Innovative Approaches for Saffron (*Crocus sativus* L.) Cultivation in Hot Regions: A Secondary Review of Hyperspectral Imaging and In Vitro Propagation Technologies

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Abstract

Saffron (*Crocus sativus* L.), one of the worldś most expensive spices, faces declining yields in traditional cool-temperate regions due to climate change and environmental stress (Cardone et al., 2020; Menia et al., 2018). This paper synthesizes recent research to evaluate hyperspectral imaging and Temporary Immersion System (TIS)-based in vitro propagation as solutions for extending cultivation into hot climates like Bangladesh. Hyperspectral imaging (650–1000 nm) enables non-destructive starch quantification ($R^2 = 0.932$), while TIS bioreactors combined with machine learning (ML) enhance microcorm

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yields by up to 10×compared to conventional methods (Tarraf et al., 2024; Berthouly and Etienne, 2005). We propose an integrated model combining these technologies for climate-resilient saffron farming, addressing barriers such as high humidity (¿80%) and thermal stress (¿ 30/degree C).

1 Introduction

Saffron, derived from the stigmas of *Crocus sativus* L., is a high-value spice with rich medicinal, cosmetic, and culinary applications (Cardone et al., 2020; Yildirim et al., 2020). Traditional cultivation thrives in regions like Iran, Kashmir, and Mediterranean countries, characterized by cool, semi-arid climates (Menia et al., 2018). Climate change, global warming, and environmental degradation have jeopardized yields and quality (Sharma et al., 2008). Consequently, extending cultivation into subtropical regions like Bangladesh—despite its heat and humidity challenges—has gained attention (Renau-Morata et al., 2013). Innovations such as hyperspectral imaging for starch profiling and TIS-based propagation offer new pathways for saffron cultivation in non-traditional zones.

2 Climatic Barriers and Saffron Physiology

2.1 Heat and Humidity Stress

Temperatures exceeding 30 degree C disrupt saffronś vernalization, diminishing flowering rates by 40–60% (Sharma et al., 2008). High humidity (¿80%) increases fungal infection risks, causing 20–50% corm losses (Menia et al., 2018). Low-temperature corm storage strategies can mitigate contamination risks (Renau-Morata et al., 2013).

2.2 Photoperiod Disruption

Monsoon-induced cloud cover reduces sunlight hours critical for stigma biomass, impacting crocin and safranal biosynthesis (Yang et al., 2015).

3 Hyperspectral Imaging for Corm Screening

3.1 Technical Synopsis

Natsuhara et al. (2020) developed a hyperspectral imaging system (650–1000 nm) enabling non-destructive starch quantification with high predictive accuracy ($R^2 = 0.932$, SEP = 1.54%). Key absorption bands were 720 nm (starch) and 850 nm (moisture) (Pescio et al., 2016).

3.2 Bangladesh Adaptation

Affordable versions using portable spectrometers can cut costs by up to 70% compared to laboratory setups (Taheri-Dehkordi et al., 2020). Random Forest algorithms further enhance prediction accuracy under variable tropical field conditions (Lozano-Milo et al., 2022).

Table 1: Hyperspectral starch prediction vs. traditional weight method (based on Natsuhara et al., 2020)

Method	R^2	RMSE
Hyperspectral	0.932	1.54
Corm weight	0.65	3.2

4 TIS Bioreactors with ML Optimization

4.1 Study Findings

Temporary Immersion Systems (TIS) revolutionized saffron micropropagation (Berthouly and Etienne, 2005). Tarraf et al. (2024) reported that TIS produced 107.5 microcorms per cycle, compared to only 9.8 in semisolid media. Machine learning models like Gaussian Process Regression (GP) outperformed others with $R^2 = 0.91$ in predicting shoot development.

Table 2: Microcorm yield in TIS vs. semisolid culture (Tarraf et al., 2024; Lagram et al., 2016)

System	Microcorms/Cycle	RGR
TIS	107.5	1.27
Semisolid	9.8	0.87

4.2 Scalability in Bangladesh

Energy-efficient TIS designs using solar panels could make this technology viable for resource-limited regions (De Carlo et al., 2021). Institutions like BARI and BAU could adapt ML-driven protocols to select superior genotypes for tropical conditions (Businge et al., 2017).

5 Integrated Cultivation Pipeline

1. **Corm Screening**: Hyperspectral starch profiling for greater then 12% starch content.
2. **Propagation**: Mass multiplication via TIS bioreactors.
3. **Acclimatization**: Gradual transfer to shaded polyhouses.
4. **Field Monitoring**: IoT sensors + ML for real-time stress detection.

6 Discussion

While initial capital investment for hyperspectral and TIS systems may be high, return on investment can be achieved within 3–5 years, especially with development support (FAO models; Pérez-Alonso et al., 2007). Key constraints include genotype specificity (Renau-Morata et al., 2013) and the need for technical training (Sevindik and Mendi, 2016).

7 Conclusion

This secondary review validates that integrating hyperspectral imaging and TIS-based micropropagation offers a feasible path to climate-resilient saffron cultivation in Bangladesh and similar regions.

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