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## Innovative Climate-Resilient Protection Technologies for Saffron Under Controlled Conditions

\*Posham Raghu Ram<sup>1</sup>, Deshapaka Harshini<sup>2</sup> and Bolle Sowmya<sup>3</sup>

<sup>1</sup>M.Sc. (Sericulture), Kakatiya University, Warangal, Telangana, India

<sup>2</sup>M.Sc. (Food Science and Technology), Osmania University, Telangana, India

<sup>3</sup>M.Sc. (Floriculture and Landscape Architecture), SKLTGHU, Telangana, India

\*Corresponding Author's email: [poshamraghu968@gmail.com](mailto:poshamraghu968@gmail.com)

Saffron, scientifically named *Crocus sativus* L., is one of the most expensive spices in the world. It is prized for its red stigmas, which are used both as a flavouring and a natural dye. Saudi Arabia is a major importer of saffron, but the high cost of bringing in quality corms makes it economically unwise compared to the profits that could be made from local saffron farming. Additionally, the region's high temperatures and difficult growing conditions make it hard to grow saffron outdoors. To overcome these issues, we looked into growing saffron in greenhouses with cooling systems.



### Saffron has great economic and cultural importance

It is used widely in many cuisines around the world for its colour, flavour, and bioactive substances such as crocin, picrocrocin, and safranal. These compounds have health benefits, including antioxidant, anticancer, and antidepressant effects. In some cases, the health benefits of saffron are similar to those of fluoxetine. Saffron may help in treating conditions like neurodegenerative and respiratory diseases, including complications from SARS-CoV-2. In many cultures, especially in Persia, India, and the Mediterranean, saffron is a symbol of luxury and is deeply tied to tradition. However, climate change is a threat to saffron cultivation by affecting temperature and water availability.

### The three main bioactive compounds in saffron are

- **Crocin** is responsible for the yellow-orange colour and is part of the apocarotenoid family.
- **Picrocrocin** gives saffron its unique bitter taste.
- **Safranal** is a volatile compound that gives saffron its distinctive aroma.

Increasing the number of plants per square meter led to higher flower and stigma production per unit area, but it resulted in fewer flowers and lower stigma production per plant, along with less plant weight. Planting deeper (13 cm) led to a decrease in new corm production, especially at higher densities. The largest corms and the highest percentage of large corms were found at lower planting densities (67 corms per square meter), and planting depth had little effect on corm production. Given the high cost of quality corms, it is important to balance flower production with the plant's ability to reproduce. Based on our study, we recommend a moderate planting density of 100 corms per



square meter with a shallow planting depth of 8 cm. These conditions provide a balanced approach, optimizing both flower yield and corm production. Implementing these recommendations can improve the efficiency and sustainability of saffron cultivation in greenhouses with cooling systems, making it a viable option in areas with difficult growing conditions.

### Saffron Production Technology

Saffron is grown in both traditional open-field methods in places like Iran and Kashmir, and in modern protected cultivation methods using greenhouses or indoor systems, such as hydroponics and aeroponics, to increase yield and allow harvesting throughout the year.



### Protected Cultivation Density

Greenhouses generally use a higher planting density, ranging from 67 to 200 corms per square meter, with depths between 8 and 13 cm. Vertical stacking is also used to make the most of space. This density helps balance flower yield (up to 15–20 kg per hectare of stigmas) with corm quality. The best planting density for a balanced approach is 100 corms per square meter. Corms weighing 10–15 grams that have been pre-treated at temperatures between 23–27°C are recommended. Planting at densities below 50 per square meter results in larger corms (68–75% larger than 2 cm), which is suitable for long-term multiplication.

### Climatic Factors

Saffron can be grown in various geographic areas and is suitable for temperate, semi-arid, and arid climates. However, the yield of saffron depends heavily on the characteristics of the corms and environmental conditions. The critical stages of saffron growth—sprouting, flower initiation, and flowering—are affected by temperature and water availability.

- A maximum day temperature of 23–25°C in September is essential for corm sprouting.
- Flowering begins when the maximum day temperature drops below 17°C.
- Nighttime temperatures should be around 10°C.

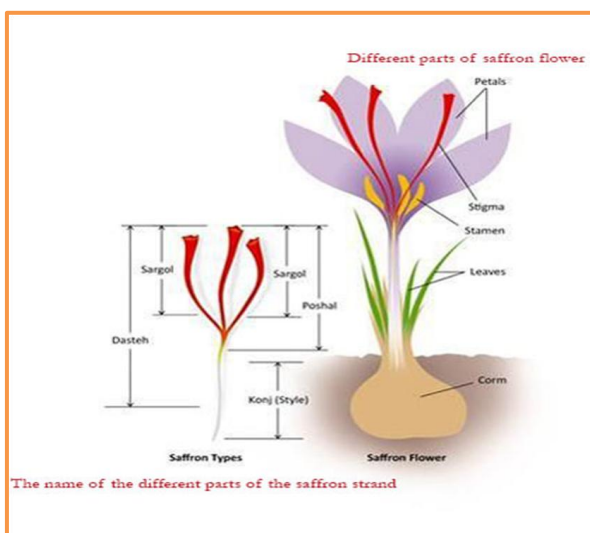
Controlled environments help maintain the ideal conditions for saffron growth, such as temperatures between 15–20°C, precise humidity levels (60–70%), and protection from pests through screens. Greenhouses with HVAC systems and sensors use 90% less water than open fields and allow for year-round harvesting, unlike open fields, which are vulnerable to temperatures exceeding 35°C. These controlled environments also offer opportunities for sustainable farming practices, including water recycling, energy-efficient technologies, and waste reduction strategies. Advancements in technology, such as advanced LED lighting and climate control chambers, are also being explored for use in controlled environments.

## Top High-Yield Varieties

**1. Super Negin (Iranian):** A premium grade from the Khorasan region. In protected cultivation, this variety yields up to 15–20 kg per hectare of stigmas. It has crocin levels greater than 260, ensuring a strong color, and dense planting can increase output by four times.

**2. Mongra (Kashmiri):** Pure stigmas from the Pampore Valley. Although it produces only 5–10 kg per hectare despite low overall production (2–3 tons per year), it is highly valued for its thick threads and crocin levels of 240–260. It thrives at planting densities of 50–75 corms per square meter.

**3. Negin (Iranian):** High-quality whole stigmas. It supports 10–15 kg per hectare in aeroponics. It also has strong daughter corm regeneration and performs well at planting densities of 67–100 corms per square meter.



## Nutrition and Irrigation

Provide pH 5.5–6.5 hydroponic solutions with elevated K, N:P:K ratios through misters or drips in aeroponics, recycling 90% of the water without the risk of soil pathogens. Supplement with foliar applications of zinc and iron to gain a 20–30% increase in yield. Monitor EC levels to avoid salt buildup in rockwool or perlite media.



## Pruning and Maintenance

Remove faded flowers after harvesting to direct energy toward corm development. Thin overcrowded layers in vertical racks every 3–4 years during July lifting and division. Sterile setups eliminate the need for weeding; integrated pest management (IPM) uses biological agents and ventilation instead of chemical treatments.

## Problem to be Faced during Cultivation

Producing saffron in a controlled environment presents high initial setup costs and technical challenges, but it allows for year-round yields up to 15–20 kg per hectare of stigmas through greenhouses.

## Precise Climate Control

Maintaining specific temperatures for different growth stages—below 13°C for dormancy, 14–18°C for flowering—requires constant use of air conditioning and humidifiers (45–60%

relative humidity). Any failure in maintaining these conditions can lead to low sprouting or fungal outbreaks in enclosed spaces. In hot climates, temperature reductions may exceed 15°C, which increases energy usage.

### Skilled Management Needs

Automation demands expertise in monitoring and IPM; deviations in airflow or light spectra lower crocin content and market value. Labor shifts from fields to tech maintenance without full mechanization of harvesting.



### Timing and Flower Selection

Harvest early morning after dew dries but before full bloom, typically over 2–3 weeks in autumn when flowers emerge. Pick only fully open, undamaged purple flowers at the base with fingers or scissors to avoid bruising stigmas. In greenhouses, daily checks ensure peak flavor and aroma capture.

### Yield

In protected cultivation like greenhouses, this labour-intensive process aligns with controlled conditions to maximize yields of 5–15 kg/ha stigmas.

### Extraction Process

Gently pluck the intact red stigmas (threads) from each flower by hand, discarding petals and styles. Use clean hands or tools; process immediately in batches to maintain purity. For scale, separate via gentle threshing or automation in commercial setups.

### Drying and Storage

Spread stigmas thinly on breathable trays or cloth out of direct sun at 20–40°C for 2–5 days until brittle and curled. Store in airtight, dark glass jars in cool, dry conditions to retain color, aroma, and crocin content for 2+ years. Yields improve 4x in controlled environments with proper post-harvest handling.



## Conclusion

Protected saffron cultivation revolutionizes traditional farming by enabling consistent high yields (up to 15–20 kg/ha stigmas), year-round production, and resilience against climate variability through precise control of temperature (14–25°C), humidity (45–60% RH), and soilless systems like aeroponics. While high setup costs (₹4–10 lakh for small units) and technical demands pose barriers, benefits like 90% water savings, sterile disease-free growth, and 4x output over open fields make it viable for regions like India and Iran.

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