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ADVANCING SAFFRON (*CROCUS SATIVUS* L.) CULTIVATION THROUGH HYDROPONICS SYSTEM: A REVIEW

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ABSTRACT

Saffron or Kesar or Red gold (2n= 24) is one of the most premium spices in the world valued for medicinal and bioactive compounds. With 80% of worldwide saffron production, Iran ranks first while India contributes 5%. 90% of India's cultivation is in the Jammu & Kashmir region. Traditionally, saffron cultivation has been limited to specific regions with ideal climatic conditions, making it a challenging and labor-intensive process. In recent years, the potential of hydroponic farming to cultivate saffron has gained significant attention. This review examines the benefits and challenges of hydroponic saffron cultivation, drawing insights from the current research on growing media and nutrient solutions. Hydroponic systems offer controlled environmental conditions, efficient water and nutrient management, and the potential for higher yields. The challenges associated with hydroponic saffron farming, such as the high initial investment, technical complexities, long-term research and the need for specialized knowledge. Despite these challenges, the review concludes that hydroponic saffron cultivation holds promising potential to revolutionize the saffron industry. With advancements in technology and growing demand for sustainable farming practices, hydroponic saffron farming could become a viable and economically viable solution, making this high-value spice more accessible to consumers worldwide.

***Key words*:** Controlled environment, Growing media, Hydroponics, Nutrient, Saffron

Introduction

Saffron (*Crocus sativus* L.) from the Iridaceae family is one of the most expensive spices cultivated worldwide rich in proteins, carbohydrates and nitrogen-free extract as mentioned in Table 1. A geophyte herbaceous sterile triploid (2n= 3x= 24) (Alavi-Siney *et al.*, 2022) plant known for rich vitamins and secondary metabolites such as anthocyanins, carotenoids, flavonoids, terpenes, etc (Cardone *et al.,* 2020). This vegetatively propagated, auto-triploid monocotyledon (Nemati *et al.,* 2019) corm possesses antimicrobial, antifungal, antiseptic, anticancer and antidepressant properties. It is used to treat some diseases such as Depression, Withdrawal syndrome, Diabetes, Spatial memory, Alzheimer's, Parkinson's disease, Anxiety and Insomnia (Maqbool *et al.,* 2022). Out of the total annual 200 metric tonnes (MT) worldwide saffron production, Iran ranks first with approximately 178 tonnes (t) of production contributing about 90 percent (%) of the world's saffron production (Khajeh-Hosseini and Fallahpour, 2020). The three main bioactive compounds i.e., crocin ($C_{44}H_{64}O_{24}$), picrocrocin ($C_{16}H_{26}O_{7}$) and safranal ($C_{10}H_{14}O$) (Abu-Izneid *et al.,* 2022) determines the colour intensity, flavour and aroma strength, respectively, thus making Kesar the red gold for the country's economy.

Saffron is cultivated in countries like Iran, Afghanistan, India, Greece, Morocco, Spain, France, Italy, Turkey, United Arab Emirates, Tibet, Portugal, Azerbaijan, Israel, Mexico, Pakistan, China, Japan and Australia where this spice is cultivated and exported to other countries (Vlahova, 2022). Iran holds the first rank in saffron production, with around 80% worldwide, whereas India contributes only 5% to the total saffron production. Of these, 90% is cultivated in India's Jammu & Kashmir region. The agronomical conditions and climate change vary the saffron production. From 1997 to 2015 the

Table 1: Chemical composition of Saffron (*Crocus sativus* L.) (Menia *et al.*, 2018).

Constituents	Percentage (%)
Nitrogen free extract	54.5-57.5
Water	14.5-15.5
Crocin	13.5-15.0
Protein	12.5-13.5
Carbohydrate	12.0-13.5
Essential Oils	4.7-8.5
Valuable Crude fiber	4.0-5.0
Ash	4.0-4.5
Picrocrocin, Safranal, Phosphorus, Boron	In traces

decrease in area and productivity of saffron was observed by 83% and 72% respectively (Kumar *et al.*, 2022). The small and fragile plant cannot be exposed to mechanization due to which saffron cultivation becomes a labour-intensive and time-consuming activity. Due to this, new strategies are designed to overcome these problems. For almost 20 years, various studies have been conducted on the quality and production of saffron grown hydroponically or on different (Valenzuela *et al.*, 2024).

Higher quality yield can be obtained through saffron corm cultivation in controlled environment conditions like adequate light intensity, proper temperature and humidity, essential plant nutrients and pest-disease-free environment in the hydroponics systems (Nardi *et al.*, 2022). In recent years, hydroponics has emerged as a promising crop production technique due to several factors like limited availability of arable land, resource efficiency, improved crop quality and yields, adaptability to climate change, technological advancements, sustainability advantages and increased knowledge sharing (Maliqa *et al.*, 2023). Depending on the medium type, hydroponics techniques can be classified into several categories as shown in Fig. 1. The Nutrient Film Technique (NFT) uses small channels or tubes for the continual supply of nutrient solution through the cluster of plants. The Ebb & Flow system works on the principle of flooding and drains the nutrient movements. The Drip or trickle hydroponics uses emitters for sprinkling nutrient-rich solutions on the plant foliar. The Wick system works on the capillary action of roots and nutrients from the reservoir reach each plant through wicks. The Continuous flow system operates on recycling and reusing of nutrient-rich water for plant growth and development. The Deep/direct water culture involves continuous reimbursement of plant roots in a nutrient and oxygen-rich solution (Maiti and Saha, 2020). Extensive researchers have designed various hydroponics systems based on parameters like light intensity, temperature, pH, humidity, liquid levels, oxygen concentration, etc.

Hydroponics provide optimal conditions for plant growth avoiding any biotic or abiotic stresses (Sharma *et al.*, 2018), thus conserving the plant-nutrient interaction and can be an innovative system to boost the saffron yield across the country (Sambo *et al.*, 2019). This intensive *in-vitro* cultivation increases plant density and guarantees quality and healthy corm production, resulting in higher stigma yield and improved stigma colorimetric parameters. The system also enables the shortening of the dormancy stage, thus accelerating the developmental cycle of the saffron (Valenzuela *et al.*, 2024). In addition, flower harvesting in the hydroponics system is faster, cheaper and cleaner, not affecting the flowers (Fallahi *et al.*, 2023). Thus, hydroponics saffron cultivation can take over open-field cultivation and holds great promise for quality stock corms, promising long-term saffron production.

Cultivation Environment Parameters

The controlled environmental factors like temperature, relative humidity (RH) and illumination play a key role in determining the hydroponics cultivation of saffron spice as highlighted in Table 2 (Schroeder *et al.*, 2020). Hydroponic systems also control the CO2 levels, which can be tailored to create the ideal growing conditions for saffron, ensuring better yields and consistent quality (Kour *et al.*, 2022). Among all the environmental parameters, light or illumination is one of the influential factors in promoting plant growth and development along with the phytonutrient content in plants. For most herbs, red, blue and ultraviolet (UV) light enhances the concentration of

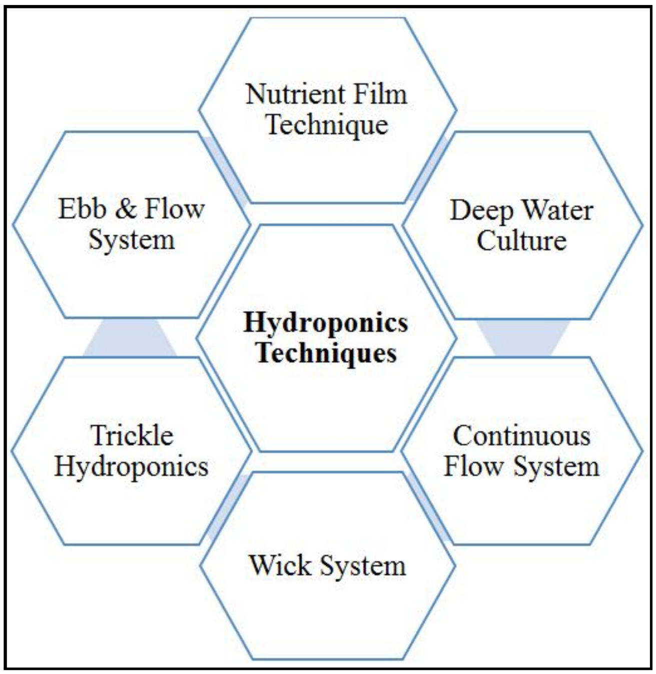

Fig. 1: Hydroponics Techniques based on the type of mediums.

Table 2: Effective Environmental Conditions for Hydroponics Saffron Cultivation.

Parameters	Value	References
Temperature	23-27ºC (for initial 90-150 days), then 25ºC	Wang *et al.*, 2021
Incubation temperature	16-23ºC	Wang *et al.*, 2021
Temperature after incubation	17 ± 2ºC	Wang *et al.*, 2021
Flowering temperature	23-27ºC	Wang *et al.*, 2021
Corm germination temperature	23-30ºC	Anuar *et al.*, 2024
Storage temperature	25ºC	Saeidirad and Zarifneshat, 2019
Relative humidity	60-85%	Nardi *et al.*, 2022
Relative humidity after incubation	60%	Dewir *et al.*, 2022
Light	8-11 hours	Kour *et al.*, 2022
CO_2	400 ppm	Kour *et al.*, 2022

essential oils, phenolic compounds and antioxidant capacities. Other light spectra within the photosynthetically active region such as cyan, green, yellow, orange and far-red light are absorbed by photosynthetic pigments and utilized in leaves (Dou *et al.*, 2017). The recent advances in LED light technology made it possible to modulate the light intensity, duration and focus of the light beam to adjust the plant reaction (Teixeira, 2020). The action of red radiation stimulates photosynthesis along with the synthesis and accumulation of carbohydrates (Landi *et al.*, 2020); in the case of *C. sativus*, an effect on the production and quality of saffron with increasing size and number of stigmas (Gresta *et al.*, 2009) and regulating the activity of corm amylase and indole-3-acetic acid (IAA) (Zhu *et al.*, 2022). Blue radiation acts on the secondary metabolism in saffron and increases the weight of offspring corms by reducing their number and altering biomass distribution in favor of corms and flowers (Moradi *et al.*, 2021). In saffron, a low red/far-red ratio during the development of offspring corms activates a phytochrome-mediated response, preparing the corms to produce flowers with a higher concentration of crocin in the stigmas (Kajikawa *et al.*, 2018).

The optimum temperature is crucial for vegetative growth, incubation, flowering initiation and drying of saffron stigmas. The ambient temperature is vital to breaking the dormancy of saffron too. Premature blooming and delay in flower formation may also impact flowering quality and yield if the flowering period is delayed to May, but not if flowering time is delayed from the beginning of November to the end of December, indicating that temperature and incubation time impact saffron floral transition (Wang *et al.*, 2021). In an experiment, out of three temperatures (10ºC, 23ºC and 30ºC) were tested for corm germination and three temperatures (16ºC, 23ºC and 30ºC) were tested for flowering, the optimum temperature for flowering was 16ºC and corm germination was 23-30ºC (Anuar *et al.*, 2024). The optimum storage temperature of dried saffron stigma is 25ºC during the 30-day storage period (Saeidirad and Zarifneshat, 2019). To extend the storage life, some fluctuations in temperature are essential to store the phenolic compounds present in the herb.

Maintaining adequate relative humidity is essential for the healthy growth and flowering of saffron plants (Askari-Khorasgani and Pessarakli, 2019). The optimum RH is observed to be 60% (Dewir *et al.*, 2022; Nardi *et al.*, 2022). Higher RH can make the saffron plant more susceptible to fungal pathogens whereas low RH affects moisture retention capacity, stunted growth and damage root aeration (Stelluti *et al.*, 2023). The transition in the RH depends on the temperature and light intensity in the hydroponics system. Rather these factors are interrelated with each other.

Growing Media

The viability of the controlled environment mainly depends on the plant-nutrient interaction, growing medium and nutrient solutions. The primary factors influencing a growth medium's interaction with the nutrient solution are porosity, water holding capacity, water availability, buffering capacity and cation exchange capacity (CEC) (Chhetri *et al.*, 2022). Plants grow in a soil-less medium like clay pebbles, peat moss, rock wool or coco coir to nurture plant roots and maintain the water-to-oxygen ratio (Das Gupta, 2020).

A scientific report stated an optimal substrate composition of 15% cocopeat, 15% coco chips and 70% perlite has shown an increasing effect on the weight of the leaf, total photosynthesis rate and large-sized cormlets (>8g) to nearly 50% of total cormlets (Naseri *et al.*, 2025).

An experiment was performed to choose the suitable growth media for soilless saffron corm yield with different particle sizes of perlite and mixing ratios with peat moss. 17.89 g was obtained as the maximum corm weight in a mixed growth media containing 50% perlite (1-1.5 mm) and 50% peat moss and is considered as an optimal growth media (Feyzizadeh *et al.,* 2023). Another study conducted in Abi-Jarash Farm, Syria highlighted that the number of roots, shoots, leaves and flowers per corm, root length, leaf length, stigma length and dry and fresh weight of stigmas was higher in peat moss and perlite mix as compared to nutrient film technique. In contrast, the weight of daughter corms, mean weight of corms and commercial corms were higher in the nutrient film technique (Razan *et al.,* 2023).

A comparative study between protected soil-based cultivation (PS_1) and protected soilless cultivation (PS_2) using a 1:1 mixture of peat and crushed silica demonstrated that the dry foliage weight, root dry weight, mother bulb weight and daughter bulb weight were higher in the PS_2 than the PS_1, which highlighted that soilless protected cultivation is more effective for saffron production (Maliqa *et al.,* 2023).

In an experiment, the six growing media types influenced saffron corm growth. Three media of different soils *i.e.*, loamy soil (M_1), silty soil (M_2) and sandy soil (M_3), and the rest three were peatmoss (M_4), sandy soil and peat moss mix (M_5) and peat moss and foam mix (M_6). The longest root lengths, fresh weight of roots, number of flowers per plant, fresh and dry stigma weight and vegetative growth are higher in M_4, M_5 and M_6 mediums than in M_1, M_2 and M_3 mediums. The M6 medium even produced the highest values of Chlorophyll a (3.5 mg per g fresh weight), Chlorophyll b (0.8 mg per g fresh weight) and carotenoids (0.33 mg per g fresh weight) in saffron plants. The corm diameter, corm fresh weight and number of corms were higher in the M_6 medium, followed by the M_4 and M_5 mediums and lesser in the M_1, M_2 and M_3 mediums. Overall, the experiment concluded that peat moss and foam mix (M_6) media was the most suited for saffron production (El-Mahrouk *et al.,* 2023).

Kour *et al.,* (2022) stated that 6-6.4 is the optimum pH and 1.1 dS per m is the appropriate EC of nutrient solution used for hydroponics saffron cultivation. Another study obtained the highest stigma yield (number of flowers= 1.9, stigma length= 39.4 mm), stigma fresh weight (42.8 mg), dry stigma weight (5.3 mg) and daughter corm yield (number of daughter corms= 5.7, average corm diameter= 25 mm, fresh weight= 6.4 g) using mother corms sized more than or equals to 32 mm diameter grown hydroponically in the volcanic rock–based continuous immersion system highly influenced the plant growth, photosynthetic rate and daughter corm yield (Dewir *et al.,* 2022).

In a comparative experimental study of saffron cultivation in vertical and horizontal systems, fabric bags were used for planting saffron corms containing potting soil with an area of each side of the cube being equal to 2.25 m^2 hung from a metal hook and three plots with 2.25 m^2 area each, respectively. The results demonstrated that the number of flowers (10), dry weight of the flower (347.34 mg) and dry weight of the stigma (0.56 mg) in the vertical system were three times higher than the horizontal system whereas the number of lateral corms (2.4), dry weight of lateral corms (0.36 g) and dry weight of apical corm (0.88 g) in the horizontal system were comparatively higher than the vertical system. Similarly, the dry weight of the leaves and roots were higher in the vertical system. The total number of leaves and buds were higher in the horizontal culture. However, the maximum leaf length of the vertical planting system was higher than that of the horizontal system (Ali Ahmad *et al.,* 2017).

In a cold greenhouse, the first experiment was conducted with two substrates perlite and a 1:1 (v/v) mix of peat and perlite. Both the substrates started flowering 111 days after transplanting (DAT) but the flower yield was higher in perlite (260 flowers per m^2) compared to the peat and perlite mix (190 flowers per m^2). In the second experiment, two substrates (perlite and vermiculite) were compared in two different environments *i.e.*, a cold glasshouse and a climate chamber in optimal conditions. The flowering started in 103 and 93 DAT in the cold glasshouse and climate chamber, respectively. The yield was doubled than the traditional field cultivation (Maggio *et al.,* 2006).

Nutrient Solution

The plant nutrient requirement in hydroponics is attained by solubilizing the nutrients in water in either inorganic or ionic forms from soluble salts of key elements for plants. These essential nutrients are supplied in various chemical combinations to establish a favourable ratio of ions for plant growth and development in hydroponics systems (Al Meselmani, 2022). Except for Carbon and Oxygen from the atmosphere, the remaining 15 essential elements are obtained from the growth media. Additional elements like sodium, silicon, vanadium, selenium, cobalt, aluminum, and iodine are thought to be advantageous since some of them can promote growth, counteract the harmful effects of other elements or substitute vital nutrients in a less specific capacity (Trejo-Téllez and Gómez-Merino, 2012). The overall composition of the nutrient solution regulates the hydroponics unit's pH and electrical conductivity (EC), the key essentials of yield and quality. The optimal pH for the root zone in hydroponics ranges between 5.5-6.5 and may exceed 7. However, when exposed to external pH levels > 7 or < 5, plants show growth restrictions. Sodium hydroxide (NaOH) or Potassium hydroxide (KOH) can be used to increase the pH while Sulphuric acid (H_2SO_4), Phosphoric acid (H_3PO_4) or Nitric acid (HNO_3) can be used to reduce the pH (Lu and Shimamura, 2018). Additionally, various plant species have various requirements about nutrient ratios in the nutrient solution. Therefore, it is critical to identify the optimal nutrient ratio for each species. The majority of studies examining the impact of nutrient ratios in nutritional solutions concentrated on the ratios of NH_4 + to total nitrogen, the N:K (or K:N) ratio, nutrient anion ratios and the metallic macronutrients (K:Ca or K:Ca:Mg). Because too high Ca:K or Mg:K might cause these ions to accumulate, the ratio of the metallic macronutrients is crucial for maintaining the EC in the root zone (Putra and Yuliando, 2015). Thus, the effective manipulation of nutrients is crucial for the effective growth of plants in a hydroponics system.

A two-year study highlighted that the concentration and volume of phosphate and irrigation schedules in the first year and the effects of nutrient solution of nitrate and iron have promising results on saffron cultivation in the second year. Upto 9800 µM of the nitrate concentration significantly increased the leaf weight, total photosynthesis rate and large-sized cormlets (>8 g) to nearly 50% of total cormlets but the weight of total and large-sized cormlets decreased with the increase in the iron concentration. The concentration of boron again showed no significant effect on the parameters. The highest productivity was achieved with a 150 (ml per pot per week) nutrient solution containing 9800 µM nitrogen and 25 µM iron. This report saw the importance of effective irrigation and nutrition management in enhancing the quantity and quality of cormlet production, potentially boosting perennial saffron yield (Naseri *et al.*, 2025).

A study in the protected soilless saffron cultivation used "Radongrow" as a standard hydroponic fertilizer solution along with a soilless substrate of a 1:1 mixture of peat and crushed silica after manually measuring the EC and pH of the soilless medium. Around 22 fertigation events were conducted over the entire crop growth cycle. The overall foliage weight of saffron was highest compared to soil-based cultivation (Maliqa *et al.*, 2023).

Another study in the Department of Agricultural, Forest and Food Science, University of Turin, Italy used 0.5 dS per m EC and 7.4 pH water for fertigation for root emergence along with modified Long-Ashton nutrient solution in aqueous form ($MgSO_4$, $NaNO_3$, K_2SO_4, $MnSO_4$, $CuSO_4$, $ZnSO_4$, $CaCl_2$, Na_2HPO_4, FeNa-EDTA, H_3BO_3 and Na_2MoO_4) (Chitarra *et al.*, 2016) every 2 weeks until leaf senescence in spring. The pH was adjusted using H_2SO_4 0.1N to 7 and 0.979 dS per m at 22ºC (Stelluti *et al.*, 2023).

In an experiment, the EC of the nutrient solution was 1.4 dS per m with a pH value of 5.8 ± 0.2. The nutrient solution contained macronutrients (mg per L) as 163.20 nitrogen (N), 34.53 phosphorus (P), 172.56 potassium (K), 105.11 calcium (Ca), 33.83 magnesium (Mg) and 62.70 sulphur (S) and micronutrients as 1.83 iron (Fe), 0.23 boron (B), 0.27 manganese (Mn), 0.19 zinc (Zn), 0.12 copper (Cu) and 0.07 molybdenum (Mo) resulting into a promising yield in hydroponics saffron cultivation (Dewir *et al.*, 2022).

The slightly acidic pH (5.5-6.5) standard nutrient solution of Sonneveld and Voogt (2009) was used for fertigation. The alternative fertigation was supplied at 0.33 L per plant per day. Three treatments were provided by a linear increase in the strength of the nutrient solution, to reach EC of 2.0 (control, $EC_{2.0}$), 2.5 ($EC_{2.5}$) and 3.0 ($EC_{3.0}$) dS per m, respectively which highlighted that the shoot length, corm number, corm yield and diameter increased with the EC. The cations (Na^+, NH_4^+, Ca^{2+}, Mg^{2+} and K^+) and anions (Cl^-, NO_3^-, PO_4^- and SO_4^-) concentration of irrigation and drainage solutions (mg per L) and ions uptake (mg per m^2 per day) also increased with the EC except for Na^+ cation, which irrigation and drainage solution was more in $EC_{2.5}$ (Salas *et al.*, 2020).

Advantages of Hydroponics Saffron Cultivation

Hydroponics saffron cultivation offers several advantages over traditional soil-based farming due to various parameters like different growing media, nutrient solutions and controlled environment. The precision in hydroponics farming has proven to be an effective system for saffron cultivation as shown in Fig. 2. Some of the key advantages are highlighted below:

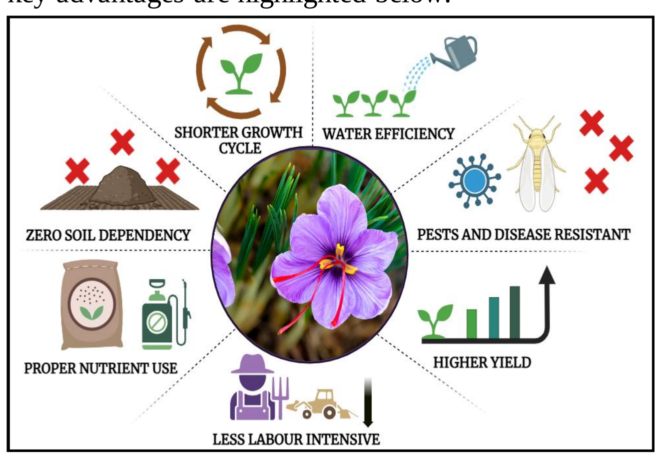

Fig. 2: Advantages of Hydroponics Saffron Cultivation

- **Shorter Growth Cycle:** Hydroponics provide an optimal environment for plants to grow faster, as the nutrients are directly available to the root zone in a water-based solution (Jan *et al.,* 2020). This can lead to a quicker flowering and harvesting cycle for saffron, which is typically a slow-growing plant in soil. This accelerates growth increases productivity and maintains a desired quality of stigma as compared to traditional soil farming (Kumar *et al.,* 2008). Thus, hydroponics can help maximize yields in a shorter period, benefiting both small and large-scale saffron growers.
- **Space and Water Efficiency:** Hydroponics allows vertical and intensive farming of saffron in small and compacted areas, forging it an ideal model for urban or limited-space farming and increasing the production rate. Additionally, since hydroponic systems do not require vast fields, saffron can be grown in controlled, indoor spaces, further optimizing land usage and enabling cultivation in non-traditional growing areas (Nájera *et al.,* 2023). Also, this modern system uses comparatively less water compared to traditional soil farming as the water is recirculated, making it more efficient, especially important for a water-intensive crop like saffron, which traditionally requires a dry environment, especially water-scarcity zones.
- **Less Pests and Diseases Infestation:** The controlled environment conditions lower the attack of harmful pests and dormant the action of fungal pathogens due to unfavourable temperature and RH. Mainly the soil-borne pests and pathogens chances are zero in the case of hydroponics saffron farming. Additionally, hydroponic setups often have better air circulation and filtration, reducing the likelihood of fungal infections and mold (Stelluti *et al.,* 2023). The enclosed environment also allows for easier monitoring and quicker intervention if any issues arise. This helps to reduce the use of pesticides and other chemicals, making the saffron crop more organic and sustainable.
- **Adequate Nutrient Utilization:** A specific concentration of nutrients with controlled pH and EC directly to the plant root zone helps to monitor and control the desired nutrient levels of the saffron plant (Lu and Shimamura, 2018). This allows for precise adjustments to the nutrient levels, ensuring that the saffron plants receive the optimal mix of essential minerals and vitamins at every stage of growth. Optimum utilization of both macro and micronutrients helps in yielding high-quality saffron stigma with enriched crocin, picrocrocin and safranal (Naik *et al.,* 2024). Thus, an adequate nutrient supply promotes consistent plant health and high-quality saffron production.
- **Zero Soil Dependency and Degradation:** Hydroponics systems do not rely on fertile soils or arable lands, thereby reducing the risk of soil degradation, salinization or erosion which is a common issue in traditional farming (Fussy and Papenbrock, 2022). This makes saffron cultivation possible in areas with poor soil quality index and enhances the scope of saffron spice as per consumer demands. Hydroponics saffron cultivation has more cultivation opportunities due to no requirement for fertile soils in various regions (Salas *et al.,* 2020).
- **Higher Saffron Yield:** A controlled environment with precise control over water, light, temperature and RH coupled with essential nutrients directly to the root zone results in boosting saffron yield per plant compared to the traditional method (Khajeh-Hosseini and Fallahpour, 2020). The growing conditions can lead to higher levels of active compounds that contribute to the flavour, colour and aroma of saffron threads (Cardone *et al.,* 2020). With faster growth cycles and improved plant health, hydroponics can significantly increase the overall saffron yield compared to conventional methods.
- **Less Labour-Intensive:** Saffron cultivation is labour-intensive due to the delicate flowers and harvesting process. However, hydroponics systems can reduce laborers' need for irrigation, soil management and pest control (Valenzuela *et al.,* 2024). Automation in the system can further reduce human intervention, thus reducing labour costs and indirectly, boosting the saffron price in the market.

Drawbacks of Hydroponics Saffron Cultivation

While hydroponic saffron farming offers several advantages, there are also notable drawbacks that need to be considered. Here are some of the challenges or disadvantages of saffron hydroponics:

- **High Initial Installment Cost:** Establishing a hydroponic system requires considerable investment in specialized equipment such as grow lights, nutrient delivery systems, pumps, reservoirs and environmental controls (Kumar *et al.*, 2024). Additionally, there are costs associated with setting up a controlled environment, such as temperature and humidity regulation, which are essential for optimal saffron growth. For small-scale or beginner growers, this initial financial burden can be prohibitive and may discourage entry into hydroponic saffron farming (Singh, 2023). These costs may take a longer time to recoup, making it less appealing compared to more traditional and less capital-intensive farming methods.

- **Technical Failures and Maintenance:** Hydroponics systems rely heavily on technology such as pumps, timers, environmental controls and nutrient delivery systems. Any malfunction can quickly harm the plants causing dehydration or nutrient deficiencies (Ragaveena *et al.,* 2021). These technical issues can result in crop loss or reduced yields if not addressed promptly. Additionally, regular maintenance is required to ensure all components function properly, which adds to the time, effort, and cost involved in running the system. For growers without technical expertise or the resources for consistent upkeep, these risks can be a significant challenge.
- **Learning Curve and Limited Expertise:** Hydroponic farming, especially for crops like saffron, requires specialized knowledge about the plant's growth cycle and the technical aspects of hydroponic systems (Kour *et al.*, 2022). There is a learning curve involved with new farmers and mistakes can result in poor crop performance. As a niche crop, saffron's unique growth requirements may not align well with the general hydroponic guidelines for other plants, creating challenges in developing a perfect system for saffron cultivation (Loman, 2018).
- **Water Quality and Risk of Waterborne Diseases:** Hydroponic systems are highly sensitive to the quality of the water used. Contaminants such as chlorine, minerals or pathogens, can negatively impact plant growth. If the water or nutrient solution becomes contaminated, it can spread infections quickly throughout the entire system, affecting multiple plants at once. This can be particularly challenging in large-scale operations (Saldinger *et al.*, 2023). Maintaining high water quality demands regular testing, filtration and potential adjustments to the water composition, which adds to operational costs and complexity.
- **Limited Research:** Lack of long-term research specifically on hydroponic saffron farming. Most studies and trials are still in the early stages, and the long-term effects of hydroponics on saffron plant health, yield, and quality remain uncertain (Cardone *et al.*, 2020). Growers may face unexpected challenges as they learn more about the crop's behavior in a soilless environment.

Conclusion

Hydroponics saffron cultivation presents a promising and innovative method for producing the high-value spice or the red gold of India by accelerating the level of active compounds determining the colour intensity, flavour and aroma strength of the spice. Controlled environmental parameters like adequate temperature, light intensity, CO_2 and relative humidity to regulate the smooth growth and development of saffron by avoiding any biotic or abiotic stresses, hydroponics farming for saffron cultivation has paved its path to the future. Effective growing media like cocopeat, clay pebbles, peat moss, coco coir, perlite, etc., offer good aeration and water retention capacity to the root zone of saffron coupled with the optimum nutrient media containing micronutrients and macronutrients regulated with appropriate pH and EC required for saffron have boosted the yield and quality of stigmas. The growing media and nutrient solution have shown promising results on the leaf weight, total photosynthesis rate, large-sized cormlets, corm weight, number of roots, shoots, leaves and flowers per corm, root length, leaf length, stigma length and dry and fresh stigmas weight, stigma yield, Chlorophyll a and Chlorophyll b content was observed to be doubled than the traditional field cultivation. Apart from the morphological and phytochemical characteristics of the saffron grown in a hydroponics system, other advantages like short crop cycle, efficiency in water and nutrient utilization, less land dependency, zero soil requirement, reduced production and labour costs, negative pest and disease infestation and adaptability to the adverse ecosystem, makes hydroponics saffron cultivation a boon for India's and global economy. However, some reversible drawbacks like higher initial investment costs, technical failures, limited research and lack of awareness can be modified to ease up the acclimatization of saffron cultivation in hydroponics systems. The long-term benefits of higher yields, sustainability and the growing demand for quality saffron make hydroponics a viable and future-forward method of cultivation. With advances in technology and growing demand for quality products, hydroponic saffron farming could revolutionize the saffron industry, making it more accessible and economically viable. As global interest in sustainable farming practices grows, hydroponics will likely play a pivotal role in the future of high-value crop cultivation.

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Authors Contributions

S.O.: Conceptualization, Data analysis and curation, Manuscript writing and editing. S.K.: Conceptualization, Formal Analysis, Validation. P.R.B.: Manuscript writing and editing. A.S.: Manuscript writing and editing. S.: Supervision and Validation. All the authors have reviewed the final version of the manuscript.

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