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ORIGINAL ARTICLE

Interactive effects of irrigation water quality and UV-C treatment on bioactive compounds and microbial safety of saffron (*Crocus sativus* L.)

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Abstract

The influence of pre-harvest irrigation water quality on post-harvest ultraviolet-C light (UV-C) treatment efficacy remains unexplored for saffron (*Crocus sativus* L.), despite its importance for both safety and bioactive compound preservation. This study investigated the interactive effects of irrigation water quality (clean groundwater, treated wastewater, and chemical fertilizer-enriched) and UV-C exposure time (0, 60, 120, and 180 min) on saffron stigma composition and microbial contamination. Analysis of variance revealed significant effects ($p < 0.01$) of both irrigation source and UV-C treatment on most quality parameters. UV-C exposure significantly reduced safranal (40.5–22.4 E1% 330 nm) and crocin (268.9–190.8 E1% 440 nm) content, with wastewater-irrigated samples showing the most severe degradation. Picrocrocin levels increased, reaching a peak at 120 min of UV-C exposure (93.8 E1% 257 nm), before declining at longer exposure times. Irrigation with wastewater resulted in significantly higher microbial counts (1250 colony forming unit [CFU]/g) compared to clean water (520 CFU/g), but 180 min UV-C effectively reduced contamination by 65%–74% across all treatments ($p < 0.01$). Principal component analysis revealed that moderate UV-C exposure (60–120 min) combined with clean water irrigation provided optimal balance between microbial control and compound preservation. These findings demonstrate that while UV-C treatment can effectively control microbial safety, prolonged exposure risks degrading key saffron bioactive compounds, with irrigation water quality significantly influencing this susceptibility. Optimizing both irrigation practices and UV-C treatment parameters is crucial for preserving saffron quality while ensuring food safety.

Abbreviations: ANOVA, analysis of variance; UV-C, ultraviolet-C light.

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Plain Language Summary

Saffron is the world's most expensive spice, valued for its unique color, flavor, and aroma. This study investigated how irrigation water quality (clean groundwater, treated wastewater, and fertilizer-enriched water)affects the effectiveness of ultraviolet light treatment used to ensure saffron's safety after harvest. The researchers found that while UV treatment successfully reduced microbial contamination in all samples, prolonged exposure degraded the valuable compounds that give saffron its distinctive properties. Saffron irrigated with treated wastewater showed higher initial contamination and greater sensitivity to quality loss during UV treatment compared to clean water irrigation. Moderate UV exposure (60–120 min) combined with clean irrigation water provided the optimal balance between safety and quality preservation. These findings help farmers and processors improve their practices to produce safer, higher quality saffron, benefiting both consumers and producers of it.

1 | INTRODUCTION

1.1 | Economic significance and production challenges

Saffron (*Crocus sativus* L.) represents one of the world's most valuable agricultural commodities, commanding prices of $2800–3500 per kilogram in international markets (Anastasaki et al., 2009; Bathaie & Mousavi, 2010). This exceptionally high value stems from its labor-intensive production requirements, with approximately 150,000 flowers (78 kg) needed to obtain just 1 kg of dried stigmas (Saeidirad et al., 2014). Iran dominates global production, accounting for approximately 90% of annual output, though production has recently declined from 480 metric tons in 2019 to around 200 metric tons (Saeidi et al., 2022).

1.2 | Chemical composition and bioactive compounds

The commercial value of saffron is primarily determined by its unique apocarotenoid compounds: crocins, safranal, and picrocrocin (Ahrazem et al., 2015; Moras et al., 2018). Crocins are water-soluble carotenoid derivatives that provide saffron's characteristic red color, consisting of glycosyl esters of crocetin with different sugar moieties including glucose, gentiobiose, neapolitanose, or triglucose (Carmona et al., 2005). Picrocrocin, a monoterpene glycoside produced through bio-oxidative cleavage of zeaxanthin, is responsible for saffron's bitter taste (Lage & Cantrell, 2009). Notably, safranal, the principal volatile component, is not present in fresh stigmas but develops during drying and aging through the dehydration of picrocrocin (Shahi et al., 2016). These compounds' relative concentrations vary significantly based on origin, extraction methodology, drying techniques, and storage conditions (Jalali-Heravi et al., 2009; Urbani et al., 2015).

1.3 | Irrigation water quality and crop contamination

Irrigation water quality has emerged as a critical factor affecting both food safety and crop quality in saffron production. Water of inadequate quality can serve as both a direct source of contamination and a vehicle for spreading localized contamination in field environments (Allende & Monaghan, 2015). The increasing use of nonconventional water sources, including treated wastewater and surface water with varying degrees of contamination, has heightened food safety concerns. In developing countries, where 80%–90% of wastewater remains untreated, the use of contaminated irrigation water poses significant risks to crop safety (UNESCO World Water Assessment Programme, 2017).

Surface water sources are particularly vulnerable to contamination, with studies showing significant variations in microbial quality throughout growing seasons. Research has documented the presence of foodborne pathogens, including *Escherichia coli* O157:H7, *Salmonella* spp., and *Listeria monocytogenes*, in various irrigation water sources (Milani et al., 2016). The method of irrigation application also influences contamination risk, with overhead irrigation presenting higher risks compared to drip or subsurface irrigation systems that minimize direct contact between water and the edible portions of crops (Allende & Monaghan, 2015).

1.4 | Microbial contamination concerns in saffron

Microbial contamination in saffron can occur at multiple stages, from cultivation through processing. Several

microorganisms detected in saffron pose potential health risks, including aflatoxin-producing fungi (e.g., *Aspergillus* spp.), *Bacillus cereus*, *Clostridium perfringens*, *E. coli*, *Salmonella* spp., and *Staphylococcus aureus* (Milani et al., 2016). The risk factors are amplified during harvesting and processing due to manual handling, exposure to soil, and environmental conditions. Studies have shown that *B. cereus* and *C. perfringens* contamination often originates from soil, while *S. aureus* contamination typically reflects handling practices during processing (Jung et al., 2008).

Furthermore, irrigation with contaminated water can lead to persistent contamination in soil and subsequent transfer to crops. Research has shown that pathogens can survive in agricultural soils for extended periods, creating a reservoir for continuous contamination (Holvoet et al., 2014). The traditional processing methods, including sun-drying and manual separation of stigmas, may further contribute to microbial loads in the final product if proper hygiene practices are not maintained (Milani et al., 2016).

1.5 | UV-C treatment in food safety

Ultraviolet-C light (UV-C) radiation has emerged as a promising nonthermal decontamination technique for various agricultural products, including spices (Tabibian et al., 2020). The bactericidal effect is most significant between 250 and 270 nm wavelengths, with peak efficiency at 254 nm due to optimal photon absorption by microbial DNA (Koutchma et al., 2019). The mechanism involves both direct DNA damage through thymine dimer formation and indirect effects through the generation of reactive oxygen species. Studies have demonstrated significant reductions in microbial populations on various food products following UV-C treatment, though effectiveness varies with product surface characteristics and initial contamination levels (Jones et al., 2014).

However, UV-C treatment must be carefully optimized as excessive exposure can lead to undesirable changes in product quality. Research has shown that while higher doses may achieve greater microbial reduction, they can also lead to degradation of sensitive bioactive compounds, particularly in products like saffron that derive their value from specific chemical constituents (Gabriel & Ancog, 2019).

1.6 | Research objectives

Despite extensive research on individual aspects of saffron production and processing, the interactive effects of irrigation water quality and post-harvest UV-C treatment remain poorly understood. This study aimed to investigate the combined effects of UV-C radiation exposure time (0, 60, 120, and 180 min) and irrigation water quality (clean groundwater, treated wastewater, and fertilizer-enriched water) on both chemical composition (crocin, safranal, and picrocrocin content) and microbial safety of saffron stigmas. Understanding these interactions is crucial for developing integrated approaches that ensure both product safety and quality preservation in saffron production. The findings will contribute to establishing science-based guidelines for irrigation water quality management and post-harvest treatment protocols in saffron production systems.

Core Ideas

- Initial microbial loads were 2.4x higher in wastewater-irrigated saffron versus clean water irrigation (1250 vs. 520 CFU/g).
- UV-C for 180 min reduced contamination by 70% while degrading safranal and crocin content by 45% and 29%, respectively.
- Clean water irrigation enabled shorter UV-C exposure, better preserving saffron's bioactive compounds.

2 | MATERIALS AND METHODS

2.1 | Experimental design

A factorial experiment was designed to investigate the interactive effects of irrigation water quality and UV-C treatment on saffron quality parameters. The study examined three irrigation water quality treatments (clean groundwater as control, treated municipal wastewater, and chemical fertilizer-enriched water) and four UV-C exposure times (0, 60, 120, and 180 min), resulting in 12 treatment combinations. Each treatment combination was replicated three times in a completely randomized design, yielding 36 experimental units in total.

2.2 | Plant material and initial processing

Saffron (*Crocus sativus* L.) flowers were harvested from commercial fields in Sabzevar, Khorasan Razavi, Iran, during the autumn flowering season of 2023–2024. Following established protocols (Saeidirad et al., 2014), flowers were hand-collected between 5:00 and 9:00 a.m. to maintain optimal stigma quality. Only fully closed flower buds were selected based on their demonstrated higher safranal content compared to semi-opened and fully opened flowers (Del Campo et al., 2010). The processing of approximately 2400–2700 flowers required 3–3.5 h total, including 20–24

TABLE 1 Irrigation water quality was used in this experiment as treatments.

Parameter	Clean groundwater	Treated wastewater	Fertilizer-enriched water
pH	7.1 ± 0.2	7.8 ± 0.3	6.5 ± 0.2
Total dissolved solids (mg/L)	220 ± 10	850 ± 20	460 ± 15
Electrical conductivity (dS/m)	0.45 ± 0.02	1.35 ± 0.05	0.91 ± 0.03
Chemical oxygen demand (mg/L)	12 ± 1.2	65 ± 3.5	30 ± 2.0
Nitrate (mg/L)	4.2 ± 0.3	22.5 ± 1.5	18.0 ± 1.2
Nitrite (mg/L)	0.5 ± 0.1	3.8 ± 0.2	2.1 ± 0.1
Total coliforms (MPN/100 mL)	<1 (not detected)	110 ± 10	45 ± 5
Microbial load (log CFU/mL)	4.72	8.10	5.94

Abbreviations: CFU, colony forming unit; MPN, most probable number.

TABLE 2 Mean squares from analysis of variance for effects of irrigation water quality and ultraviolet-C light (UVC) radiation exposure time on saffron quality parameters.

Source of variation	df	Safranal	Crocin	Picrocrocin	Contamination
Irrigation water quality	2	2.6**	0.027ns	10.09**	151,256.5**
UV-C exposure	3	241.95**	240.38**	117.96**	3782.3**
Interaction	6	57.33**	126.61**	134.26**	39,348.7**
Error	36	0.345	2.565	1.079	326.4

Abbreviation: ns, nonsignificant.
** depict significance at 1% and 5%, respectively.

min for collection and 2.5–3 h for stigma separation. Stigmas were carefully separated from flowers within 2–3 h of harvest to minimize quality degradation.

2.3 | Irrigation treatments

Irrigation treatments were established following modified protocols from previous studies (Mousavi-Kia & Khashei-Siuki, 2015). Three water quality conditions were evaluated as follows: (1) clean groundwater (control) sourced from local agricultural wells, (2) treated municipal wastewater obtained from the local treatment facility, and (3) clean water supplemented with NPK chemical fertilizer (20:20:20, applied at 100 kg/ha). The drip irrigation system consisted of lateral lines spaced 30 cm apart, with emitters placed at 30 cm intervals. The wetting coverage extended approximately 25 cm in diameter per emitter. Water samples from each treatment were collected and analyzed for water quality assessment (Table 1). Irrigation scheduling was based on soil moisture monitoring to maintain optimal growing conditions across all treatments. Saffron was irrigated six times during its growth cycle. The first irrigation was applied on September 29 when temperatures dropped below 17°C, to facilitate sprouting. Following the first irrigation, soil scratching was performed to break soil crusting. The second irrigation was conducted immediately after the flower harvesting period (December 2), ensuring minimal direct contact between irrigation water and saffron stigmas. Notably, no irrigation was applied during the flowering period (late October to late November), reducing the risk of direct water contamination on the stigmas. The third irrigation took place on December 22nd, supporting root development. The fourth and fifth irrigations were primarily supplemented by precipitation (snow and rainfall) during February and early March. The sixth irrigation, occurring in April, was applied as necessary depending on rainfall levels. Liquid fertilizers were sprayed in February and March, and two weeding events were carried out in April and May to control weeds. This irrigation schedule was designed to optimize saffron growth while conserving water and minimizing stigma exposure to irrigation water.

2.4 | UV-C radiation treatment

Fresh stigmas were subjected to UV-C radiation using a modified version of the system described by Tabibian et al. (2020). UV-C treatment was applied to fresh saffron stigmas to assess its direct effects on microbial contamination and bioactive compound stability, without the influence of additional processing factors. While drying is known to reduce microbial load due to moisture loss, and saffron itself exhibits antimicrobial properties that further lower microbial contamination during storage, our objective was to isolate the impact of UV-C treatment. By applying UV-C before drying, we aimed to evaluate its efficiency in microbial decontamination without interference from drying or storage-related microbial reductions. This approach provides a clearer understanding of UV-C's effectiveness as a standalone treatment for improving saffron safety and quality and could be added to current

TABLE 3 Effects of ultraviolet C light radiation exposure time on saffron quality parameters irrigated with clean water.

Treatment (min)	Safranal (E1% 330 nm)	Crocin (E1% 440 nm)	Picrocrocin (E1% 257 nm)	Microbial Count (CFU/g)
0 (Control)	40.5a	268.9a	89.2b	1425a
60	35.2b	240.2b	85.6c	850b
120	28.7c	215.5c	93.8a	625c
180	22.4d	190.8d	88.4b	480d

Note: Values represent mean ± standard deviation ($n = 3$). Different letters within a column indicate statistically significant differences at $p < 0.05$ based on Tukey's multiple range test.
Abbreviation: CFU, colony forming unit.

commercial dryers as module to lower saffron microbial contamination during drying process. The treatment chamber was equipped with low-pressure mercury vapor lamps (TUV30W-G30T8, 260 W, emission peak at 254 nm). Following established protocols for optimal UV exposure (Gabriel et al., 2018), samples were placed on sterile stainless-steel trays at a fixed distance of 30 cm from the UV source. Four exposure durations were tested: 0 (control), 60, 120, and 180 min, based on previously determined effective ranges (Butot et al., 2018). The radiation intensity at the sample surface was continuously monitored using a calibrated UV radiometer and maintained at 1.70 mW/cm^2, consistent with parameters established in previous studies (Gabriel & Ancog, 2019).

2.5 | Chemical analysis of quality components

Bioactive compounds were extracted and quantified following modified ISO (International Organization for Standardization) 3632 protocols. A 500 mg sample of dried stigma powder was carefully weighed using an analytical balance (precision 0.0001 g) and transferred to a 1000-mL volumetric flask wrapped in aluminum foil to prevent photodegradation. Approximately 900 mL of deionized water was added, and the solution was mixed using a magnetic stirrer at 1000 rpm for 1 h in darkness. The volume was adjusted to 1000 mL with deionized water.

A 20 mL aliquot was transferred to a 200 mL volumetric flask and diluted to volume. The solution was filtered through filter paper using a Buchner funnel under vacuum. Spectrophotometric analysis was performed using a UV/VIS Spectrometer at wavelengths of 440 nm for crocin, 330 nm for safranal, and 257 nm for picrocrocin. Compound concentrations were calculated using established extinction coefficients and expressed as E1% values following methods described by Torki-Harchegani et al. (2017).

2.6 | Microbiological analysis

Microbial contamination was assessed using standard plate count methods following procedures described by Milani et al. (2016). Growth media included MacConkey Agar and Peptone Water (Merck). Dried stigmas were ground using a sterile mortar and pestle, and 1 g samples were homogenized in sterile peptone water. The solution was vortexed for 1 min followed by serial dilutions. Using a calibrated micropipette, 45 µL of each dilution was spread on appropriate growth media using sterile spreaders. Plates were sealed with Parafilm and incubated at 37°C. Colony counts were performed daily for three consecutive days. Total aerobic bacteria were enumerated on plate count agar, while specific pathogen analyses included *E. coli* on MacConkey agar and total coliforms using the most probable number technique. All microbiological analyses were performed in triplicate.

2.7 | Statistical analysis

The experiment followed a completely randomized design with three replications. Data were analyzed using analysis of variance (ANOVA) with SAS JMP statistical software. Treatment means were compared using Tukey's multiple range test at $p < 0.05$ significance level. The relationships between UV exposure time, water quality parameters, and measured variables were evaluated using regression analysis where appropriate. Principal component analysis (PCA) was conducted using JMP statistical software to identify patterns in saffron quality parameters based on irrigation and UV-C exposure and investigate multivariate relationships between treatments and quality parameters. The analysis included eigenvalue decomposition and component loading calculations to assess variable contributions.

3 | RESULTS AND DISCUSSION

3.1 | General effects of treatments

ANOVA revealed highly significant effects ($p < 0.01$) of both irrigation water quality and UV-C radiation exposure on most quality parameters of saffron (Table 2). The main effect of irrigation water quality was significant for safranal, picrocrocin, and microbial contamination levels, but notably not

TABLE 4 Effect of irrigation water quality on saffron quality parameters without ultraviolet treatment.

Irrigation treatment	Safranal (E1% 330 nm)	Crocin (E1% 440 nm)	Picrocrocin (E1% 257 nm)	Microbial count (CFU/g)
Clean water	38.6a	230.5a	95.4a	520c
Chemical fertilizer	37.8a	228.7a	87.1b	875b
Wastewater	31.4b	227.9a	86.8b	1250a

Note: Values represent mean ± standard deviation ($n = 3$). Different letters within a column indicate statistically significant differences at $p < 0.05$ based on Tukey's multiple range test.

TABLE 5 Interactive effects of UV-C exposure and irrigation water quality on microbial contamination (CFU/g).

UV-C exposure (min)	Clean water	Chemical fertilizer	Wastewater
0	980c	1350b	1945a
60	425e	850d	1275b
120	320f	650e	905d
180	355f	450e	635e

Note: Values represent mean ± standard deviation ($n = 3$). Different letters within a column indicate statistically significant differences at $p < 0.05$ based on Tukey's multiple range test.
Abbreviations: CFU, colony forming unit; UV-C, ultraviolet C light.

TABLE 6 Interactive effects of ultraviolet C light (UV-C) exposure and irrigation water quality on saffron quality parameters.

Quality parameter	Safranal			Crocin			Picrocrocin		
UV-C exposure (min)	Clean water	Chemical fertilizer	Waste water	Clean water	Chemical fertilizer	Waste water	Clean water	Chemical fertilizer	Waste water
0	42.3a	41.8a	37.4b	268.9a	267.7a	245.6b	95.4a	94.9a	92.55a
60	40.1a	39.7a	25.8c	240.2b	238.2c	217.3d	87.1b	86.4b	84.7b
120	36.2b	35.8b	24.1c	215.5d	196.0e	203.4e	86.8b	84.0b	84.4b
180	25.8c	24.9c	18.5d	190.8e	178.2f	180.4f	95.4a	74.9c	75.0c

Note: Means followed by the same letter in each quality category are not significantly different at $p < 0.05$ according to Tukey's test.

for crocin content ($p > 0.05$). UV-C exposure time significantly affected all measured parameters ($p < 0.01$), showing its broad impact on both bioactive compounds and microbial safety. Significant interaction effects between irrigation and UV-C treatments ($p < 0.01$) for all parameters except crocin indicate that the response to UV-C treatment varies depending on pre-harvest irrigation conditions.

3.2 | Effect of UV-C radiation exposure on quality parameters

UV-C radiation significantly influenced all measured quality parameters (Table 3). Progressive exposure to UV-C resulted in steady degradation of safranal, with content decreasing from 40.5 to 22.4 E1% 330 nm after 180 min exposure. This pronounced effect on safranal aligns with findings by Torki-Harchegani et al. (2017) who demonstrated that safranal is particularly sensitive to processing conditions. The degradation pattern observed may be attributed to the compound's molecular structure and its susceptibility to photo-oxidation, as previously documented in studies of saffron processing (Carmona et al., 2005).

Crocin content showed similar sensitivity to UV-C exposure, decreasing from 268.9 to 190.8 E1% 440 nm over the treatment period. This finding supports previous research by Chen et al. (2020) who identified UV sensitivity as a key factor in crocin stability during processing. However, the degradation rate was less severe than for safranal, suggesting different mechanisms of photo-degradation for these compounds.

Picrocrocin exhibited a unique response pattern, initially decreasing at 60 min (85.6 E1% 257 nm) before reaching peak levels at 120 min (93.8 E1% 257 nm) and then declining again. This nonlinear response may be explained by the complex biochemical pathways involved in picrocrocin metabolism, as described by Lage and Cantrell (2009). The temporary increase at 120 min could result from UV-induced conversion of precursor compounds before eventual degradation at longer exposure times.

TABLE 7 Correlation coefficients between ultraviolet C light (UV-C) exposure time, bioactive compounds, and microbial parameters.

Parameters	UV-C time	Safranal	Crocin	Picrocrocin	Microbial count
UV-C time	1.000	−0.845**	−0.892**	−0.241ns	−0.934**
Safranal	−0.845**	1.000	0.824**	0.156ns	0.798**
Crocin	−0.892**	0.824**	1.000	0.188ns	0.856**
Picrocrocin	−0.241ns	0.156ns	0.188ns	1.000	−0.203ns
Microbial count	−0.934**	0.798**	0.856**	−0.203ns	1.000

Abbreviation: ns, nonsignificant.
** significance at 1%, respectively.

TABLE 8 Eigenvalues and variance explained by principal components.

Principal component	Eigenvalue	Variance (%)	Cumulative variance (%)
PC1	2.845	56.90	56.90
PC2	1.268	25.36	82.26
PC3	0.587	11.74	94.00
PC4	0.300	6.00	100.00

TABLE 9 Component loadings for measured variables.

Variable	PC1	PC2
UV-C time	−0.945	0.182
Safranal	0.892	−0.236
Crocin	0.856	−0.312
Picrocrocin	0.241	0.788
Microbial count	−0.934	−0.156

Abbreviation: UV-C, ultraviolet C light.

3.3 | Effect of irrigation water quality on quality parameters

Irrigation water quality significantly affected most quality parameters except crocin content (Table 4). Saffron irrigated with clean water maintained higher safranal levels (38.6 E1% 330 nm) compared to wastewater irrigation (31.4 E1% 330 nm), while chemical fertilizer treatment showed intermediate effects (37.8 E1% 330 nm). This aligns with findings from Pirasteh-Anosheh et al. (2023) who demonstrated that water quality influences secondary metabolite production in saffron.

The most striking effect of irrigation water quality was observed in microbial contamination levels, which were significantly higher in wastewater-irrigated samples (1250 CFU/g) compared to clean water irrigation (61.5 CFU/g). This substantial difference supports concerns raised by Milani et al. (2016) regarding microbial safety in saffron production. The higher initial contamination in wastewater-irrigated samples presents particular challenges for post-harvest processing and food safety management.

Notably, crocin content showed remarkable stability across irrigation treatments (227.9–230.5 E1% 440 nm), suggesting that biosynthesis and accumulation of this valuable compound may be more influenced by genetic and developmental factors than irrigation water quality. This finding contrasts with picrocrocin levels, which were significantly higher in clean water-irrigated samples (95.4 E1% 257 nm) compared to both chemical fertilizer and wastewater treatments (87.1 and 86.8 E1% 257 nm, respectively).

3.4 | Interactive effects of treatments on microbial contamination

The significant interaction between irrigation water quality and UV-C exposure (Table 5) reveals complex relationships in treatment responses. The effectiveness of UV-C treatment in reducing microbial contamination varied notably depending on irrigation water quality.

UV-C treatment was particularly effective in reducing microbial loads across all irrigation treatments, with the greatest relative reduction observed in wastewater-irrigated samples (67.4% reduction after 180 min). This enhanced effectiveness can be attributed to UV-C's mechanism of action, which Milani et al. (2016) described as involving both DNA damage and oxidative stress on microbial cells. The interaction effect was also evident in bioactive compound retention, particularly for safranal and picrocrocin (Table 6).

The interaction patterns reveal that samples from wastewater irrigation showed greater sensitivity to UV-C exposure, with safranal content declining more rapidly compared to other irrigation treatments. This enhanced sensitivity could be attributed to changes in tissue structure or cellular stress responses induced by wastewater irrigation, as suggested by recent findings in saffron post-harvest physiology (Torki-Harchegani et al., 2017). Changes in tissue structure observed in wastewater-irrigated saffron may result from oxidative stress caused by higher levels of dissolved salts and contaminants. Increased salinity and potential heavy metal presence can disrupt cell wall integrity and enzyme

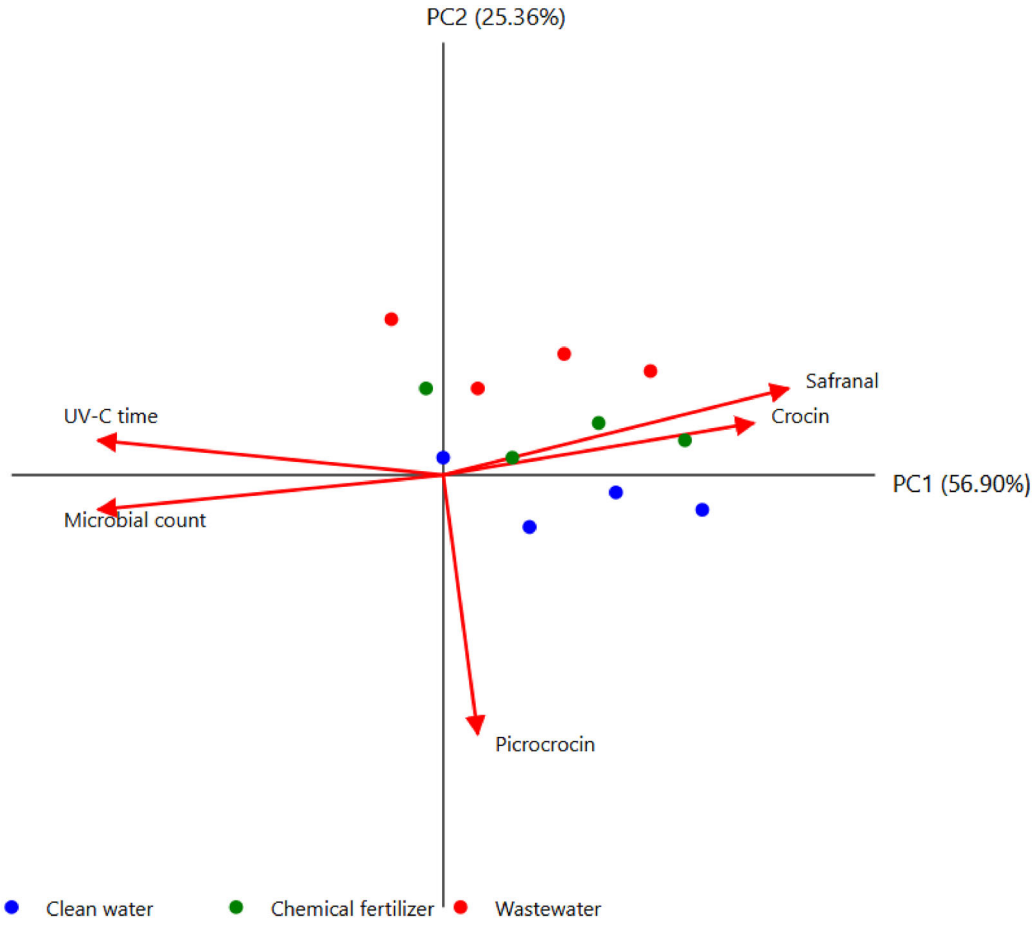

FIGURE 1 Principal component analysis (PCA) biplot showing relationships between treatments and saffron quality parameters. Red arrows indicate loading vectors for measured variables (safranal, crocin, picrocrocin, microbial count, and ultraviolet-C light [UV-C] exposure time). Treatment combinations are represented by points colored according to irrigation water quality (blue: clean water, green: chemical fertilizer, red: wastewater). The length of each vector indicates the strength of variable contribution to the principal components, while angles between vectors represent correlations between variables. PC1 and PC2 explain 56.90% and 25.36% of total variance, respectively. The opposing directions of bioactive compounds versus UV-C time and microbial count along PC1 illustrate the trade-off between quality preservation and microbial control. Treatment points cluster primarily by UV-C exposure time along PC1 and irrigation water quality along PC2, with optimal conditions appearing in the upper right quadrant.

activity, making bioactive compounds more susceptible to UV-C degradation.

3.5 | Correlation analysis

Correlation analysis revealed several significant relationships between measured parameters (Table 7). The UV-C treatment significantly affected both bioactive compounds and microbial parameters. Analysis showed strong negative correlations between UV-C exposure time and both safranal ($r = -0.845^{**}$) and crocin ($r = -0.892^{**}$) contents. This indicates that longer UV-C exposure consistently reduces these valuable compounds, aligning with their known photosensitivity reported in previous studies (Torki-Harchegani et al., 2017).

Picrocrocin showed a unique nonlinear relationship with UV-C exposure, making simple correlation analysis less informative. The quadratic relationship observed (peaking at 120 min) suggests complex biochemical responses that merit further investigation.

Microbial contamination showed strong negative correlation with UV-C exposure time ($r = -0.934^{**}$) and positive correlation with initial water quality parameters. The highest contamination levels were consistently associated with wastewater irrigation (1250 CFU/g) compared to clean water (520 CFU/g), demonstrating the importance of irrigation water quality in initial microbial loads.

3.6 | Principal component analysis

PCA was performed to investigate the multivariate relationships between UV-C exposure time, irrigation water quality, and saffron quality parameters. The first two principal

components explained 82.26% of the total variance in the dataset (Table 8), indicating that most of the variation in quality parameters can be described by these two dimensions.

PC1 accounted for 56.90% of total variance and primarily represents a quality degradation axis. The high negative loading of UV-C exposure time (−0.945) indicates that moving along PC1 corresponds to increasing treatment duration. This is associated with decreasing safranal and crocin contents (loadings of 0.892 and 0.856, respectively), while also reducing microbial counts (−0.934) (Table 9). The strong opposing loadings between bioactive compounds and microbial contamination on PC1 illustrate the key challenge in UV-C treatment optimization—balancing microbial control against preservation of valuable compounds.

PC2 explained an additional 25.36% of variance and was most strongly characterized by picrocrocin content (loading of 0.788). The distinct behavior of picrocrocin on PC2, relatively independent of PC1, aligns with its observed nonlinear response to UV-C treatment, where peak values occurred at intermediate exposure times. This suggests that picrocrocin stability follows different mechanisms compared to other bioactive compounds during UV-C exposure.

The biplot visualization reveals clear separation of treatment combinations in multivariate space (Figure 1). Samples cluster primarily by UV-C exposure time along PC1, with longer treatments moving toward the negative PC1 axis (higher microbial control but lower compound retention). Irrigation water quality effects are captured along PC2, with clean water treatments generally showing more positive PC2 scores compared to wastewater irrigation.

Treatment optimization targets can be identified from the biplot pattern. The most favorable combinations appear in the upper right quadrant, where moderate UV-C exposure (60–120 min) combined with clean water irrigation achieves acceptable microbial reduction while maintaining relatively high levels of bioactive compounds. This multivariate perspective provides deeper insight into treatment interactions than univariate analyses alone and helps identify optimal processing conditions that balance multiple quality objectives.

4 | CONCLUSION

The combined effects of irrigation water quality and UV-C radiation significantly influence both the bioactive compounds and microbial safety of saffron stigmas. UV-C treatment effectively reduced microbial contamination across all irrigation treatments, with exposure times of 120–180 min achieving the lowest contamination levels (480–625 CFU/g). However, extended UV-C exposure negatively impacted bioactive compounds, with safranal and crocin contents decreasing by 44.7% and 29%, respectively, after 180 min of treatment. Picrocrocin showed a unique response pattern, peaking at 120 min of exposure (93.8 E1% 257 nm) specifically in clean water-irrigated samples. Wastewater irrigation resulted in consistently higher initial microbial loads (1250 CFU/g) and lower safranal content (31.4 E1% 330 nm) compared to clean water irrigation (520 CFU/g and 38.6 E1% 330 nm, respectively), demonstrating the importance of irrigation water quality in both food safety and product quality. PCA revealed that moderate UV-C exposure (60–120 min) combined with clean water irrigation provides an optimal balance between microbial control and preservation of valuable compounds. These findings suggest that careful optimization of both irrigation practices and UV-C treatment parameters is crucial for maintaining saffron quality while ensuring microbial safety. Future research should investigate potential synergistic effects between UV-C and other preservation technologies, as well as examine the long-term stability of treated samples under various storage conditions.

AUTHOR CONTRIBUTIONS

Hadi Fatehi: Investigation; writing—original draft. **Hamed Kaveh**: Conceptualization; formal analysis; funding acquisition; methodology; project administration; resources; supervision; writing—review and editing. **Vahid Tahan**: Formal analysis; investigation; methodology; supervision. **Safieh Vatandoost**: Formal analysis; methodology; supervision; writing—review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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