essential to preserve traditional methods while introducing modern technologies. Innovations in cultivation, postharvest processing, and marketing are required to stabilize production and meet global demand (Fernandez, 2004b). Techniques like controlled environment farming, smart farming, and organic cultivation can enhance yield, quality, and sustainability (Molina et al., 2004c).

Irrigation Management in Saffron Cultivation

Although saffron is relatively drought-tolerant once established, it requires careful management of water during its growth cycle. In many saffron-producing regions, efficient irrigation systems are essential to support crop growth while conserving limited water resources. Advanced irrigation techniques have proven particularly beneficial:

(i) ***Drip Irrigation:*** Drip irrigation, which delivers water directly to the root zone, is one of the most efficient methods for saffron cultivation. It minimizes water wastage and ensures that the corms receive the necessary moisture without becoming waterlogged. In regions facing water scarcity, drip irrigation significantly reduces water consumption while maximizing crop yield (Sepaskhah and Kamgar-Haghighi, 2009).

(ii) ***Irrigation Scheduling:*** saffron requires infrequent, deep watering, especially during critical growth stages such as bulb formation and flowering. Overwatering can lead to fungal diseases, while underwatering can result in poor flower formation. Through research and experimentation, Afghan farmers are developing customized irrigation schedules based on local climatic conditions. Timing irrigation based on weather patterns and seasonal rainfall is vital for sustaining healthy saffron crops (Sepaskhah and Kamgar-Haghighi, 2009).

(iii) ***Rainwater Harvesting:*** In regions where access to consistent water sources is limited, rainwater harvesting systems provide an excellent solution. By capturing and storing rainwater during wet seasons, farmers can supplement their irrigation needs during dry months, thereby reducing dependence on external water supplies. This sustainable practice not only improves water availability for saffron cultivation but also contributes to long-term resource conservation (Velasco-Munoz et al., 2019).

(iv) ***Production Under Controlled Environments****:* Evaluating land suitability for saffron cultivation involves a multidimensional approach, considering physical, economic, and social factors. Studies indicate that these factors contribute approximately 48 percent, 43 percent, and 9 percent, respectively, to overall land suitability modelling for saffron production. However, challenges such as environmental limitations, resource constraints, and socio-economic conditions continue to restrict saffron expansion in certain regions worldwide (Wali et al., 2016).

To address these challenges, cultivation under controlled environments has been proposed as an alternative to traditional outdoor farming (Koocheki & Seyyedi, 2016c; Sabet-Teimouri et al., 2010). This method allows for better control overgrowth conditions and nutrition, leading to higher yields and improved quality (Fallahi et al., 2017). Controlled environments can also alleviate issues such as labor costs and water scarcity, particularly in areas facing water-deficit conditions (Mollafilabi et al., 2013b). Moreover, vertical farming systems, such as the use of vertical columns and suspended grow bags, have been shown to increase resource use efficiency, particularly in arid regions where water is a limiting factor (Ali-Ahmad et al., 2017; Touliatos et al., 2016). Vertical farming is especially suited for small-scale, household-level saffron production, ensuring better resource management. Ultimately, controlled environments enable higher crop density, extended flowering periods, and improved yields, particularly when coupled with high-quality plant propagation materials.

(i) ***Soilless Beds:*** hydroponic and aeroponic systems have revolutionized plant cultivation by enabling precise control over environmental factors such as temperature, humidity, and light, as well as plant nutrition. These systems offer a viable solution for growing plants in conditions where traditional soil-based cultivation would be challenging or even unfeasible. By eliminating the need for soil, these soilless techniques allow for optimized growing conditions, which can be especially beneficial in regions with poor soil quality or limited arable land (Nehvi, 2014).

(ii) ***Hydroponics and Aeroponics in Saffron Production:*** hydroponics and aeroponics are two soilless cultivation systems that have been explored as alternatives to traditional field-based saffron production. In hydroponics, saffron plant roots are submerged in a nutrient solution, either in a static or continuously aerated form, or a periodically flowing liquid solution. In contrast, aeroponics delivers water and nutrients to the roots in the form of a fine mist, which ensures that the roots are suspended in the air while receiving essential nutrients. These methods have been proposed as viable alternatives for saffron cultivation, especially in regions with environmental limitations (Mollafilabi et al., 2013c). The benefits of soilless cultivation for saffron have been well-documented. Saffron corms grown in aeroponic and hydroponic systems produced more flowers and leaves than those grown in traditional soil-based conditions. Not only did these systems not hinder stigma production, but they also significantly increased the dry weight of corms and the concentration of key compounds like crocin and crocetin in the dried stigmas. Moreover, Maggio et al. (2006a) evaluated saffron cultivation in controlled environments, such as cold glasshouses and climate chambers, where optimal conditions were maintained throughout the growing season. Their findings showed that saffron corms planted in such systems had increased planting density, sprouted and flowered earlier, and produced yields that were nearly double those of traditional field-based cultivation, reaching approximately 22 kg ha^{-1} compared to just 10 kg ha^{-1} in the field. Further studies by Sorooshzadeh and Tabibzadeh (2015) examined the effect of copper (Cu) concentrations on saffron growth in hydroponic systems. Their results demonstrated that copper concentrations up to 5 μM positively affected both root and leaf growth, while higher concentrations inhibited growth. Additionally, soilless cultivation provides the advantage of easier pest and pathogen management, which can be more challenging in field conditions Maggio et al., (2006a). In conclusion, controlled environment farming, particularly hydroponics and aeroponics, holds significant promise for improving saffron yield and quality. However, further research is needed to refine these systems and assess their long-term sustainability and cost-effectiveness.

(iii) ***Growth Chambers in Saffron Cultivation:*** several studies have explored the growth, yield, and quality of saffron in growth chambers, with mixed results. Poggi et al. (2010) reported that incubating saffron corms under controlled conditions improved the quality of the saffron produced. However, Garcia-Rodríguez et al. (2017) focused on the potential to shift saffron flowering to the offseason by storing corms in ultralow oxygen (ULO) cooling chambers, followed by incubation to advance flower initiation. Afterward, the corms were hydroponically cultivated in a flowering room. Despite the two-month delay in flowering compared to traditional methods, extending the incubation period significantly reduced saffron quality, as determined by ISO 3632 standards. The extended ULO and incubation periods also negatively impacted the levels of crocetin esters and picrocrocin, though the effect on safranal content was inconsistent. These findings suggest that while incubation conditions influence both saffron yield and quality, further research is required to determine the optimal conditions for saffron cultivation in growth chambers.

(iv) ***In Vitro*** **Cultivation of Saffron:** as Saffron (*Crocus sativus* L.) is a triploid, sterile plant (2n = 3X = 24) that is typically propagated vegetatively using daughter corms or cormlets (Fernandez, 2004a). These corms only survive for one growing season, and each mother corm produces only four to five cormlets annually. However, some of these new corms may be unproductive in the following season due to their small size or damage caused by pests, such as acari, or fungal pathogens. This results in limited multiplication rates of cormlets in fields, reducing the availability of planting material and, consequently, saffron productivity. The lack of access to high-quality corms, characterized by purity, homogeneity, and health, is a significant constraint on expanding saffron cultivation areas (Renau-Morata et al., 2013a). Furthermore, the vegetative propagation method used in saffron cultivation limits genetic diversity, which can lead to genetic erosion (Ahmad et al., 2011). The scarcity of high-quality planting material remains a major bottleneck in saffron production, as it may take several years to produce enough corms to sow one hectare (Yasmin et al., 2013). Saffron's sterility also prevents the use of conventional breeding techniques for genetic improvement, but tissue culture presents a promising alternative for large-scale propagation. Research into *in vitro* propagation techniques for saffron began in the early 1980s (Parray et al., 2012). Notable progress has been made in this area, including studies on *in vitro* cormlet production (Quadri et al., 2010), plantlet regeneration (Majourhat et al., 2007), and somatic embryogenesis (Raja et al., 2007). Yasmin et al., (2014) developed a commercially viable protocol for *in vitro* corm production, utilizing minicorms and corm sections with apical, subapical, and auxiliary meristematic regions as explants. To ensure low contamination levels and efficient propagation, Renau-Morata et al., (2013b) found that storing nonplanted mother corms at low temperatures (1-3°C) for nine months can produce daughter corms suitable for *in vitro* multiplication.

(v) ***Forced Flowering of Saffron:*** one of the challenges in saffron production is the significant labour involved in handpicking the stigmas from the flowers. The flowering period of saffron is typically brief, lasting only 2-3 weeks or up to 5-6 weeks in some regions, generally in the autumn. Extending the flowering period can help alleviate the intensive labour demands, making it easier to mechanize the collection of flowers, especially in containerized systems rather than traditional field cultivation (Molina et al., 2004a). Forced flowering is a technique used to manipulate temperature, humidity, and light conditions to prolong the flowering period. Several studies have outlined methods for inducing forced flowering in saffron corms (Molina et al., 2005a, 2004b), even enabling year-round flowering by controlling the different stages of saffron growth. For example, creating an artificial winter during the summer months can help achieve this goal. According to Molina et al., (2004b, 2005b), saffron blooms can be extended by regulating both temperature and light intensity. With corm forcing, the flowering period can be extended throughout the year under controlled greenhouse conditions, which helps avoid labour peaks. While these methods may be costly and may not be feasible on an industrial scale, they could be considered valuable innovations in the future. The cost of harvesting saffron is influenced by the length of both the corm-to-flower and flowering stages, which impacts labour requirements and the scheduling of harvest activities. Adjusting the timing and duration of saffron flowering is crucial for improving yields (Maggio et al., 2006b). In traditional field conditions, flower initiation typically occurs in the summer, coinciding with the start of meristematic activity in the apical bud. The time taken for flower initiation is often influenced by corm size. Additionally, both air and soil temperatures can extend the saffron flowering period by up to 2 months (Maggio et al., 2006c). In greenhouse environments, natural light can be managed using automatic blinds and curtains (Tripanagnostopoulos et al., 2004), along with ventilation control systems (Souliotis et al., 2006). Supplementary lighting, which is often required in such controlled environments, necessitates the use of specialized equipment and suitable light sources (Wang et al., 2002). These practices are typically carried out in storage rooms or macro tunnels and can enable earlier flowering compared to traditional field cultivation by adjusting temperature, humidity, and lighting.

(vi) ***Nonconventional Breeding Techniques for Saffron Improvement:*** with the increasing global demand for saffron, it is essential to find ways to enhance both its production and quality. Potential strategies include developing plants with more flowers per plant, increasing the number of stigmas on each flower, enlarging the stigmas, or enhancing the colour and aroma of the stigmas. All these objectives are tied to advanced breeding techniques. Traditional plant breeding approaches generally rely on selecting the best individuals from natural or cultivated populations, as well as utilizing genetic breeding methods with wild ancestors or introducing mutations through natural or induced processes. However, saffron's inherent sterility significantly restricts the application of conventional breeding methods to improve the crop (Fernandez, 2004c). The limited genetic knowledge of saffron presents another challenge, as there are only a small number of studies dedicated to understanding its genetic makeup. Research into saffron's genome could aid in tracing its origins and developing more sophisticated breeding methods. Several studies have conducted DNA analyses of saffron, but these often show little genetic variation between saffron plants from different regions of the world, although phenotypic differences have been observed. The limited genetic variation in saffron, which is compounded by its vegetative propagation and the risk of genetic erosion, underscores the need for additional research to explore saffron's biodiversity and evaluate new breeding techniques for sustainable production.

(vii) ***Application of Hormones in Saffron Cultivation:*** various types of hormones and regulatory chemicals play an essential role in modern agriculture, particularly in manipulating plant development. In saffron cultivation, phytohormones exert significant biochemical, physiological, and morphological effects, influencing key processes such as root system development, flower induction, and overall plant growth stimulation. The application of hormones in saffron farming can take place during the growing season, as well as on dormant corms, with each method serving specific purposes to enhance various aspects of saffron production (Amirshekari et al., 2007).

(viii) ***Organic Production:*** saffron cultivation in its native regions has evolved based on local environmental, social, and agricultural conditions, with most producers relying on traditional, non-chemical methods to enhance soil fertility and manage pests, diseases, and weeds, following organic farming principles. However, these practices are often not certified. In developing countries, saffron farmers, typically smallholders, may lack the resources for costly international certification. To address this, the International Federation of Organic Agriculture Movements (IFOAM) introduced the Internal Control System (ICS) in 1996, allowing group certification for smallholder producers (Ghorbani & Koocheki, 2007). Though the ICS system was initially designed to offer an alternative to individual certification, its reliability remains debated. ISO standards exist to evaluate saffron quality and validate organic saffron. For instance, the European Union has set regulations for organic production, processing, and labelling under Regulation (EC) No. 834/2007, emphasizing sustainability, waste recycling, and the use of organic corms (The Council of the European Union, 2007). Key organic principles for saffron include minimizing non-renewable energy use, protecting the environment from contamination, and relying on natural methods to control pests and diseases. These regulations also prohibit the use of synthetic chemicals and genetically modified organisms (International Trade Centre, 2018). Integrating indigenous knowledge with academic research is essential for developing sustainable organic practices suited to each region.

(ix) ***Mechanization:*** saffron production has traditionally relied on family-based farming practices, using conventional techniques that have seen limited advancements. While mechanization is commonplace in many other agricultural sectors, it has been slow to penetrate saffron cultivation. For example, farm vehicles like modified onion or potato planters have been explored for planting saffron corms, though issues such as misplacement of corms, which can delay emergence and reduce yield, remain challenges (Gresta et al., 2008c). Specialized tools, such as adapted potato diggers, can be used for lifting corms, potentially replacing human labour in this aspect of cultivation. However, the most labour-intensive and delicate stages—flower harvesting and stigma separation are still carried out by hand (UNIDO, 2014). The scarcity of mechanization in saffron production is primarily due to the delicate nature of the corms and flowers, which require careful handling. Other factors include the variation in corm size and the need for precise planting. Some attempts to mechanize certain cultivation practices have been made, though they have had limited success. Flower harvesting, which requires great care, is often carried out manually by family members, who cut the base of the flower stem to avoid damaging the leaves and preventing daughter corm production. Since saffron flowers bloom for only a short time, they must be picked on the same day, usually early in the morning when the corolla is still closed, to ensure optimal stigma quality. Once harvested, the stigmas must be carefully separated from the rest of the flower, a process that also relies heavily on manual labour. Given that labour costs constitute a significant portion of saffron production expenses, there is considerable interest in mechanization and automation to reduce these costs. While some automated systems for saffron cultivation have been proposed, most are still not feasible for large-scale industrial use.

(x) ***Smart Farming:*** smart farming refers to the integration of modern information and communication technologies (ICT) in agriculture to improve both the quantity and quality of agricultural outputs. This approach involves the use of technologies such as the Internet of Things (IoT), sensors, actuators, GPS systems, big data, robotics, and precision tools, all of which enhance agricultural practices to create more productive and sustainable farming processes (Kernecker et al., 2018). One of the significant advantages of smart farming is its potential to reduce the environmental impact of agricultural practices, enabling more efficient water use, optimized input application, and better management of resources. In 2011, nearly 80 per cent of farmers in the United States adopted smart farming technologies, compared to only 24 per cent in Europe (Lawson et al., 2011). The primary goal of smart farming is to provide farmers with value through improved decision-making and more efficient management techniques. Smart farming is also applicable to saffron cultivation. While its use is often associated with large-scale, conventional farming systems, smart farming technologies can also be implemented in smaller, more complex environments, such as family-owned farms and those managed organically (Akis, 2019). By precisely measuring variations across their fields and adapting their strategies, saffron farmers can significantly enhance the efficiency of pesticide and fertilizer use, reducing the environmental impact associated with their application.

(xi) ***Saffron Byproducts:*** historically, saffron has been used primarily for food, textiles, and medicinal purposes, with the stigmas being the most valuable part of the flower. Once the stigmas are removed, the remaining parts of the saffron flower are typically discarded as waste. However, studies have highlighted the potential of saffron byproducts for applications in the cosmetic, fragrance, and flavouring industries. Due to the large quantities produced and the low cost of saffron petals, they are increasingly being considered for a variety of uses. Research by Argento et al., (2010) explored the composition of hydroalcoholic extracts from saffron petals using advanced analytical techniques, such as LC/UV-vis-DAD/ESI-MS and GC/MS. Their findings revealed that saffron flower extracts had a notable resemblance to the aroma of commercial cocoa powder. Additionally, they identified 17 different flavonoids known for their antioxidant properties. Bergoin et al., (2004) also noted a honey-like aroma in fresh saffron flowers, further suggesting their potential for use in the flavour and fragrance sectors. This honey-like scent was similarly reported by (Lech et al., 2009). Beyond fragrance, saffron petals have demonstrated promising pharmacological benefits. Hosseini et al., (2018) reviewed various medicinal properties of saffron petals, including antibacterial, antispasmodic, immunomodulatory, antidepressant, antidiabetic, and antioxidant effects. These benefits are largely attributed to the active compounds in the petals. Lahmass et al., (2018) found significant antioxidant activity in several saffron byproducts, including dry and green leaves, corms, and spathes (the part between the corm and shoot). Their study showed that the highest free radical-scavenging activity was found in corm extracts, while spaths provided the strongest protection against β-carotene bleaching. Righi et al., (2015) also recognized saffron petals as valuable for phytopharmaceutical and nutraceutical purposes. Saffron petals are considered agricultural waste, utilizing them offers a promising opportunity for the saffron industry. Considering that around 36 kg of dried petals are produced per hectare of saffron farm each year, developing processes to use this byproduct could significantly reduce waste and open up new markets.

Conclusion

In conclusion, saffron cultivation has experienced notable advancements, driven by the need to address challenges such as water scarcity, labour-intensive harvesting, and declining yields in traditional farming systems. The shift towards controlled environment farming, including hydroponics, aeroponics, and vertical farming, has shown great promise in enhancing saffron production efficiency and quality. Innovations in water management, mechanization, and smart farming technologies also hold potential to improve sustainability and reduce labour costs in saffron farming. Effective irrigation management is crucial to optimizing saffron yield, especially in regions where water availability is a significant concern. Advances in drip irrigation systems, precision irrigation technologies, and water recycling techniques are helping to reduce water waste and ensure that saffron plants receive the appropriate moisture levels throughout their growing cycle. These sustainable irrigation practices not only improve the efficiency of water use but also contribute to the overall health and productivity of saffron crops.

However, challenges related to the sterility of saffron plants and limited genetic diversity remain, hindering progress in breeding and propagation. Nonconventional breeding techniques, including tissue culture and *in vitro* propagation, offer a viable solution to meet the growing demand for high-quality saffron corms. Furthermore, the exploration of saffron byproducts for use in industries such as cosmetics, food, and livestock feed provides an opportunity to minimize waste and open new markets.

To ensure the long-term sustainability of saffron cultivation, it is crucial to balance traditional farming methods with modern technological innovations. Continued research and collaboration between farmers, scientists, and industry stakeholders will be essential in developing strategies that improve yield, enhance quality, and contribute to the economic viability of saffron production globally.

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