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Contribution of Lean Management to Saffron (*Crocus sativus* L.) Harvesting: Preserving Stigma Quality through Optimal Timing of Flower Collection

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ABSTRACT

One of the critical factors compromising the efficiency of the saffron supply chain is the precise timing of flower harvesting. While delayed harvesting is known to impact quality, existing studies offer contradictory findings regarding the specific intra-day temporal threshold. This study introduces a novel interdisciplinary approach, integrating Lean Management principles -specifically Value Stream Mapping (VSM) - with agronomic analysis to define harvest delays as a form of operational "waste." We aimed to determine the optimal harvesting window that preserves stigma quality without disrupting workflow. Results indicated that while delayed harvesting did not significantly reduce stigma yield, it critically affected quality parameters. Specifically, delaying harvest beyond six hours after sunrise caused a significant decline in safranal (57.45% reduction after nine hours) and crocin (53.9% reduction). This granular data resolves discrepancies in prior literature by identifying the precise "tipping point" where stability ends and degradation accelerates. In addition, chromatic parameters changed significantly: values for '*a*' and the '*a*/*b*' index increased, while '*L*' and '*b*' decreased. A strong correlation was observed between chemical content and color parameters, validating colorimetry as a robust Visual Management tool for rapid quality sorting. By quantifying the exact temporal limit for waiting time, this research fills a gap in perishable food logistics, providing farmers with actionable, science-based schedules to minimize waste and maximize nutritional value.

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1. Introduction

The efficiency of food supply chains hinges on precise temporal coordination from producers to consumers. Saffron (*Crocus sativus* L.), derived from the dried stigmas of the flower, is the world's most expensive spice and a highly nutritious product. However, it is particularly susceptible to loss and wastage along the supply chain compared to staple foods like cereals (Christopher and Towill, 2000; Yu and Nagurney, 2013; Lahmass *et al.*, 2017; Christopher, 2022). Consequently, effective temporal coordination during the harvest and post-harvest process is crucial for preserving the nutrient quality of foods such as saffron (Artés *et al.*, 2007; Francis *et al.*, 2012; Behdani and Fallahi, 2015; Aghhavani-Shajari *et al.*, 2021; Aghhavani-Shajari and Rezvani Moghaddam, 2022). A significant uncertainty in saffron production is the impact of delayed flower harvesting on the yield and quality of the stigma. During flower harvesting periods, labor shortages often result in flowers being harvested after sunrise, throughout the day, or even in subsequent days (Behdani and Fallahi, 2015; INSO, 2013). Delayed harvesting increases the likelihood of damage from

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environmental factors such as wind and rain and diminishes the aroma and nutritional quality of the stigma. Therefore, managing time and minimizing delays at this stage of saffron production is critical (De Steur *et al*., 2016).

To address these inefficiencies, this study adopts a Lean Management framework. Lean management is characterized by the continuous elimination of waste (Muda) in production processes to enhance productivity and product quality (Hines *et al*., 2004; Halloran *et al*., 2014; Martínez-Jurado and Moyano-Fuentes, 2014). Within this framework, Value Stream Mapping (VSM) serves as an essential tool. Defined by Rother and Shook (2003), VSM enables organizations to map and analyze the movement of materials and information throughout the production process to identify non-value-added activities. Previous studies in food supply chains (e.g., Melin and Barth, 2020; De Steur *et al*., 2016) have demonstrated that VSM is effective in preserving food quality. Specifically, it has been applied in the agri-food industry (Panwar *et al*., 2015; Wesana *et al*., 2019) to expose the seven types of waste, including unnecessary waiting and inappropriate processing. By viewing the harvest delay through the lens of VSM, the biological degradation of the flower can be categorized as operational waste that must be minimized. Furthermore, Lean methodologies emphasize Visual Management (Liker, 2020), a principle that aims to make quality status immediately observable. In an agronomic context, this supports the potential use of rapid chromatic indicators to monitor this waste in real-time, rather than relying solely on delayed laboratory analysis.

However, from an agronomic perspective, the precise impact of this "waiting time" on saffron quality remains a subject of debate in existing literature. While the general consensus suggests that delayed harvesting compromises quality, findings regarding specific chemical components are contradictory. For instance, Esmaeilian et al. (2012) and Erden and Özel (2016) reported that delayed harvest caused a significant decrease in safranal, crocin, and picrocrocin content. In contrast, Aghhavani-Shajari and Rezvani Moghaddam (2022) observed that while safranal content was maximized before sunrise, the content of crocin and picrocrocin actually increased by 2.1% and 6.7%, respectively, when harvest was postponed to after sunrise. Additionally, Zhou et al. (2020) highlighted that apocarotenoid accumulation fluctuates significantly depending on the developmental stage, shifting from accumulation to degradation. They studied the color changes of saffron stigma at the six developmental stages. It was found that the color of stigma changes from light yellow to yellow, orange, red and scarlet (at pre-anthesis and anthesis stages), respectively. They also reported that apocarotenoids (crocin and picrocrocin) accumulation, first sharply enhanced up to red stage, and then gradually decreased with stigma development.

These conflicting findings suggest a significant gap in the literature: the lack of a standardized, high-resolution investigation into the specific effects of hourly delays during the day. The harvest delay variable has likely been treated too broadly in previous research, leading to inconsistent conclusions. Therefore, this study aimed to investigate the optimal duration of flower harvesting and its effect on the yield and quality of saffron stigma. By employing a quantitative methodology within a Lean/VSM framework, we seek to determine the precise temporal threshold where waiting becomes waste. This interdisciplinary approach not only resolves existing agronomic contradictions but also provides actionable management insights for optimizing the saffron supply chain.

2. Materials and methods

2.1. Treatments and flower harvesting

This experiment was carried out in the field and laboratory of the Sarayan Agriculture Faculty, University of Birjand, Iran, during the flowering season of 2019. The effect of four times of flower harvesting during the day was evaluated on the stigma yield and quality based on a completely randomized experimental design with three replicates of 400 plants. The flowers were harvested just before sunrise or three, six and nine hours after sunrise. In each harvesting time, 100 flowers were collected and sampled by three replicates and then stigmas were separated and dried at room temperature (~ 25°C) in shade conditions for 10 days. The dried stigmas in each replicate were weighed separately and then used for quality evaluation.

The experiment was conducted at the research field of Sarayan Agriculture Faculty, located in South Khorasan Province, Iran (33°N, 58°E, elevation 1,450 m above sea level). The region is characterized by cold

winters and hot, dry summers. It has a semi-arid climate with an annual long-term rainfall of 120 mm and a mean temperature of 17 ºC (Fallahi *et al*., 2017b). During the experimental period (flowering season, October-November 2019), the mean daily temperature ranged from ~ 12-18°C, with maximum temperatures reaching 24°C during midday, with negligible precipitation. The soil texture was loam with pH 7.6 and organic matter content of 0.51%. The saffron field was in its second year of production. Corms (cv. local Sarayan ecotype) were planted in September 2017 at a density of 75 corms per m² with planting depth of 15-20 cm in rows spaced 20 cm apart. Flood irrigation was done on time before flowering and five more times after flowering, during growing season. Fertilization consisted of farmyard manure (20 t ha^{-1}) applied before planting. Weeds were controlled manually throughout the season. No pesticides or fungicides were applied during the experimental year.

2.2. Quality assessment of stigma

ISO 3632: Spices — Saffron (*Crocus sativus* L.) was used for safranal and crocin content measurement using UV-vis spectrometric method (ISO 3632, 2010). By this method, 500 mg of the powdered stigma was transferred to a 1000 ml volumetric flask and 900 ml of distilled water was added to it. Then, the mixture was dissolved for one hour in the dark using a magnetic stirrer (1000 rpm), and the flask was filled with distilled water to the mark line. Then the lid of the flask was closed and stirred until a homogenized solution was obtained. In the next stage, 20 ml of solution was transferred to a 200 ml volumetric flask, and it was filled to the mark line with distilled water. Then the lid of the flask was closed and stirred to a homogeneous diluted solution. The solution was filtered quickly using a strainer, away from the direct light, to obtain a clear solution. The absorbance of 1% aqueous solution was read at 330 and 440 nm, for safranal and crocin, respectively, by spectrophotometer. The absorbance at two mentioned wavelengths was evaluated by a 1 cm pathway quartz cell. Distilled water was used as reference liquid. The obtained data were put in Equation 1, to calculate the amount of each compound. In this Equation, D= Specific absorbance at 330 and 440 nm, M = stigma sample weight (g), and H = stigma sample moisture and volatile content (Fallahi *et al*., 2021).

$$(1) \qquad A_{1cm}^{1\%}(\lambda max) = \frac{D \times 10000}{M \times (100 - H)}$$

To measure H, in Equation 1, a sample of stigma was weighed initially, and then placed uncovered in an oven (103±2˚C for 16 h). After that, the final weight was determined and Equation 2 was used (Fallahi *et al*., 2021).

$$(2) \qquad H = \left[\frac{(initial\ mass\ of\ sample - final\ mass)}{initial\ mass}\right] \times 100$$

Color parameters (Hunter color values including *L*, *a* and *b*) of the whole stigma were determined using a colorimeter (TES 135, Shenzhen Youfu Tools Co., Ltd., Taiwan). *L* (ranges from black = 0 to white = 100) is used to denote lightness, *a* redness and greenness (it ranges from +60 for red to -60 for green), and *b* yellowness and blueness (it varies from +60 for yellow to -60 for blue) (Fallahi *et al*., 2017a; Khayyat *et al*., 2018; Aghhavani-Shajari and Rezvani-Moghaddam, 2022).

2.3. Data analysis

SAS 9.2 was used for data analysis. The experiment data were analyzed based on a CRD design and means were compared using the LSD test at 5% level of probability. Prior to ANOVA, all assumptions were verified: normality of residuals was tested using the Shapiro-Wilk test (p>0.05 for all variables), homogeneity of variance was confirmed using Levene's test (p>0.05), and independence of observations was ensured by the experimental design with spatially separated replications.

3. Results and discussion

3.1. Stigma yield

Most farmers strongly believe that saffron flowers should be harvested in early morning to avoid exposure to light, wind, and rain and thereby lowering quality and quantity. However, in some cases, especially during the peak flowering phase of the fields, the flower harvesting is postponed to the afternoon or sometimes to the next day (Behdani and Fallahi, 2015). Results showed that there was no significant difference between various harvesting times during the day in terms of stigma yield (Table 1; Fig. 1). In a similar study, Erden and Özel (2016) reported that the effect of harvesting time (blooming, one or two days after

blooming) was not significant on the stigma weight and length, but a 6.6% increase in saffron yield was recorded by delaying the harvest for two days after blooming.

Table 1. Analysis of variance for the effect of daily harvesting time of flowers on stigma yield and quality of saffron

S.O.V	df	Stigma yield	*L*	*a*	*b*	*a*/*b*	Safranal	Crocin
Harvesting time	3	0.0005^{ns}	79.5**	25.6*	9.92**	1.33**	166.6**	10112**
Error	8	0.0002	05.9	6.19	0.28	0.15	11.97	267.1
C.V. (%)	-	3.7	9.1	7.2	4.5	13.1	6.6	8.6

ns: no-significant; *, ** Significant at 5%, and 1% probability level, respectively. (*L*: lightness, *a*: redness, *b*: yellowness).

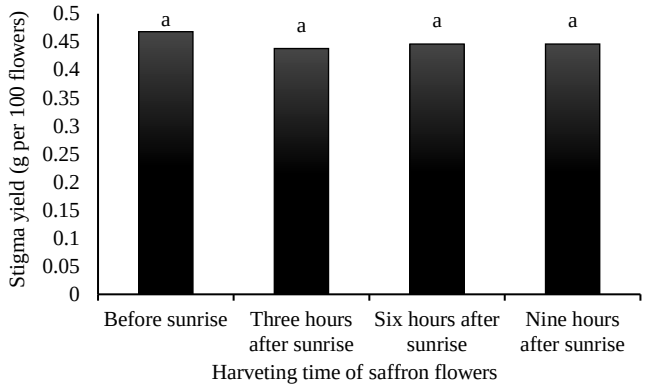


Figure 1. Effect of harvesting time of saffron flowers on dry stigma yield.

However, experiences from dry regions of Khorasan indicate that when saffron flowers remain in the field for more than two days, they tend to wither and their stigmas may begin to fall (Behdani and Fallahi, 2015). Flower durability under open-field conditions may vary depending on regional climatic factors, particularly temperature and air humidity.

3.2. Hunter color parameters

Harvesting time exerted a significant effect on Hunter's color parameters, including *L*, *a* and *b* (Table 1). The highest and the lowest *L* were obtained before sunrise flower harvesting and harvesting nine hours after sunrise, respectively, with a 38.6% difference (Fig. 2A), which means that stigma brightness has a negative relation with postponing the time of flower harvesting. The amount of *a* had an increasing trend with delayed flower harvesting (Fig. 2B), while there was an opposite trend for *b* (Fig. 2C). This procedure was also realizable from the negative correlation (-0.70**) between *a* and *b* criteria (Table 2). Finally, *a*/*b* ratio increased by delay in flower harvesting, reaching its maximum value obtained when flowers were harvested nine hours after sunrise (Fig. 2D).

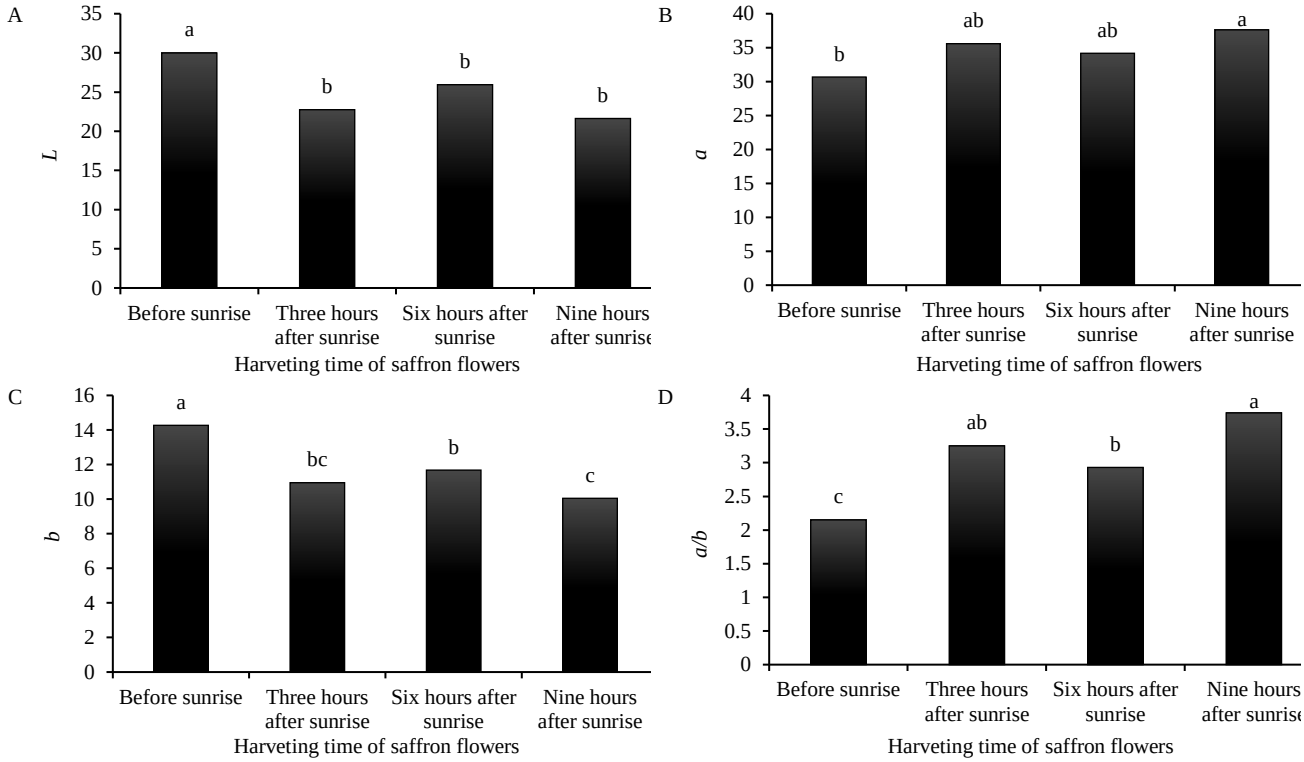


Figure 2. Effect of harvesting time of saffron flowers during a day on Hunter's color parameters in stigma. *L* (A), *a* (B), *b* (C) and *a*/*b* (D).

The positive values of *a* and *b* chromatic parameters, which were recorded in the present study (Fig. 2B, C), represent the redness and yellowness of stigma, respectively (Fallahi *et al*., 2017a; Fallahi *et al*., 2018).

Accordingly, delay in saffron flowers harvesting resulted in an increase in stigma redness (Fig. 2B), but reduced its yellowness (Fig. 2C).

Decrease in luminosity (Fig. 2A), the lower positive *b* values (in the yellow part of the colorimetric space) (Fig. 2C), and the higher positive *a* values (in the red region of the colorimetric space) (Fig. 2B) associated with delayed flower harvesting show the red-dark appearance of those stigma samples. Similarly, Gohari et al. (2013) stated that if saffron remains under sunlight, the products will become darker.

In our study, the mean values of *L*, *a* and *b* for the filament form of saffron were around 26.5, 34.5 and 11.5, respectively. According to Aghhavani-Shajari and Rezvani-Moghaddam (2022), the mean values of *L*, *a* and *b*, for saffron whole stigma were 23.5, 22.0 and 8.3, respectively. The range of colorimetric data in the present study is also close to those reported by Yadollahi et al. (2007) for saffron powder (50, 17 and 14 for *L*, *a* and b, respectively), but with high differences compared with those obtained by them in stigma solution. In this regard, Alonso et al. (2003) also found that the chromatic parameters of saffron in filament form were lower than those recorded in powdered form.

Table 2. Correlation between the different qualitative indices of saffron stigma

Parameter	*L*	*a*	*b*	*a*/*b*	Safranal	Crocin
L	1					
a	-0.51^{ns}	1				
b	0.69**	-0.70**	1			
a/*b*	-0.73**	0.87**	-0.88**	1		
Safranal	0.56*	-0.36^{ns}	0.51^{ns}	-0.50^{ns}	1	
Crocin	0.55*	-0.59*	0.61*	-0.68**	0.88**	1

ns: no-significant; *, ** Significant at 5%, and 1% probability level, respectively. (*L*: lightness, *a*: redness, *b*: yellowness).

3.3. Crocin and safranal content

The safranal content in stigma was affected significantly by the harvesting time of saffron flowers during a day (Table 1). The amount of safranal was not decreased with delay in flower harvesting up to six hours after sunrise, but a longer delay in harvesting reduced it significantly by 34%, compared with the control (before sunrise) treatment (Fig. 3A). Safranal, as the main aroma component of stigma, is mainly produced from picrocrocin during post-harvest stage (Shahi *et al*., 2016). Accordingly, in the present study, it is probable that sunlight has exerted a negative effect on picrocrocin as the precursor of stigma aroma component. Gohari et al. (2013) also stated that if the flowers of saffron remain under warm weather and sunlight, then the stigma quality, in terms of color and aroma, would decrease. In the study of Erden and Özel (2016), it was also reported that picrocrocin, as the precursor of safranal, decreased by 3.3 and 7.1% in flowers harvested one or two days after blooming, compared with the flowers harvested at blooming stage. The safranal content of the stigma also decreased by 6.9% and 11.6%, respectively, by the delay of the flower harvesting for one and two days. Aghhavani Shajari (2020) also found a negative relation between delayed harvest of flowers and the content of safranal in stigma. In their study, the amount of safranal before and after sunrise was 0.015 and 0.012 g 100 g^{-1} stigma, respectively. In a study conducted by Moraga et al. (2009) on the metabolite analysis during saffron stigma development, from before to after anthesis, the highest level of picrocrocin was obtained at anthesis, namely the flower development stage with high level of safranal, which is suitable for stigma harvesting. They observed that during stigma maturation, safranal was only detected at low levels, although a safranal-related compound increased quickly at the anthesis stage and also in senescent stigmas. They stated that final biosynthetic reactions, which occur when the flowers begin to open, are responsible for fragrance production during flower anthesis. Therefore, fresh flower buds – almost equivalent to flower harvesting before or sometimes after sunrise in our study- do not have a scent (safranal). Although in dried stigma, the safranal will be produced from picrocrocin by dehydration (Shahi *et al*., 2016).

The observed degradation of apocarotenoids can be attributed to several interconnected biochemical and environmental mechanisms. Photo-oxidation appears to be a primary pathway in which prolonged exposure to solar radiation induces the formation of reactive oxygen species that attack the conjugated double bonds of carotenoids, resulting in chromophore degradation and color fading. This process is further intensified by thermal stress, as elevated midday temperatures enhance enzymatic activity. In the case of picrocrocin, the direct precursor of safranal, enzymatic hydrolysis is strongly temperature-dependent and accelerates under stress conditions. Moreover, water loss from unharvested flowers, due to increased transpiration rates, leads to concentration of cellular constituents and

disruption of membrane integrity. Such changes may alter the compartmentalization of enzymes and substrates, thereby promoting undesirable degradation reactions. Collectively, the synergistic effects of light exposure, thermal stress, and desiccation trigger a cascade of oxidative damage that progressively reduces both pigment content (crocin) and aroma precursors (picrocrocin/safranal) in stigmas remaining attached to flowers under field conditions.

The effect of flower harvesting time was significant on the content of crocin in stigma (Table 1). The stigma obtained from flowers harvested before sunrise and three or six hours after sunrise were in the same statistical group in terms of crocin content, but a significant decrease (53.9%) was observed when flower harvesting was postponed by nine hours after sunrise (Fig. 3B).

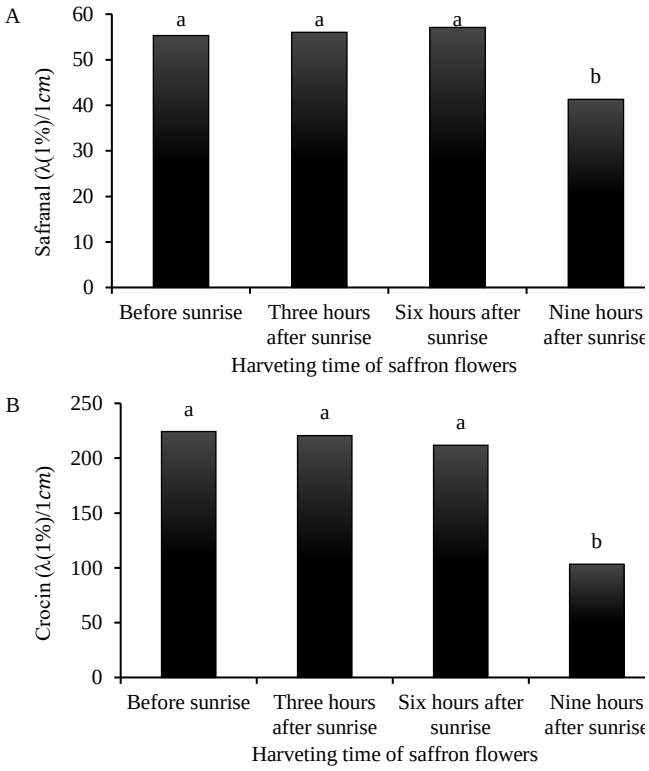


Figure 3. Effect of harvesting time of saffron flowers during the day on safranal (A) and crocin (B) content of stigma (the units are absorbance of 1% aqueous stigma extract at 330 nm for safranal and 440 nm for crocin).

Esmaeilian et al. (2012) findings revealed similar results about safranal but contradictory results about crocin. In the study of Aghhavani-Shajari and Rezvani Moghaddam (2022), the content of crocin was 23.8 and 24.3 g 100 g^{-1} stigma, at harvesting times of before sunrise and two hours after sunrise, respectively. Erden and Özel (2016) also found that one and two-day delay in flower harvesting resulted in a 7.7 and 13.7% decrease in crocin concentration, respectively, compared with the flowers harvested at the full blooming stage. These seemingly conflicting findings highlight the importance of the high temporal resolution applied in our study. By tracking hourly changes, we identified that the "tipping point" for quality loss lies specifically between 6 and 9 hours. The stability or slight increase observed by Aghhavani-Shajari (2020) fits within our safe 6-hour window, while the degradation reported by Erden and Özel (2016) corresponds to delays extending beyond this critical threshold. Moraga et al. (2009) revealed that the highest level of crocins of low glucose content was detected in the red stage of stigma (closed bud inside the perianth tubes), but in the scarlet stages of stigma (including three days before anthesis, day of anthesis and two days after anthesis), the crocins with the major glucosylation level reached the highest levels.

3.4. Colorimetry calibration models for quality prediction

To evaluate the potential of colorimetric parameters as rapid predictors of biochemical quality, different regression models were developed relating Hunter color values to crocin and safranal content. The quadratic binomial model showed an acceptable fit of the relationship between the safranal content of the stigma and the lightness color index ($R^2 = 0.77$) (Fig. 4).

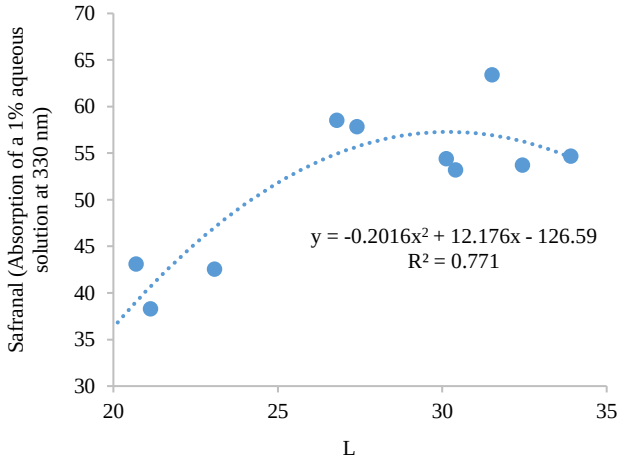


Figure 4. Regression relationship between safranal and *L* index in saffron stigma.

The relationship between the crocin content and the color indices, including lightness ($R^2 = 0.84$), *a* (R^2 =

0.59), *b* (R^2 = 0.81) and *a/b* (R^2 = 0.92), also showed that these indices were able to well represent the crocin content of the stigma (Fig. 5). The quadratic regression model also fitted well for these indices. While the relationship between crocin content and *b* and lightness indices was positive, regression relationships indicated a negative relationship between crocin content and two indices *a* and *a/b* (Fig. 5). While these models require further validation across multiple locations, they demonstrate proof-of-concept for colorimetry as a rapid, non-destructive screening tool for saffron quality assessment in field conditions, potentially reducing reliance on laboratory spectrophotometry for routine quality monitoring.

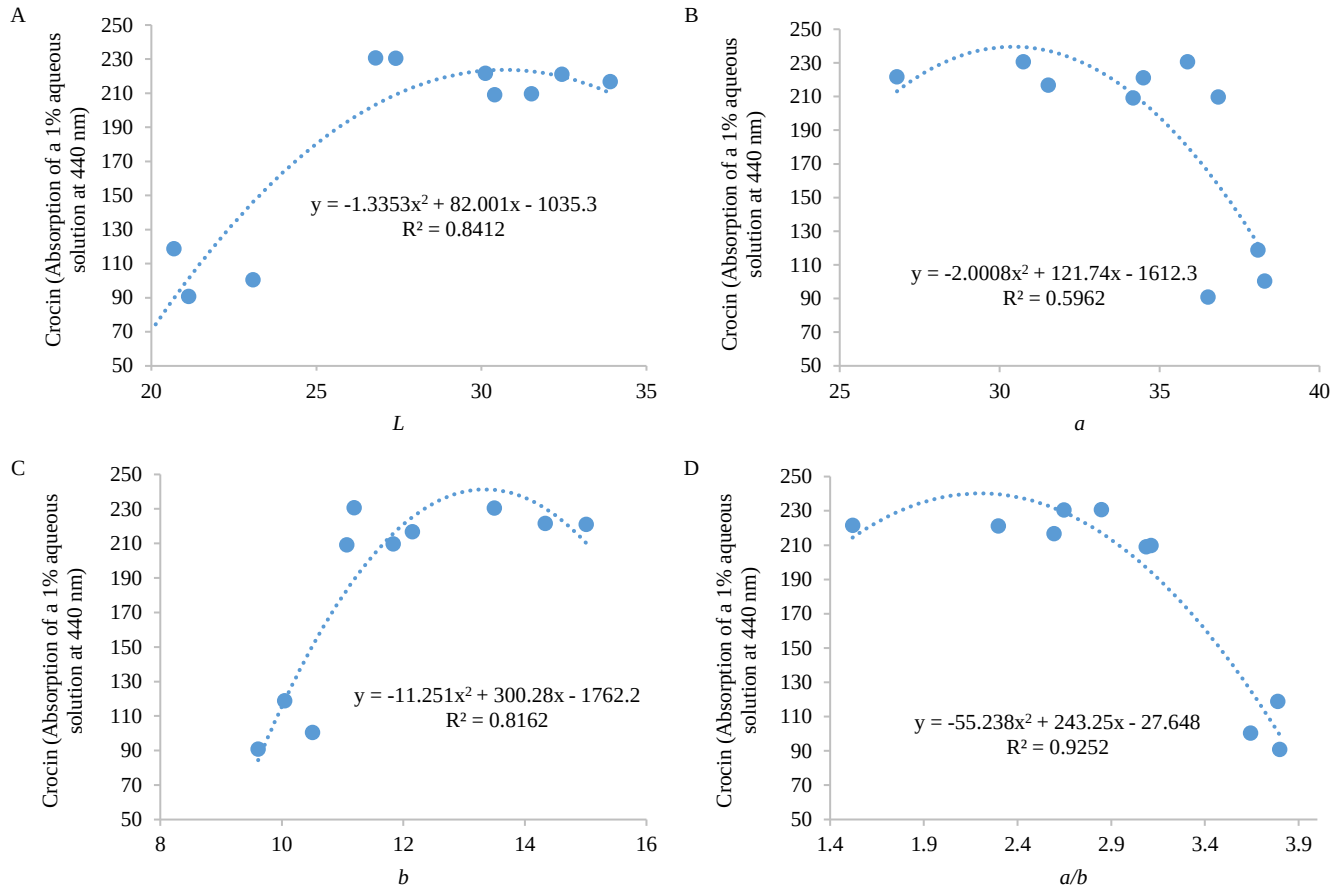


Figure 5. Regression relationship between crocin content and different colorimetric indices in saffron stigma.

3.5. Correlation coefficients

In food authentication, techniques such as chromatography, spectroscopy and organoleptic assessment, which are time-consuming, high-cost and off-line in nature, are used (Kiani and Minaei, 2016). The colorimetric method can possibly be used to solve those problems, because it is a rapid and low-cost method. Colorimetry, as a non-destructive method, plays a fundamental role in consumer choices, considering it is well associated with quality and genuineness and could specify the presence of some compound in herbal samples (Patsilinakos *et al*., 2018). In our study, crocin content in saffron stigma had a positive correlation with *L*, *b* and safranal but a negative relation with *a* and *a*/*b* chromatic parameters. There was also a positive correlation between *L* and safranal content in stigma (Table 2). This observation is consistent with the results of Aghhavani-Shajari and Rezvani-Moghaddam (2022), who reported that colorimetry had an acceptable correlation with biochemical traits of saffron stigma. From a Lean Management perspective, this strong correlation validates colorimetry as a reliable tool for Visual Management, allowing for rapid, non-destructive quality sorting without the waste of waiting for laboratory results.

Crocin, as the main pigment in saffron stigma (approx. 80%), in contrast with most other carotenoids, is water-soluble and is used mainly as a colorant in medicine and food industries. This pigment is stable

under ambient conditions and is responsible for the golden bright yellow-red color of stigma, when crocins dissolve in water (Shahi *et al*., 2016). Accordingly, the presence of a correlation between the amount of this compound and the Hunter color parameters of the stigma is expected. Yadollahi et al. (2007) also concluded that chroma parameter in powdered stigma had a good correlation (R^2= 0.84) with coloring strength values due to the ISO/TS 3632-2 method, which confirms that the HunterLab method could be considered as a standard method for saffron quality evaluation. Similarly, Alonso et al. (2003) concluded that colorimetry is a useful technique for the evaluation of saffron quality, because there was a good correlation between chromatic parameters of saffron with its coloring power. In another study, Cuko et al. (2004) found that colorimetry is a rapid method for saffron coloring strength assessment. In their study, correlations among data obtained from HPLC (crocin content), colorimetric and spectrometric (E1%, 440nm) methods.

3.6. ISO 3632 quality classification

Based on the ISO 3632-2 standard for saffron quality grading, samples were classified into quality categories according to their crocin (E1%1 cm at 440 nm) and safranal (E1%1cm at 330 nm) content (Fallahi *et al*., 2024). Stigmas from flowers harvested before sunrise exhibited crocin values of 224.3 and safranal values of 55.31, placing them firmly in Category I (highest quality, requiring crocin ≥200 and safranal 20-50). Similarly, stigmas from flowers harvested 3 and 6 hours after sunrise maintained Category I status with crocin values of 220.6 and 211.8, and safranal values of 56.0 and 57.0, respectively. However, stigmas from flowers harvested 9 hours after sunrise showed a sharp reduction in crocin content (103.3), falling into Category III. This demonstrates that delayed harvesting beyond 6 hours results not only in biochemical quality degradation but also in commercial downgrading with significant economic implications for producers.

3.7. Lean management and value stream mapping framework

This study applies Lean Management principles to identify and quantify waste in the saffron harvesting process. According to Lean methodology, any activity that consumes resources without adding value constitutes waste. In the context of saffron production, delayed flower harvesting represents two types of Lean waste: (1) 'waiting' - flowers remaining in the field beyond optimal harvest time, and (2) 'inappropriate processing' - harvesting under conditions that degrade product quality. Value Stream Mapping (VSM) was conceptually applied to visualize the harvesting workflow from flower emergence through stigma separation and drying (Liker, 2020).

The Current-State VSM (Fig. 6) identifies the critical control point where harvest delay transitions from value-preserving to value-destroying activity. By quantifying quality degradation at specific time intervals (3, 6, and 9 hours post-sunrise), this study provides data-driven parameters for defining the acceptable processing window. This approach enables practitioners to establish standard work procedures that eliminate quality-compromising delays while optimizing labor allocation during peak flowering periods. The VSM framework transforms traditional agronomic harvest timing recommendations into quantifiable operational constraints that can be integrated into production planning and workforce management systems.

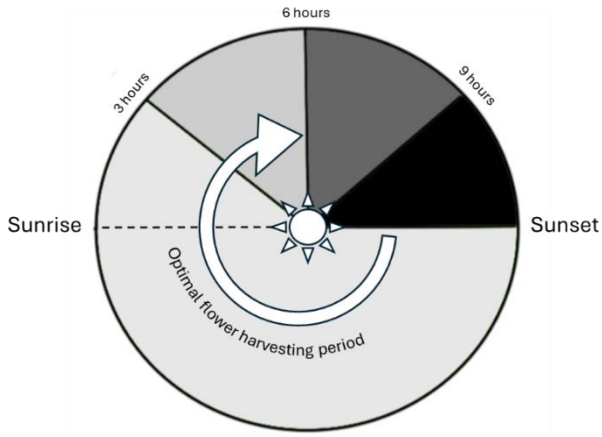


Figure 6. The limit of time delay in the process of harvesting saffron flowers from the field is based on the results of the current research.

3.8. Study limitations and future directions

While this study provides valuable insights into harvest timing effects on saffron quality, several limitations should be acknowledged. First, our findings are specific to the semi-arid climatic conditions of Birjand, Iran. Results may not be directly generalizable to Mediterranean regions with higher humidity or areas with different temperature regimes and solar radiation patterns without site-specific validation. Second, we employed only one post-harvest drying method (shade-

drying at ambient temperature ~25°C). The interaction between harvest timing and alternative drying techniques (oven-drying at various temperatures, freeze-drying, or vacuum-drying) remains unexplored and could reveal opportunities to mitigate quality losses from delayed harvesting. Third, we did not measure picrocrocin content directly. As the immediate precursor to safranal and an important quality parameter in its own right, picrocrocin quantification would provide a more complete understanding of apocarotenoid biosynthesis and degradation dynamics during delayed harvest. Fourth, this study represents a single growing season. Multi-year experiments would account for inter-annual climatic variation and strengthen the robustness of the 6-hour threshold recommendation. Fifth, we used a single local ecotype. Genetic variation among saffron accessions in stress tolerance and apocarotenoid stability could influence harvest timing recommendations for different cultivars. Future research should address these limitations through: (1) multi-location trials across diverse climatic zones, (2) factorial experiments combining harvest timing with various drying methods, (3) comprehensive metabolomic profiling including picrocrocin and crocin isomers, (4) multi-year validation studies, and (5) comparative evaluation of diverse saffron genotypes. Additionally, development of portable, field-deployable colorimeters with integrated quality prediction algorithms could enable real-time harvest quality monitoring.

4. Conclusion

This study bridges the gap between supply chain management and agronomy by applying Lean Management principles, specifically Value Stream Mapping, to the critical stage of saffron flower harvesting. To our knowledge, this is one of the first interdisciplinary attempts to rigorously quantify waiting time as a form of operational waste in the saffron supply chain. From an agronomic perspective, our quantitative methodology resolved the contradictions found in previous literature regarding intra-day delays. The results pinpoint a clear temporal threshold: while harvesting delays up to six hours after sunrise are tolerable, extending this window creates significant waste in terms of quality loss. Specifically, a delay beyond six hours leads to a drastic reduction in key bioactive compounds (33.9% loss in safranal and significant drops in crocin) and alters visual quality (decrease in lightness 'L' and yellowness 'b'). This confirms that the biological degradation of the stigma is time-sensitive and non-linear, validating the need for precise hourly coordination. Furthermore, the strong correlation observed between Hunter color parameters and apocarotenoid content offers a practical tool for Lean implementation. Since laboratory analysis of safranal and crocin is time-consuming and expensive, the validity of colorimetry as a rapid, low-cost, and non-destructive proxy allows for visual management—a core Lean concept. This enables immediate quality sorting at the farm gate without complex equipment.

In managerial terms, these findings translate into actionable insights into the “Future State Map” of saffron production. As illustrated in Fig. 6, the “six-hour rule” provides a concrete target for workforce scheduling. Farmers must align their available labor force and field size to ensure harvesting is completed within this optimal window. Failure to do so does not merely result in a logistical delay but constitutes a direct destruction of value (nutritional and sensory). Consequently, balancing labor capacity with harvest volume becomes a critical factor in eliminating the waste of inappropriate processing. Future research should expand this Lean framework to post-harvest processing steps, such as drying and storage, to create a fully optimized, waste-free value stream for saffron.

Conflict of interests

All authors declare no conflict of interest.

Ethics approval and consent to participate

No humans or animals were used in the present research. The authors have adhered to ethical standards, including avoiding plagiarism, data fabrication, and double publication.

Consent for publications

All authors read and approved the final manuscript for publication.

Availability of data and material

All the data are embedded in the manuscript.

Authors' contributions

Hamid-Reza Fallahi: Research idea, grant acquisition, conducting experiments, data analysis,

manuscript writing, addressing reviewers' comments; Mahsa Aghhavani Shajari: Research idea, performing laboratory analyses, final review of the manuscript; Hossein Sahabi: Research idea, support, and grant acquisition; Benyamin Shajari: Establishing the link between crop management and Lean management, manuscript writing, addressing reviewers' comments; Hamed Kaveh: Assistance in rewriting and final revision of the manuscript based on reviewers' comments; Ferdinando Branca: Coordination, consultation, and assistance in the preparation and interpretation of the manuscript.

Informed consent

The authors declare not to use any patients in this research.

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Generative AI statement

The author declares that generative AI (artificial intelligence) tools, including Grammarly & QuillBot, were used to enhance the language & clarity of this work. The author takes full responsibility for the accuracy & integrity of the content.

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