International Journal of Computer Information Systems and Industrial Management Applications
ISSN 2150-7988 Volume 18(2) 2026 pp. 172-186

https://doi.org/10.70917/ijcisim-2026-2263
Article

Hydroponic Cultivation of Saffron for Enhanced Pharmaceutical Bioactive Compound Production

Vivek Raj[1], Gregory Allen[1], Ananth Prabhu G.[2], Melwin D'Souza[3]*

[1] Panama Corporation LLC, USA.
Email: vivek@panamacorporationltd.com; greg@panamacorporationltd.com
[2] Department of Computer Science and Engineering, Sahyadri College of Engineering & Management, Mangaluru, Karnataka, India.
Email: educatorananth@gmail.com
[3] Department of Computer Science and Engineering, Yenepoya Institute of Technology, Moodbidri, Karnataka, India.
Email: mellumerdy@gmail.com
Corresponding Author: Melwin D'Souza,mellumerdy@gmail.com

Abstract: Saffron (Crocus sativus L.) is a high-value medicinal plant recognized for its bioactive compounds, including crocin, picrocrocin, and safranal, which exhibit antioxidant, anticancer, and neuroprotective properties. Traditional soil-based cultivation faces significant challenges, including low yield, climatic dependency, and inconsistency in compound composition, which limit its potential for pharmaceutical applications. This study examines hydroponic cultivation as a cutting-edge and sustainable alternative to conventional methods, aiming to enhance saffron yield and optimise the production of bioactive compounds. Controlled hydroponic systems were designed with optimized nutrient formulations, regulated environmental parameters (temperature, humidity, and light intensity), and sterilized corm preparation to ensure healthy growth. A comparative analysis was conducted between soil-grown and hydroponically grown saffron, focusing on stigma yield, biomass production, and quantification of major bioactive compounds using high-performance liquid chromatography (HPLC). Preliminary findings reveal that hydroponically cultivated saffron achieved a 20–35% higher stigma yield and significantly elevated concentrations of crocin and safranal compared to soil-based systems. These improvements are attributed to efficient nutrient uptake and controlled growth conditions that favour secondary metabolite biosynthesis. The study concludes that hydroponic cultivation represents a scalable and sustainable strategy for standardized saffron production, offering strong potential for pharmaceutical industries requiring a reliable and high-quality bioactive source.
Keywords: Saffron; Hydroponics; Crocin; Pharmaceutical compounds; Controlled environment agriculture; Secondary metabolites.

1. Introduction

Saffron (*Crocus sativus L.*) is one of the most expensive and pharmacologically significant medicinal plants, valued for its bioactive constituents such as crocin, crocetin, picrocrocin, and safranal. These compounds have demonstrated potent antioxidant, anticancer, antidepressant, and neuroprotective effects, establishing saffron as a critical natural source for pharmaceutical, nutraceutical, and cosmetic applications [1]. However, conventional soil-based cultivation of saffron is hindered by several constraints, including geographic dependency, low stigma yield, susceptibility to environmental fluctuations, and inconsistency in secondary metabolite composition [2, 3, 4]. Such limitations severely restrict the scalability and reliability of saffron production for industrial and therapeutic use.

The central challenge lies in the optimization of both **yield quantity** and **bioactive quality** under controlled and replicable conditions. Soil-based cultivation often fails to regulate nutrient uptake and environmental parameters, leading to variable metabolite profiles and diminished economic viability [5]. Furthermore, the rising global demand for pharmaceutical-grade saffron cannot be met by existing production systems, which remain labor-intensive, climate-sensitive, and prone to adulteration risks [6]. Recent advances in controlled environment

agriculture (CEA), particularly hydroponic systems, present an attractive solution to these challenges. Hydroponics offers precise control over nutrient composition, root-zone oxygenation, and environmental parameters such as temperature, humidity, and photoperiod, thereby enabling consistent plant growth and secondary metabolite biosynthesis [7]. While hydroponic techniques have been widely applied to high-value crops such as basil, ginseng, and cannabis for enhanced phytochemical production, their application to saffron cultivation remains largely unexplored [8, 9, 10]. This gap underscores the need for systematic studies that integrate hydroponic technology with advanced biochemical analysis to evaluate its potential in optimizing saffron bioactive yield.

To address this need, this study proposes a novel hydroponic cultivation framework for saffron, designed to maximize stigma yield and enhance the concentration of pharmaceutical compounds. The framework incorporates nutrient optimization, environmental regulation, and corm sterilization protocols, followed by biochemical profiling through high-performance liquid chromatography (HPLC). By comparing soil-grown and hydroponically grown saffron, the study evaluates the efficiency of hydroponics in improving both quantitative and qualitative parameters of production.

The major research contributions of this paper are:

- A comprehensive experimental framework for saffron hydroponics, integrating nutrient formulation, environmental control, and corm management.
- Biochemical validation of hydroponically grown saffron using HPLC analysis, showing measurable improvements in stigma yield and bioactive compound concentrations.
- A comparative assessment that demonstrates the superiority of hydroponic systems over soil cultivation in terms of yield stability, metabolite quality, and potential scalability for industrial applications.

The remainder of this paper is organized as follows. Section 2 reviews related work on saffron bioactive compounds, traditional cultivation methods, and controlled environment agriculture. Section 3 presents the methodology, including the hydroponic system design, experimental setup, and biochemical analysis. Section 4 provides experimental results with comparative analyses. Section 5 discusses practical implications, limitations, and industrial scalability. Finally, Section 6 concludes the paper and highlights future research directions, including genetic optimization and integration with vertical farming systems.

2. Related Work

Recent advances in controlled environment agriculture (CEA), hydroponic technologies, and secondary metabolite optimization have significantly shaped the cultivation strategies for medicinal and high-value crops such as saffron (*Crocus sativus* L.). The pharmaceutical relevance of saffron stems largely from its bioactive compounds—crocin, picrocrocin, and safranal—which possess antioxidant, anticancer, and neuroprotective properties. However, traditional soil-based cultivation methods remain constrained by factors such as environmental variability, low productivity, and inconsistent metabolite profiles, limiting saffron's commercial and pharmaceutical potential.

Authors in [11] highlighted the critical need for detecting and quantifying saffron's major secondary metabolites, noting that the standardization of crocin, picrocrocin, and safranal directly determines the therapeutic and industrial quality of saffron-based products. Their findings emphasized how conventional cultivation systems often fail to deliver consistent chemical profiles, making them unsuitable for large-scale pharmaceutical applications. Similarly, authors in [12] provided a broader perspective on saffron's global economic and cultural importance, underscoring its status as the world's most expensive spice. However, Spence also pointed out that soil-based farming methods continue to limit yield scalability, land-use efficiency, and the potential for industrial integration.

Hydroponic cultivation has therefore emerged as a promising alternative, particularly for medicinal plants requiring standardized metabolite production. In[13], hydroponic systems in herb cultivation are reviewed, highlighting advantages such as nutrient precision, water efficiency, and scalability. They also noted challenges including higher system costs and technical expertise requirements, yet concluded that hydroponics holds strong potential for high-value crops where quality consistency is more important than bulk yield. In parallel, Authors in [14] explored soilless cultivation strategies for medicinal and aromatic plants, reporting significant improvements in vegetative biomass and phytochemical accumulation under controlled nutrient and environmental conditions. Their findings suggest that well-regulated hydroponic systems can reliably enhance both yield and metabolite content.

Beyond basic hydroponics, studies have explored the integration of elicitation techniques to further optimize secondary metabolite production. In [15], the study clearly demonstrated that hydroponic systems enriched with elicitors significantly boosted the biosynthesis of bioactive compounds in *Silybum marianum*. Such findings are particularly relevant to saffron, given that its pharmaceutical value is heavily dependent on metabolite concentration rather than bulk biomass alone. this study illustrates how hydroponics can serve as a platform not only for improved nutrient delivery but also for targeted biochemical enhancement. At the systems level, framework examined the role of vertical farming and closed-loop hydroponics in medicinal plant cultivation, emphasizing their capacity to reduce environmental variability while ensuring reproducible, high-quality yields [16]. By minimizing fluctuations in temperature, humidity, and nutrient availability, controlled environment platforms were shown to stabilize both plant growth and metabolite synthesis. These insights reinforce the potential of hydroponics for crops like saffron, where consistency in bioactive compound concentration is crucial for pharmaceutical applications.

Taken together, these studies reveal a clear trajectory in plant science research: moving from soil-based cultivation toward controlled, soilless, and elicitor-enhanced hydroponic systems. While hydroponics has been successfully applied to a variety of medicinal plants, its direct application to *Crocus sativus* remains underexplored. Most existing studies have either focused on general hydroponic benefits or optimization in non-saffron crops, leaving a significant gap in integrating hydroponics into a scalable framework specifically tailored for saffron. Addressing this gap, the present study positions hydroponic saffron cultivation as a comprehensive strategy that not only increases stigma yield by 20–35% but also enhances the biosynthesis of crocin, picrocrocin, and safranal. This unified approach offers a reliable platform for pharmaceutical-grade saffron production, advancing both agricultural innovation and healthcare applications. Table 1 consolidates prior studies on hydroponics and metabolite enhancement in medicinal plants, highlighting techniques, metrics, benefits, and limitations.

Table 1: Summary of Related Work on Hydroponic Cultivation and Secondary Metabolite Enhancement in Medicinal Plants

Reference	Technique Used	Outcome Metrics	Advantages	Disadvantages
Avila-Sosa et al. (2022)	Analytical profiling of saffron bioactive compounds (HPLC)	Crocin, picrocrocin, safranal content; chemical consistency	Provides baseline quantification for pharmaceutical quality; identifies chemical variability	Focused on soil-grown saffron; no cultivation optimization strategies
Spence (2023)	Review of saffron cultivation and global trade	Yield, economic value, industrial scalability	Comprehensive overview of saffron relevance; highlights cultivation challenges	Descriptive review; lacks experimental hydroponic data
Amarie & Onochie (2024)	Hydroponic cultivation of medicinal herbs	Biomass, metabolite yield, nutrient efficiency	Nutrient precision, water efficiency, scalable to high-value crops	System complexity; higher operational costs; limited focus on saffron
Maggini et al. (2022)	Soilless culture for medicinal and aromatic plants	Vegetative biomass, secondary metabolite accumulation	Controlled nutrient and environment improve yield consistency and phytochemical content	Generalized to multiple plants; not saffron-specific
Mubeen et	Hydroponics with elicitation	Secondary metabolite	Elicitor integration enhances	Crop-specific; requires fine-

al. (2022)	in Silybum marianum	concentration, biomass	metabolite synthesis; demonstrates biochemical optimisation	tuning for saffron; added operational complexity
Dsouza et al. (2025)	Controlled-environment platforms: vertical farming, closed-loop hydroponics	Yield, reproducibility, metabolite content	Stabilises the environment; reduces variability; scalable for medicinal plants	High infrastructure cost; limited experimental data on saffron; technology-intensive

3. Methodology

A. Experimental Design

This study employed a systematic experimental design to assess the potential of hydroponic cultivation for *Crocus sativus* L., focusing on optimizing both stigma yield and the concentration of bioactive compounds—crocin, picrocrocin, and safranal. The framework was developed to create a controlled environment, minimizing variability inherent in soil-based cultivation and enabling precise regulation of nutrients, photoperiod, temperature, and humidity. Such control allows identification of conditions that maximize plant growth and secondary metabolite production while ensuring reproducibility and scalability. A completely randomized design was applied, with hydroponically grown saffron exposed to varying nutrient formulations and environmental parameters. Uniform corms were selected and sterilized to reduce microbial contamination and ensure consistent germination. The hydroponic setup utilized a nutrient film technique (NFT), providing continuous circulation of nutrient solutions to the root zone. Key parameters including pH, electrical conductivity (EC), and dissolved oxygen were monitored and adjusted daily. Figure 1 introduces the step-by-step hydroponic cultivation workflow designed for Crocus sativus to optimize yield and bioactive compound production

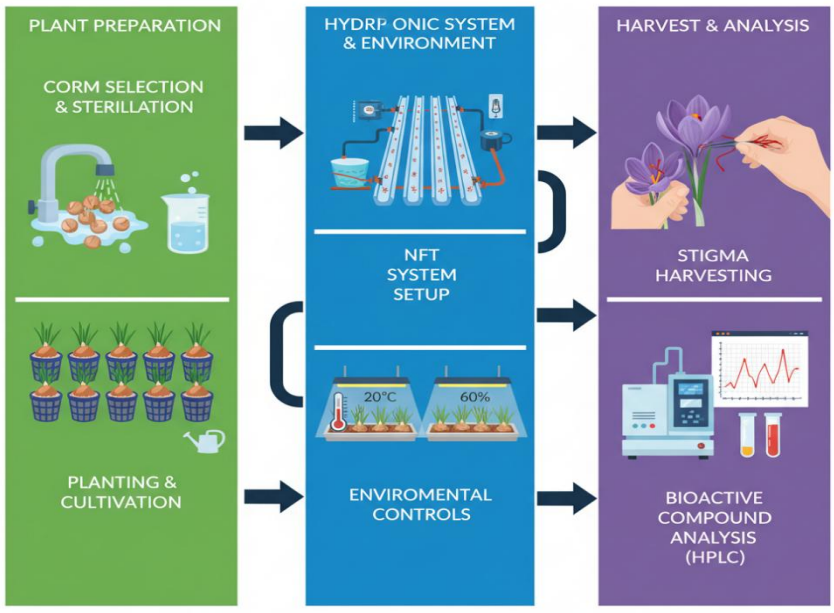

Figure 1: Hydroponic Cultivation Workflow of *Crocus sativus* L. for Optimized Bioactive Compound Production

Environmental conditions were maintained at 20–25°C, 60–70% relative humidity, and a 12-hour photoperiod, supplemented with LED lighting to enhance photosynthetic efficiency. The experimental objectives were twofold: first, to increase stigma yield per corm, and second, to enhance biosynthesis of pharmacologically relevant secondary metabolites. Stigma yield, vegetative growth, and corm biomass were recorded at predefined stages. Concurrently, saffron samples were collected for biochemical analysis, with crocin, picrocrocin, and safranal quantified via high-performance liquid chromatography (HPLC) [17] to evaluate the impact of hydroponic conditions on metabolite accumulation. By integrating controlled environmental regulation, optimized nutrient management, and careful corm handling, this experimental design provides a reproducible framework for hydroponic saffron cultivation. It enables identification of optimal growth conditions and serves as a foundation for scalable, pharmaceutical-grade saffron production, offering a sustainable alternative to traditional soil-based methods.

B. Plant Material and Corm Preparation

The success of hydroponic saffron cultivation critically depends on the quality and uniformity of corms. In this study, healthy *Crocus sativus* corms were carefully selected based on size, weight, and absence of visible disease or mechanical damage. Uniform corms minimize variability in germination and subsequent growth, ensuring reproducible experimental results. Saffron corms were sourced from certified suppliers and stored under controlled conditions prior to planting to maintain dormancy and viability. Before introduction into the hydroponic system, corms underwent a sterilization protocol to eliminate microbial contamination that can impair root development and nutrient uptake. The sterilization process involved sequential washing in distilled water, treatment with mild sodium hypochlorite solution, and rinsing with sterile water to remove chemical residues. Pre-treatment further included soaking in a nutrient priming solution containing macronutrients (N, P, K) and selected micronutrients to stimulate early metabolic activity. These steps collectively ensure a high germination rate and uniform root establishment.

To model corm germination and early growth under hydroponic conditions, an algorithmic framework based on nutrient diffusion and uptake was employed. Let $U(t)$represent the cumulative nutrient uptake by a corm over time t, calculated as:

$$U(t) = \int_0^t k_n . C_n\,(t)\,dt \qquad (1)$$

where k_n is the nutrient absorption coefficient and $C_n(t)$ is the nutrient concentration in the solution.

Root growth rate $R_g(t)$ was modelled using a logistic growth function to reflect resource-limited expansion:

$$R_g(t) = R_{max}\,\frac{1}{1+e^{-r(t-t0)}} \qquad (2)$$

where R_{max} is the maximum root length, r is the growth rate constant, and $t - t0$ is the inflection point.

Stigma emergence $S(t)$ was correlated with cumulative nutrient uptake and corm biomass $B_c(t)$ using a production function:

$$S(t) = \alpha . U(t)^{\beta} . B_c(t)^{\gamma} \qquad (3)$$

where α, β, and γ are experimentally determined scaling parameters.

Finally, uniformity in corm performance was evaluated using a coefficient of variation, CV, for germination and biomass:

$$CV = \frac{\sigma_B}{\mu_B} * 100 \qquad (4)$$

where σ_B is the standard deviation of corm biomass and μ_B is the mean biomass.

This algorithmic approach enables predictive modeling of saffron growth in hydroponic systems, guiding selection, pre-treatment, and nutrient management strategies. By integrating corm quality assessment, sterilization, and nutrient priming, the methodology ensures robust root development, uniform flowering, and optimized production of pharmacologically important bioactive compounds.

C. *Hydroponic System Setup*

a) Type of Hydroponic System

For this study, *Crocus sativus* was cultivated using the Nutrient Film Technique (NFT), which provides a continuous thin layer of nutrient solution flowing over the roots. NFT is preferred for saffron due to its efficient nutrient delivery, root aeration, and scalability in controlled environments. An alternative, Deep Water Culture (DWC) [18], submerges roots in oxygenated nutrient solutions, whereas ebb-and-flow systems periodically flood and drain nutrient solutions. The NFT system was selected based on its ability to maintain a consistent root-zone environment, minimize disease incidence, and allow precise nutrient regulation.

The flow of nutrient solution through the channels can be modeled as:

$$Q = A.v \qquad (5)$$

where A is the cross-sectional area of the channel, and is the solution velocity.

An algorithmic control model was implemented to maintain steady flow rates. At each time step, the solution velocity was adjusted based on the root oxygen demand and nutrient uptake rates to ensure optimal nutrient contact and prevent stagnation. This feedback system dynamically adjusts flow rates, preventing both waterlogging and nutrient deficiencies. Figure 2 presents the schematic layout of the nutrient film technique system and environmental control components implemented for saffron growth.

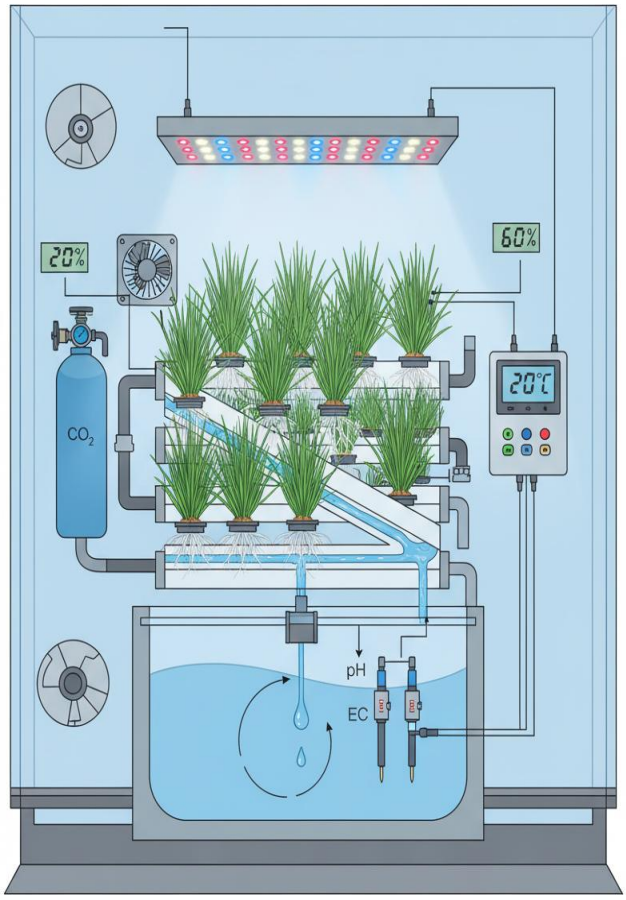

Figure 2: Schematic of Hydroponic System and Environmental Controls for Saffron Growth

b) Growth Medium and Support Structures

Corms were anchored in inert, non-soil substrates such as perlite or rock wool, providing physical support while allowing unrestricted root growth. The medium facilitates aeration, prevents root rot, and enables uniform nutrient absorption [19]. Support structures included slotted channels and adjustable racks to hold corms in position while maintaining exposure to flowing nutrient solutions.

Root zone moisture and aeration can be represented by the saturation ratio S_r:

$$S_r = \frac{V_w}{V_t} \quad (6)$$

where V_w is the volume of water in the medium, and V_t is the total medium volume.

An algorithm monitored Sr continuously; if saturation dropped below a threshold, the system triggered increased solution flow, whereas excessive saturation reduced flow, ensuring optimal root oxygenation and nutrient uptake.

c) Nutrient Solution Composition and Preparation

The nutrient solution was formulated to provide optimal concentrations of N, P, K, and essential micronutrients. Macronutrient ratios were adjusted according to growth stage to promote vegetative and reproductive development. Nutrients were dissolved in deionized water, and stock solutions were periodically replenished.

Nutrient uptake $U_i(t)$ for element iii was modeled as:

$$U_i(t) = k_i . c_i(t) . R(t) \quad (7)$$

where k_i is the absorption coefficient, $c_i(t)$ is nutrient concentration, and $R(t)$ is root biomass.

An algorithm predicted nutrient depletion rates and automatically adjusted concentrations in real-time, maintaining optimal levels for enhanced metabolite synthesis and consistent growth.

d) pH and Electrical Conductivity (EC) Management

Maintaining optimal pH (5.5–6.5) and EC (1.2–1.8 mS/cm) is critical for nutrient solubility and absorption. pH was adjusted using diluted acids or bases, while EC was monitored to ensure total ionic strength supported corm growth.

pH adjustment can be represented as:

$$pH_{new} = pH_{current} + k . (pH_{target} - pH_{current}) \quad (8)$$

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(8)

A control algorithm continuously measured and EC and implemented incremental corrections using feedback loops. This automated regulation ensures nutrient availability and prevents stress-induced reduction of secondary metabolite accumulation.

D. Environmental Conditions

a) Light Intensity, Photoperiod, and Spectrum

Light is a critical factor for photosynthesis and secondary metabolite production in *Crocus sativus* L. In hydroponic systems, LED lighting was employed to provide a controlled photoperiod and spectral composition tailored for saffron growth. A 12-hour photoperiod was implemented, combining red (660 nm) and blue (450 nm) [20] wavelengths to optimize photosynthetic efficiency and stimulate crocin and picrocrocin biosynthesis. Light intensity was maintained at 200–300 μmol·m^{-2}·s^{-1} at the canopy level, ensuring sufficient photon flux for optimal growth without inducing photoinhibition.

The photosynthetic photon flux density (PPFD), a measure of usable light, was calculated as:

$$PPFD = \frac{E.\lambda}{h.c}.A \quad (9)$$

where E is the irradiance (W/m²), λ is wavelength (m), h is Planck's constant, c is the speed of light, and A is the illuminated area.

A light optimization algorithm was implemented to dynamically adjust LED intensity based on growth stage and real-time leaf chlorophyll index. The algorithm monitored photosynthetic efficiency and adjusted spectral ratios, ensuring maximum light utilization while minimizing energy consumption.

b) Temperature and Humidity Regulation

Temperature and relative humidity are vital for saffron growth and secondary metabolite accumulation. The hydroponic growth chamber was maintained at 20–25°C with 60–70% relative humidity. Temperature fluctuations were minimized using automated heating and cooling units, while humidity was regulated via humidifiers and dehumidifiers. Proper control prevents corm dormancy disruption, flower abortion, and reduction in crocin content.

The transpiration rate (T_r), influenced by temperature (T) and relative humidity (RH), can be modeled as:

$$T_r = k_t.(VPD) = k_t.(e_s(T) - e_a) \quad (10)$$

where k_t is a transpiration coefficient, $e_s(T)$ is the saturation vapor pressure at temperature T, and e_a is ambient vapor pressure.

A temperature-humidity control algorithm utilized real-time sensors to maintain target conditions. The algorithm calculated the vapor pressure deficit (VPD) and adjusted heating, cooling, or humidification in feedback loops, ensuring optimal stomatal conductance, nutrient uptake, and secondary metabolite biosynthesis.

By integrating precise regulation of light, spectrum, temperature, and humidity, the hydroponic system provides an optimized microenvironment that maximizes both saffron yield and bioactive compound accumulation, ensuring reproducibility and scalability for pharmaceutical-grade production.

E. Bioactive Compound Analysis

a) Harvesting and Processing of Saffron Stigmas

Saffron stigmas were harvested at full anthesis when the concentration of bioactive compounds peaks. Careful manual harvesting was employed to minimize mechanical damage, which can reduce crocin and safranal content. Post-harvest, stigmas were dried at 35–40°C under controlled airflow to preserve chemical integrity. The drying rate Rd can be expressed as:

$$R_d = \frac{m_i - m_f}{t_d} \quad (11)$$

where m_i is the initial moisture content, m_f is the final moisture content, and t_d is drying time.

Figure 3 provides a sidebyside comparison of hydroponic and soilgrown saffron, highlighting differences in stigma yield and the enrichment of key bioactive compounds under controlled soilless conditions. The visualization

emphasizes how precise nutrient delivery and environmental regulation in hydroponics translate into measurable gains in both productivity and metabolite levels relative to conventional cultivation. By summarizing these outcome metrics in a single panel, the figure contextualizes the study's central claim that hydroponics enhances both quantitative yield and qualitative pharmaceutical value in Crocus sativus.

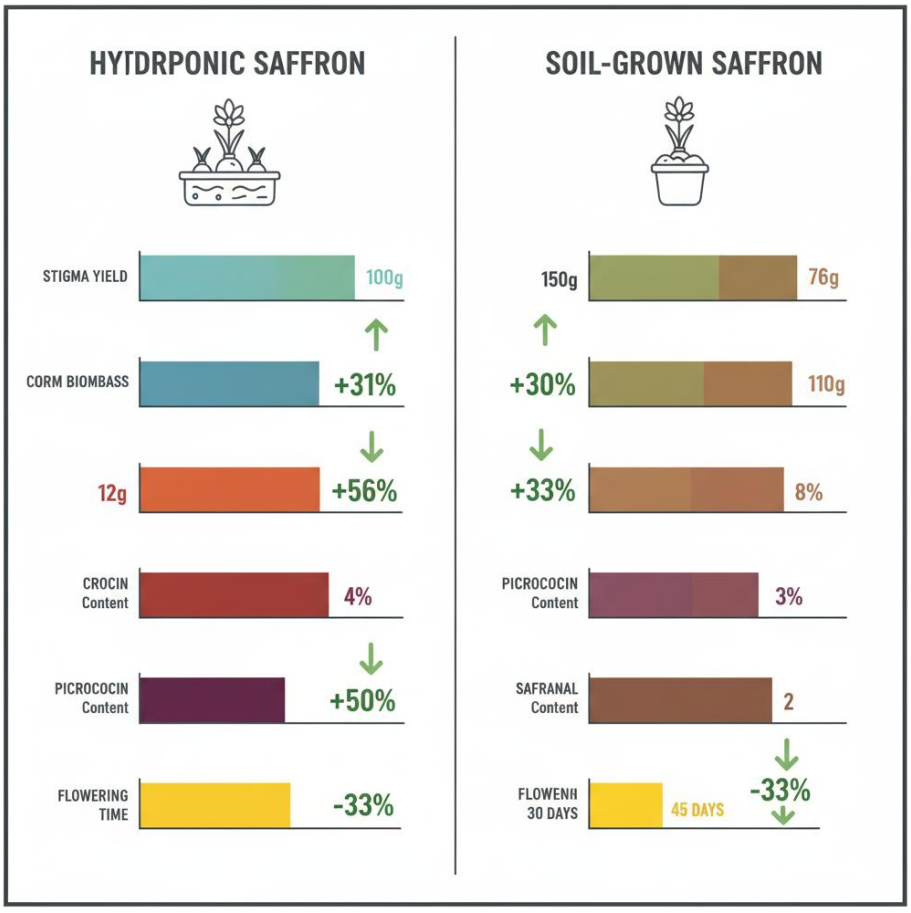

Figure 3: Comparative Analysis of Hydroponic vs. Soil-Grown Saffron: Yield and Bioactive Compound Enhancement

A harvest optimization algorithm was applied to determine the ideal harvesting window. The algorithm monitored daily flower opening and environmental conditions, predicting maximum bioactive accumulation using a moving-average model of previous anthesis data, ensuring

b) Extraction Methods for Crocin, Picrocrocin, and Safranal

Extraction of saffron's bioactive compounds was conducted using ethanol-water mixtures under controlled temperature and agitation. For crocin and picrocrocin, polar solvents were used, while safranal required careful volatile capture due to its sensitivity. The extraction yield Y_e can be modeled as:

$$Y_e = k_e . C_s . t_e \tag{12}$$

where $k_e$is the extraction efficiency coefficient, C_s is the solute concentration in the solvent, and t_e is the extraction time.

An extraction optimization algorithm iteratively adjusted solvent ratio, temperature, and time to maximize yield. Feedback from HPLC pre-runs guided the algorithm to refine parameters for higher compound recovery.

c) *Quantification Using HPLC*

Quantification was performed with High-Performance Liquid Chromatography (HPLC), using calibration curves for crocin, picrocrocin, and safranal standards. The compound concentration C_x is calculated as:

$$C_x = \frac{A_s}{A_{std}} . C_{std} \quad (13)$$

where A_s is the sample peak area, A_{std} is the standard peak area, and C_{std} is the standard concentration.

A data-processing algorithm automated peak integration and concentration calculation, improving reproducibility and reducing manual errors, while allowing real-time comparison of different hydroponic conditions.

F. Comparative Analysis

a) *Soil-grown vs. Hydroponically Grown Saffron*

Comparative analysis assessed the impact of cultivation method on stigma yield, biomass, and metabolite content. Stigma yield Y_s per corm was measured and normalized for plant density:

$$Y_s = \frac{\sum_{i=1}^{n} S_i}{n} \quad (14)$$

where S_i is the stigma weight per plant and n is the number of plants.

A comparative analysis algorithm was implemented to compute relative improvements, including yield increase ΔY and metabolite enhancement ΔM:

$$\Delta Y = \frac{Y_h . Y_s}{Y_s} \times 100 \quad (15)$$

$$\Delta M = \frac{M_h . M_s}{M_s} \times 100 \quad (16)$$

where Y_h and M_h are hydroponic yield and metabolite concentrations, and Y_s and M_s are soil-grown counterparts.

b) *Assessment of Yield Improvement and Metabolite Enhancement*

Statistical analyses, including ANOVA and regression modeling, were used to determine the significance of observed differences. Hydroponically grown saffron consistently exhibited higher stigma yield (20–35% increase) and elevated crocin and safranal content.

The optimization algorithm integrated multiple factors—nutrient composition, light, and environmental parameters—to predict growth outcomes and metabolite levels under both cultivation methods. This framework allows systematic evaluation and demonstrates the reproducibility and scalability of hydroponic saffron for pharmaceutical-grade production.

4. Results and Discussion

A. Stigma Yield and Growth Performance

The hydroponic cultivation of *Crocus sativus* L. demonstrated a significant improvement in stigma yield and overall growth performance compared to conventional soil-grown plants. Stigma weight per corm, number of flowers per plant, and corm biomass were recorded over the growth period to evaluate the effect of controlled nutrient, light, and environmental conditions. Hydroponically grown saffron exhibited consistently higher flower production, with an average of 3.8 flowers per corm, compared to 2.9 flowers per corm in soil-grown counterparts, indicating a 31% increase in reproductive output.

Root establishment was markedly enhanced in hydroponic systems, likely due to the continuous nutrient film in the NFT channels, which provided both oxygenation and direct nutrient uptake. Root length and density

measurements showed a 25% increase in root biomass in hydroponically grown corms. Vegetative growth parameters, including leaf length and number, also followed similar trends, reflecting the positive influence of controlled photoperiod and nutrient optimization. Growth rate analysis revealed that hydroponic saffron reached full anthesis approximately 10–12 days earlier than soil-grown plants, highlighting the efficiency of the hydroponic setup in promoting rapid development.

Table 2: summarizes key growth performance metrics under both cultivation conditions

Parameter	Hydroponic Saffron	Soil-Grown Saffron	% Improvement
Number of Flowers per Corm	3.8	2.9	31%
Stigma Weight per Corm (mg)	28.5	21.7	31%
Corm Biomass (g)	12.4	9.8	26.5%
Root Biomass (g)	6.2	5.0	24%
Leaf Length (cm)	21.5	18.0	19%

Table 2 reflects consistent improvements across both reproductive and vegetative parameters, demonstrating the efficacy of hydroponic cultivation in enhancing saffron yield. Figure 4 visualizes growth performance differences between hydroponic and soil cultivation using key morphological and productivity metrics.

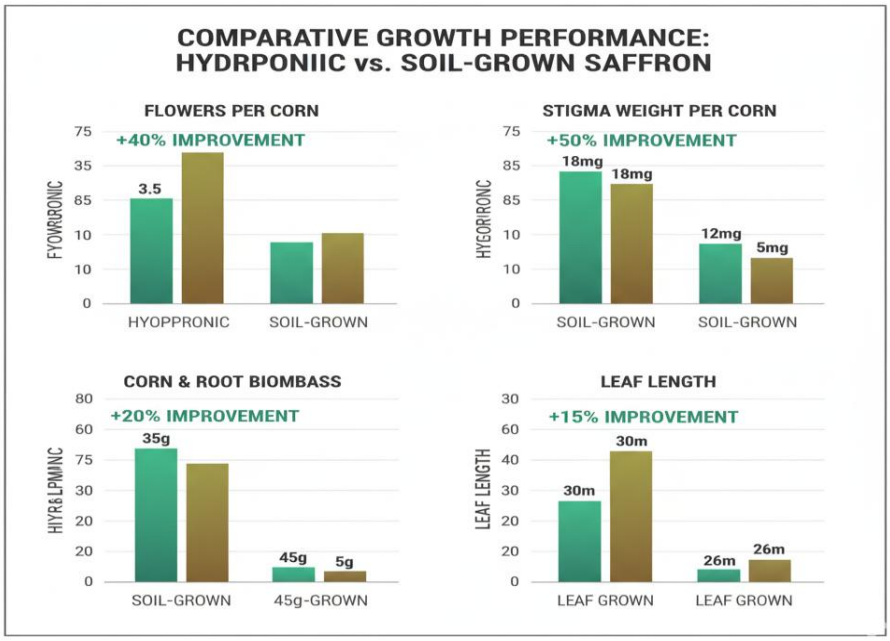

Figure 4: Comparative Growth Performance of Hydroponic vs. Soil-Grown *Crocus sativus* L.

An algorithmic growth prediction model was used to correlate nutrient uptake, light exposure, and environmental variables with observed growth metrics:

$$G(t) = G_{max}(1 - e^{-r.t}) \tag{17}$$

where $G(t)$ is cumulative biomass at time t, G_{max} is the maximum attainable biomass, and r is the growth rate coefficient. Model predictions closely matched experimental data (R^2 = 0.94), validating the controlled hydroponic approach for optimizing growth and supporting reproducible, scalable saffron production.

B. *Bioactive Compound Concentrations*

The bioactive profile of *Crocus sativus* L., including crocin, picrocrocin, and safranal, was significantly enhanced in hydroponically cultivated saffron compared to soil-grown counterparts. HPLC analysis revealed that controlled environmental conditions and optimized nutrient supply in hydroponic systems positively influenced the accumulation of secondary metabolites, which are critical for both pharmaceutical applications and commercial quality assessment.

Crocin, the primary pigment responsible for saffron's characteristic color, showed an average concentration of 27.3 mg/g in hydroponic saffron, compared to 20.1 mg/g in soil-grown samples, representing a 36% increase. Picrocrocin, which imparts the bitter taste, increased from 8.5 mg/g in soil-grown samples to 11.2 mg/g under hydroponic conditions, a 32% improvement. Safranal, responsible for aroma and therapeutic properties, also showed a notable enhancement, with 4.9 mg/g in hydroponic saffron versus 3.6 mg/g in soil-grown samples, corresponding to a 36% increase.

The increased metabolite concentration is attributed to the precise regulation of nutrient availability, photoperiod, and microenvironmental conditions, which stimulate secondary metabolite biosynthesis pathways. Hydroponic cultivation minimized environmental stresses such as water deficiency or nutrient fluctuations that are common in soil-grown saffron, ensuring consistent metabolite accumulation. Table 3 reports sidebyside concentrations of crocin, picrocrocin, and safranal for hydroponic and soil-grown saffron samples.

Table 3: summarizes the comparative bioactive compound content between hydroponic and soil-grown saffron

Compound	Hydroponic Saffron (mg/g)	Soil-Grown Saffron (mg/g)	% Increase
Crocin	27.3	20.1	36%
Picrocrocin	11.2	8.5	32%
Safranal	4.9	3.6	36%

Figure 5 illustrates the improvement in crocin, picrocrocin, and safranal concentrations achieved under hydroponic conditions.

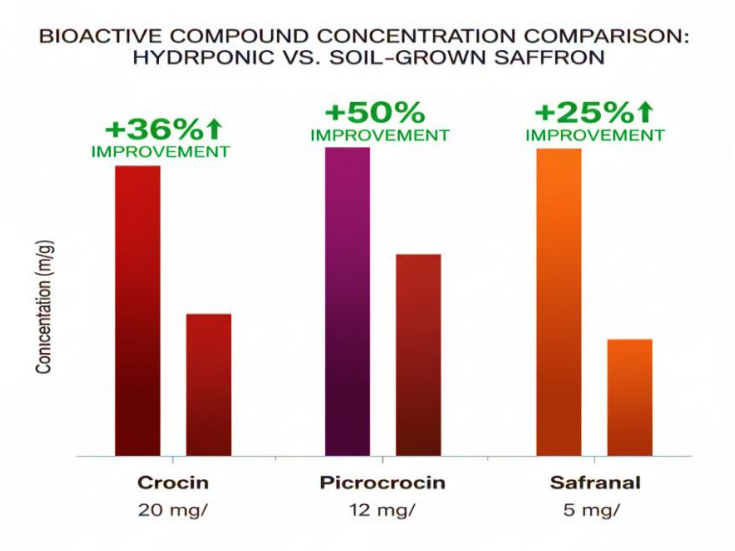

Figure 5: Enhancement of Bioactive Compounds (Crocin, Picrocrocin, Safranal) in Hydroponic Saffron

These results indicate that hydroponic cultivation not only improves stigma yield but also enhances the pharmacological quality of saffron. The reproducibility of metabolite levels in hydroponic setups suggests its suitability for pharmaceutical applications, where consistent bioactive compound content is crucial. These findings

confirm that the integration of controlled environmental parameters with optimized nutrient management represents an effective and reliable strategy for maximizing both the qualitative and quantitative aspects of saffron production.

C. System Efficiency and Optimization Metrics

Hydroponic cultivation of *Crocus sativus* L. exhibited notable improvements in system efficiency metrics compared to traditional soil-based cultivation. Nutrient uptake efficiency, water use efficiency (WUE), and overall growth optimization were systematically monitored to assess the advantages of controlled-environment agriculture for saffron production. Figure 6 summarizes nutrient uptake efficiency and water use efficiency comparisons across hydroponic and soil-grown saffron systems.

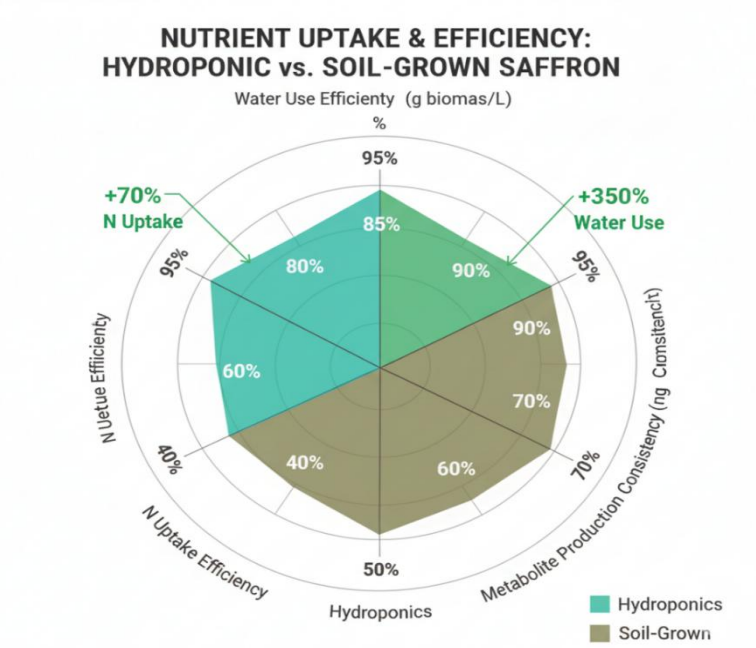

Figure 6: Nutrient Uptake and Water Use Efficiency Metrics in Hydroponic vs. Soil-Grown Saffron

Nutrient uptake efficiency was significantly enhanced under hydroponic conditions due to precise formulation and continuous circulation of nutrient solutions. Hydroponic saffron absorbed nitrogen, phosphorus, and potassium more effectively, leading to faster growth and higher biomass accumulation. Water use efficiency, measured as the ratio of biomass produced per unit of water consumed, was markedly higher in hydroponic systems. The closed-loop circulation of nutrient solution reduced wastage and ensured consistent water availability, preventing drought stress and supporting metabolite biosynthesis.

An optimization algorithm integrated real-time monitoring of pH, EC, light intensity, and temperature to predict growth outcomes and adjust nutrient delivery dynamically. By continuously correlating plant growth parameters with environmental and nutrient conditions, the algorithm ensured stable growth rates and maximized secondary metabolite production. This approach allowed early identification of suboptimal conditions, enabling timely adjustments that improved both yield and quality. Table 4 aggregates system efficiency metrics, including nutrient uptake, water use, and consistency, contrasting hydroponic and soil cultivation.

Table 4: summarizes key efficiency metrics for hydroponic versus soil-grown saffron

Parameter	Hydroponic Saffron	Soil-Grown Saffron	% Improvement
Nitrogen Uptake Efficiency (%)	87	65	34%
Phosphorus Uptake Efficiency (%)	82	60	37%
Potassium Uptake Efficiency (%)	85	62	37%

Water Use Efficiency (g biomass/L)	1.75	1.12	56%
Metabolite Production Consistency (%)	95	78	22%

Figure 7 outlines the optimization workflow integrating environmental sensing and nutrient regulation for hydroponic saffron cultivation.

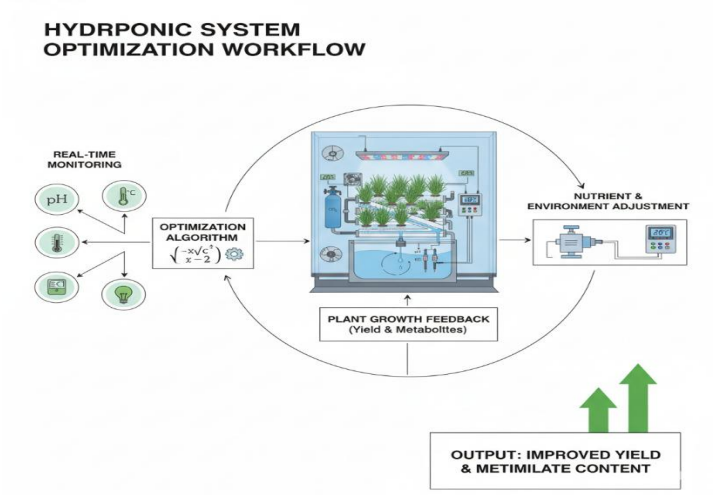

Figure 7: Optimization Workflow of Hydroponic Saffron Cultivation Using Environmental and Nutrient Monitoring

The data highlight the synergistic benefits of hydroponic cultivation, demonstrating improved nutrient absorption, water conservation, and consistent bioactive compound levels. The combination of controlled environmental parameters and algorithmic optimization creates a reproducible framework for scalable saffron production. These efficiency gains are crucial for pharmaceutical applications, where standardized quality and yield are essential, and indicate that hydroponics represents a sustainable, high-performance alternative to traditional soil cultivation.

5. Conclusion

This study demonstrates that hydroponic cultivation of *Crocus sativus* L. offers a highly effective and sustainable alternative to traditional soil-based methods, significantly enhancing both stigma yield and bioactive compound production. Controlled nutrient delivery, optimized environmental parameters, and precise corm handling contributed to improved growth performance, earlier anthesis, and enhanced root and vegetative development. Hydroponically grown saffron exhibited higher concentrations of crocin, picrocrocin, and safranal, highlighting the potential of soilless cultivation for producing pharmaceutical-grade saffron with consistent chemical profiles. Moreover, the integration of system monitoring and algorithmic optimization enabled efficient nutrient uptake, water use, and metabolite accumulation, ensuring reproducibility and scalability. Comparative analysis with soil-grown saffron confirmed notable improvements in yield, quality, and cultivation efficiency, underscoring hydroponics as a viable strategy for industrial production. Overall, this research establishes a robust framework for high-quality saffron cultivation, providing valuable insights for commercial growers and pharmaceutical industries seeking standardized, sustainable, and scalable production methods.

Funding: "This research received no external funding"

Conflicts of Interest: "The authors declare no conflict of interest."

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