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Investigating the feasibility of detecting counterfeit saffron using thermal imaging techniques

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Abstract

Saffron, the world's most valuable spice, faces significant fraud risks; this study investigates thermal imaging as a rapid, non-invasive method for its authentication, revealing key findings on distinct thermal properties differentiating pure from counterfeit saffron, highlighting its practical applications in quality control. Experiments were carried out under controlled conditions using saffron solutions prepared at three chamber temperatures (15, 25, and 35 °C) and saffron solution concentrations (0.5, 2.5, and 4 g/200 mL). Thermal diffusion rates were calculated and analyzed to distinguish pure saffron from counterfeit solutions. The results showed that increasing saffron concentration from 2 g/200 mL to 4 g/200 mL enhanced the thermal diffusion rate by approximately 33%, while raising the chamber temperature from 15 °C to 35 °C led to a 48% increase. Counterfeit saffron (Saffron Ink™) consistently exhibited higher thermal diffusion rates, indicating significant differences in thermal properties. These findings demonstrate that thermal imaging is a practical and reliable tool for saffron quality control and fraud prevention.

Keywords Saffron · Counterfeit detection · Thermal camera · Thermal diffusion · Non-contact method · Saffron quality control

Introduction

Saffron (*Crocus sativus* L.), known as “red gold,” is one of the world's most precious and expensive spices due to its unique aroma, taste, and color [1–4]. Its high economic value, however, makes it a significant target for fraud and counterfeiting, posing serious risks to consumers, the industry, and global trade [5]. The increasing prevalence of counterfeit saffron necessitates the development of reliable and efficient detection methods. Conventional methods for detecting counterfeit saffron, such as spectroscopy, electronic nose, electronic tongue, gas chromatography, liquid chromatography, and near-infrared spectroscopy, offer high accuracy but are often prohibitively expensive, time-consuming, and require specialized expertise for sample preparation and result interpretation [6–9]. This highlights a critical need for rapid, cost-effective, and user-friendly alternatives for quality control.

Thermal imaging, or thermography, represents a novel approach for assessing food quality parameters [10]. This technique leverages infrared radiation within the electromagnetic spectrum of 9 to 14 μm to capture detailed thermal

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profiles. The generated images, initially grayscale, are processed into pseudo-color formats to enhance interpretability [11]. The non-destructive and non-contact nature of thermal imaging makes it particularly appealing for applications in quality control. The images created by the thermal camera are basically black and white that are converted into pseudo color images with the help of the internal processor of the camera.

In the food and agricultural sector, thermal imaging has been successfully applied to monitor quality attributes and physiological changes in various fruits. For example, infrared cameras have been used to assess quality indices and optimal storage conditions in pineapple during cold storage, demonstrating the potential of thermography to support postharvest logistics decisions [10]. Several studies on guava, mango, apple, tomato, date palm, and citrus have further shown that subtle temperature differences on the fruit surface can be exploited to discriminate between ripeness stages, healthy and damaged tissues, sunburnt areas, and bruised versus sound fruits [12–17]. Reported temperature contrasts between classes are often on the order of 0.3–1.0 °C, yet they have been sufficient to enable classification models for grading and sorting [12–16]. These works collectively confirm that thermography can capture meaningful thermal signatures related to product quality in horticultural commodities.

Despite these promising results, most thermographic studies in horticulture have focused on solid products with relatively simple geometries and limited thermal mass. The imaging setups are often tailored to specific fruits, controlled laboratory conditions, and short observation times, which may limit their direct transferability to other products or more complex matrices such as liquid food systems. Moreover, many existing works emphasize qualitative or semi-quantitative assessments (e.g., visual classification or simple temperature thresholds), leaving room for more systematic, quantitative analysis of thermal diffusion phenomena in food authentication problems.

Beyond quality grading, thermal imaging has also been explored for contaminant detection. For instance, an infrared imaging setup combining a thermal camera with halogen lamps was developed to identify malathion-contaminated tomatoes, where significant temperature differences between treated and control samples were observed at around 40 °C [18]. Although this study highlighted the potential of infrared imaging as a rapid screening tool for pesticide residues, the approach relied on externally imposed heating conditions and was tested in a very specific matrix, raising questions about its generalizability to other food products and fraud scenarios.

Despite the growing body of work on thermographic assessment of fruits and other agricultural products [10, 12–18], our literature review indicates that thermal imaging

has not yet been systematically explored for detecting counterfeit saffron or for quantifying thermal diffusion in saffron solutions. This gap is critical given the global concern about saffron adulteration, particularly in major producing and exporting countries such as Iran.

The present study therefore aims to evaluate the feasibility of using thermal imaging as a rapid and reliable approach to distinguish counterfeit saffron from pure samples. More specifically, we address the following research questions:

Can thermal imaging effectively discriminate between pure saffron solutions and a commercially available counterfeit saffron-colored solution?

How do the thermophysical properties, in particular the apparent thermal diffusivity, differ between pure and counterfeit saffron solutions, and can these differences be quantified from the propagation of pseudo-color temperature zones in thermal images?

What is the effect of saffron concentration (e.g., 0.5–4 g/200 mL) on the measured thermal diffusion rate?

How does the ambient chamber temperature (e.g., 15–35 °C) influence the thermal diffusion behavior of saffron solutions?

Based on these findings, can the proposed thermal imaging protocol be recommended as a practical tool for saffron authentication?

To address these questions, we developed a dedicated experimental prototype and conducted controlled thermal imaging experiments on pure and counterfeit saffron solutions under different concentration and temperature conditions.

2. Material and methods

Theory

Thermal diffusivity

In heat transfer analysis, the thermal diffusivity (α) is a physical property that represents the ratio of thermal conductivity to heat capacity. It is measured in square meters per second (m^2/s) and plays a vital role in understanding how fast the heat is spread through a material. The formula for thermal diffusivity is expressed as follows [19].

$$\alpha = \frac{k}{\rho C_p} \quad (1)$$

where k is thermal conductivity, $\text{W m}^{-1} \text{K}^{-1}$, C_p is specific heat capacity, $\text{J kg}^{-1} \text{K}^{-1}$, and, ρ is density, kg m^{-3} . Since thermal diffusivity depends on the physical and thermal properties of materials, it is reasonable to expect that the heat transfer rate will differ between the counterfeit and pure

saffron solutions. So, to justify this hypothesis, a setup was developed in this study as shown in Fig. 1. To investigate heat transfer patterns, various solution samples (different concentrations) of pure saffron and counterfeit ones commercially available in a market (Saffron Ink) was prepared. The thermal diffusion rate was calculated for different temperature zones within the solution samples. In order to determine thermal diffusivity, in thermal images, the propagation area of various temperature spans (in cm^2) was calculated over the time domain.

System description

The imaging setup used in this research includes the following components. 1. Thermal camera, 2. Heating Element, 3. Temperature controller, 4. Sample, 5. Heater.

The imaging chamber is a cube box made up of 0.02 m thick medium density fiber (MDF) sheets with dimensions of $0.6 \times 0.6 \times 0.6$ m. The thermal camera holder was located on the top surface of the chamber. The solution samples were poured into rectangular glass containers with dimensions of $0.08 \times 0.15 \times 0.03$ m, a 60 W heating element was installed on an adjustable support base to provide a local heat source inside the glass container. An electrical heater coupled with an air circulation fan was located inside the chamber to set the ambient temperature of the chamber. A temperature controller ensured the

constant temperature inside the chamber by controlling the heater using an ON/Off controller. An image of the test rig is shown in Fig. 2.

Experimental trials

The experiments were conducted at the Biosystems Engineering Department of Shahid Bahonar University of Kerman, Iran. The High-quality saffron was directly purchased from a saffron grower of South Khorasan province, Qaen city, and stored in a refrigerator at 4°C in sealed containers. The saffron samples were then ground using a commercial miller (Black and Decker, JBG60, China) and sieved to obtain a uniform powder with the mesh size of 60. The experiments were conducted at three levels of the chamber's ambient temperature (15°C , 25°C , and 35°C), and four levels of the saffron solution concentrations, including 0.5 g/200 mL, 2.5 g/200 mL, and 4 g/200 mL water. Also, a saffron colored solution that is used as the food additive and called the saffron ink TM in the local markets was obtained from a local market in Kerman city to be used as the counterfeit saffron. Each solution was stored in the glass containers. Around 2 h before starting each test the solution container was kept in the imaging chamber, where its temperature had been set based on the test condition, to reach equilibrium temperature. The heating element was placed in the corner of the container, and the experiments lasted for 4 min. Each test started with turning on the heating element and thermal images were captured during the test in one minute time intervals by using the pre-installed thermal camera above the solution container.

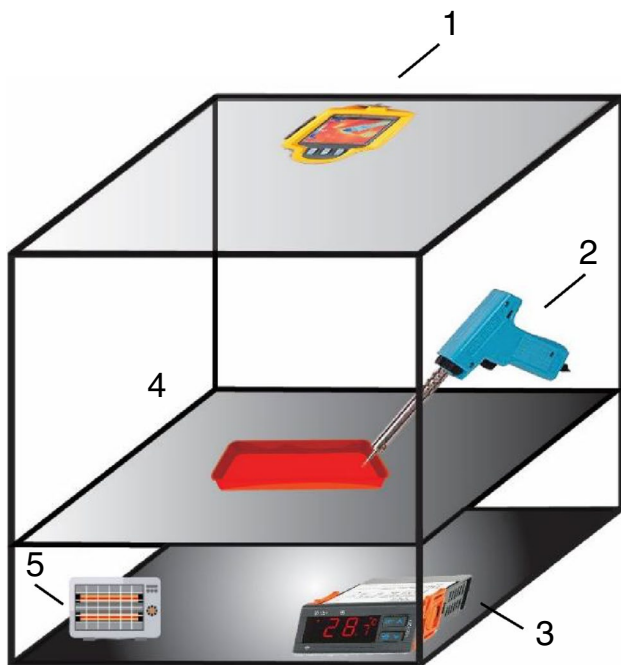


Fig. 1 Schematics of the imaging system components: 1. Thermal camera, 2. Heating Element, 3. Temperature controller, 4. Sample, 5. Heater



Fig. 2 The test rig and thermal imaging setup

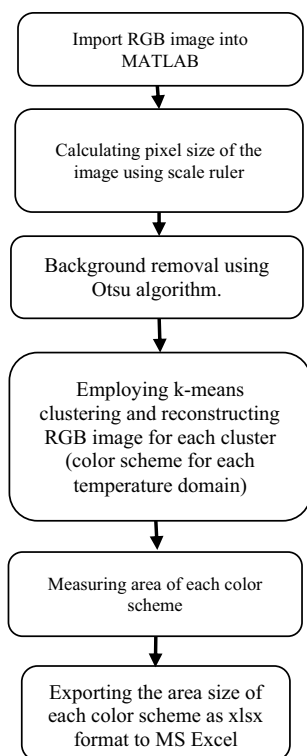


Fig. 3 Diagram image processing algorithm employed in MATLAB to determine the the temperature span/ pseudo color zone areas

Measured parameters and measurement instruments

In order to determine the heat diffusion patterns within the solutions, thermal images of all samples were captured and analyzed.

The measurement instruments used in the study were a thermal camera (FLIR ONE™, USA. The device has a resolution of 640×480 pixels, a spectral span of $8\text{--}14\ \mu\text{m}$, and a temperature range of $-20\ ^\circ\text{C}$ to $120\ ^\circ\text{C}$. A MATLAB™ software (R2021a) was used for image analysis of thermal images and, the results were statistically analyzed using SPSS 16.0 software.

To compare thermal diffusion within the prepared solutions the propagation rate of different pseudo color zones in the thermal images including temperature spans of $36\text{--}38\ ^\circ\text{C}$, $38\text{--}40\ ^\circ\text{C}$ and $40\text{--}42\ ^\circ\text{C}$, were determined.

Figures 3 and 4 illustrate the procedure of measuring the area of each temperature span in thermal images using image processing technique in MATLAB. After uploading the image in MATLAB, the area of each pixel was determined by counting number pixels in a length of 1 cm on a ruler as scale to compensate for variations in the distance between saffron solution container and thermal camera. Background elimination was done by using Otsu segmentation method and determining the proper threshold value

[20]. By selecting the ROI and employing the “Roipoly” function the exact region for thermal diffusivity calculations was determined (Part of the image that includes scale ruler should be cropped). To discriminate different color span in the thermal image, the predefined Kmeans clustering algorithm was applied to the segmented and cropped image [21]. The number of clusters was defined based on temperature spans specified in the FLIR one software. By counting the total number of pixels in each cluster and calculating the area (in mm^2) the total area for each temperature span was calculated over the time and the output results were transferred to spreadsheet in xlsx format. The image processing procedure in MATLAB to identify different temperature spans is illustrated in Fig. 4.

Figure 5 shows images of the pure saffron solution and the saffron ink™. Both solutions appear similar such that the differences cannot be visually distinguished.

Results and discussion

Samples of thermal images taken during the tests are shown in Fig. 6. This figure also shows how different temperature spans, represented by pseudo color zones, propagate within the solutions.

Analysis of Variance (ANOVA) results for the effect of the chamber temperature and the solution concentration on propagation rate of the three temperature spans ($36\text{--}38\ ^\circ\text{C}$, $38\text{--}40\ ^\circ\text{C}$ and, $40\text{--}42\ ^\circ\text{C}$, respectively indicated by Red, Yellow, and Green colored schemes) are presented in Table 1.

Table 1 indicates that the interaction between concentration and chamber temperature significantly affected the propagation rate of all pseudo-color zones ($P\text{-value} < 0.01$), highlighting the complexity of heat transfer kinetics in saffron solutions. While, higher concentrations of saffron solutions generally led to the increase in thermal diffusion rate, the growth rate was influenced by the chamber temperature as well. Similarly, the effect of temperature on the thermal diffusion rate was moderated by differences in saffron solution concentrations. It suggests that the influence of individual factors including the concentration and the chamber temperature on thermal diffusion cannot be fully understood in isolation but must be considered in conjunction to each other.

By considering the interaction effects of concentration and chamber temperature the quality control experts or inspectors can tune up the processing parameters to maximize the detecting resolution. Additionally, understanding the interdependence of these factors can guide future research efforts aimed at further elucidating the underlying mechanisms of heat transfer in saffron solutions and exploring potential applications in various fields.

The results of mean comparison for the interaction effect of the main factors of the experiment based on

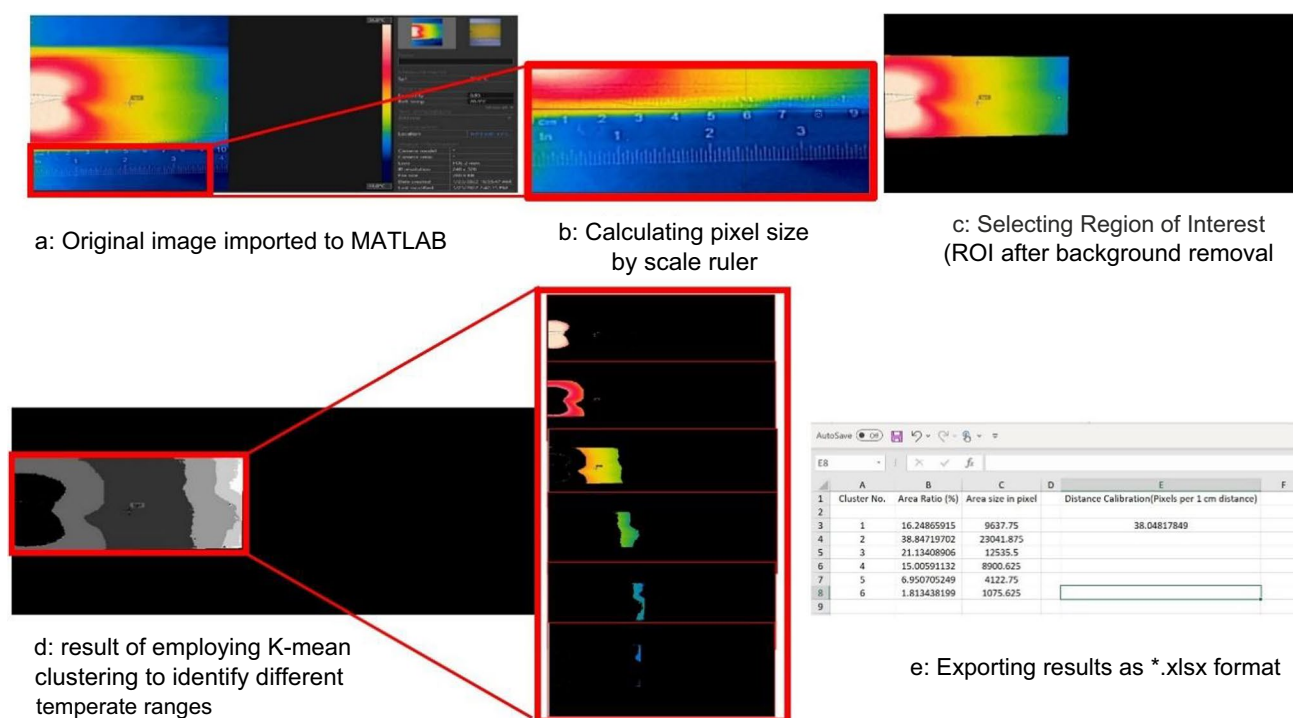


Fig. 4 Image processing procedure in MATLAB to identify different temperature spans

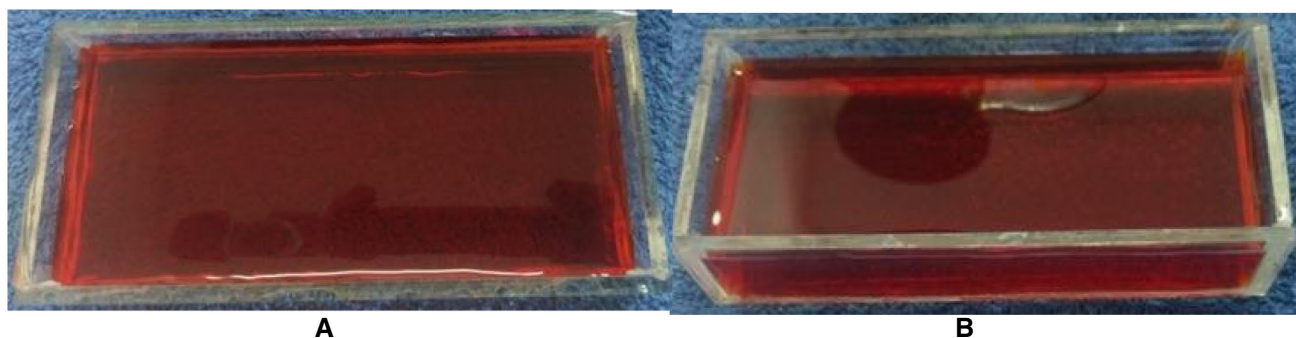


Fig. 5 A: the pure saffron solution, B: the saffron ink TM

Duncan's post hoc test for propagation rate of red, yellow, and green color schemes are shown in Figs. 7–9, respectively (Fig. 8) and (Fig. 9)

Heat propagation to temperature variations, supporting observed thermal diffusion patterns in the pseudo yellow zone.

As can be seen from Figs. 7–9, the propagation rate of all pseudo color zones increased by raising the solution concentration at each chamber temperature. This is because saffron is composed of bioactive compounds such as: safranal, crocin, and picrocrocin, and, which contribute to its aroma, color, and taste, respectively [22]. These compounds have specific molecular structures and bonding patterns that

influence thermal properties of the solutions [23, 24]. The molecular bonds within saffron compounds, such as: hydrogen bonds and Van der Waals forces, play a crucial role in determining the rate of heat propagation [25]. These bonds facilitate the transfer of thermal energy between molecules, enhancing thermal diffusion rate within the solution. In the other words, variations in concentration affects the number of saffron molecules present in the solution. This reasonably influenced the solution properties such as: density and thermal conductivity, which are key components of thermal diffusion [19]. Moreover, at higher temperatures, the thermal energy stimulates molecular motion, leading to the breaking and reforming of the molecular bonds [26]. This

Fig. 6 Thermal images of A: 0.5 g/200 mL B: 2.5 g/200 mL C: 4 g/200 mL D: Saffron ink™, at the chamber temperature of 25 °C after 4 min

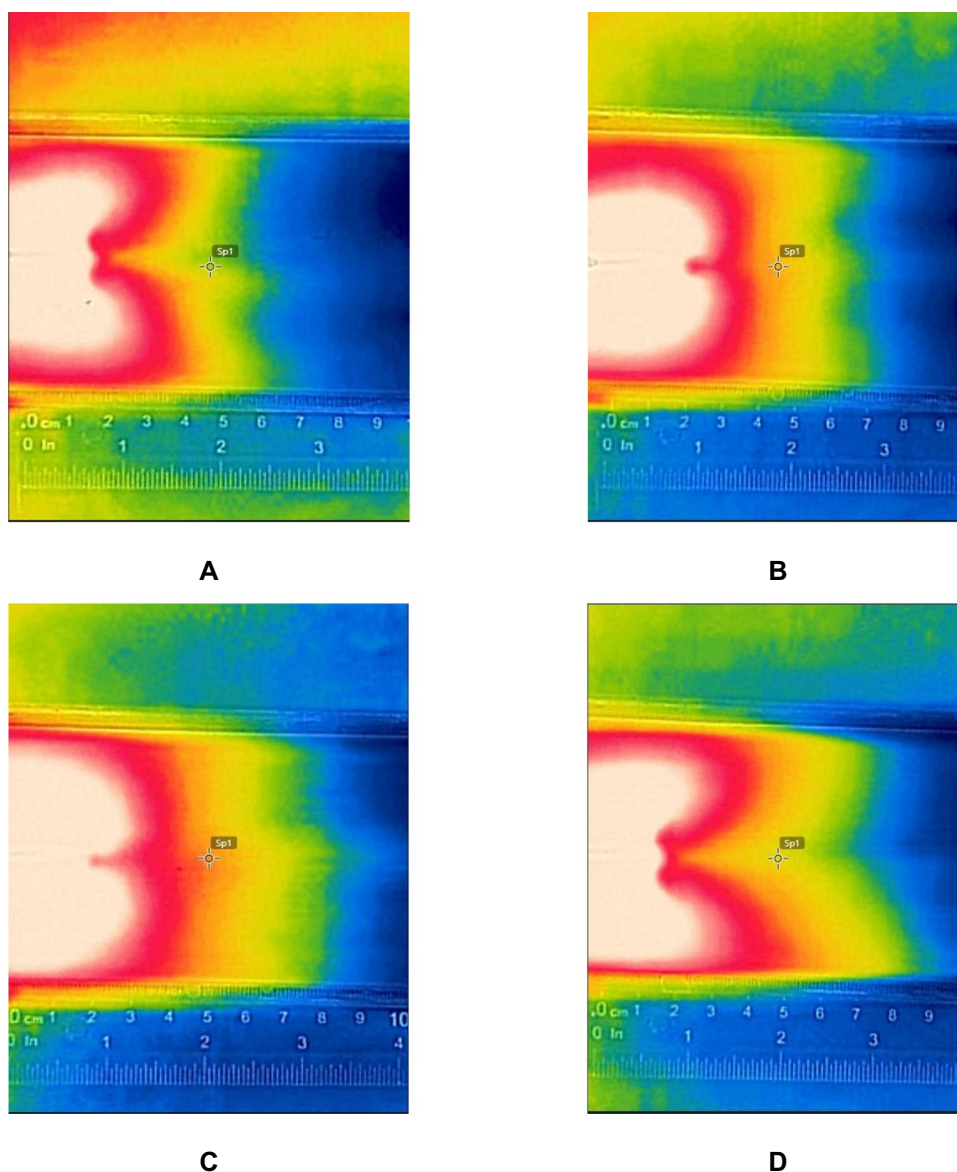


Table 1 Result of ANOVA of area propagation rate (thermal diffusion)

Source of Variation	df	Mean Squares		
		Pseudo Red	Pseudo Yellow	Pseudo Green
Concentration (A)	3	5.714**	12.744**	0.98**
Chamber temperature (B)	2	4.069**	8.757**	3.708**
A×B	6	0.284**	0.369**	0.156**
Experimental Error	24	0.008	0.096	0.036
Total	36			

**: Significant difference at the 0.01 level, df: degree of freedom

increases molecular mobility, which subsequently enhances thermal diffusion within saffron compounds and resulted in that higher thermal diffusion values observed with elevated temperatures.

By comparing Figs. 7–9, it is crystal clear that the color scheme's propagation rate in saffron ink™ is notably faster than in pure saffron solutions across all the chamber temperatures. The maximum difference and the corresponding

Fig. 7 The effect of the concentration and the chamber temperature on propagation rate of the red color scheme which represents the temperature span of 33–35 °C

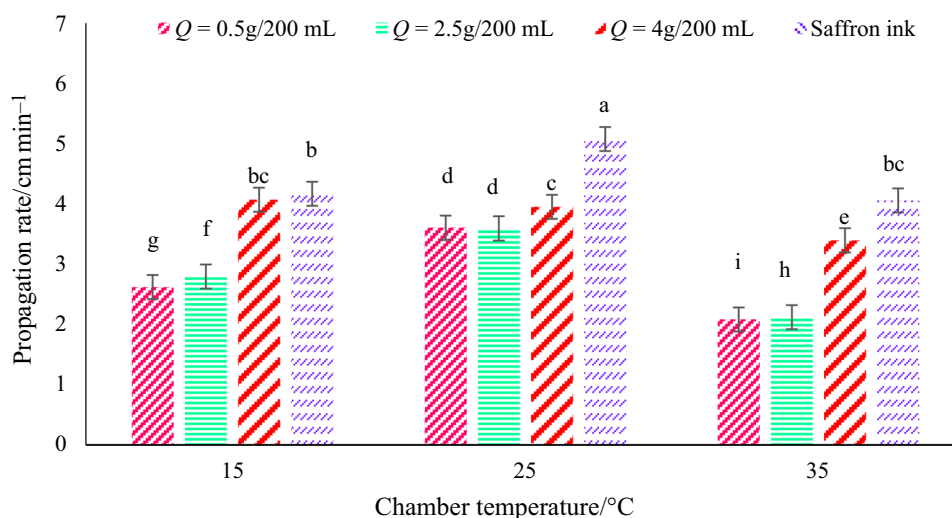
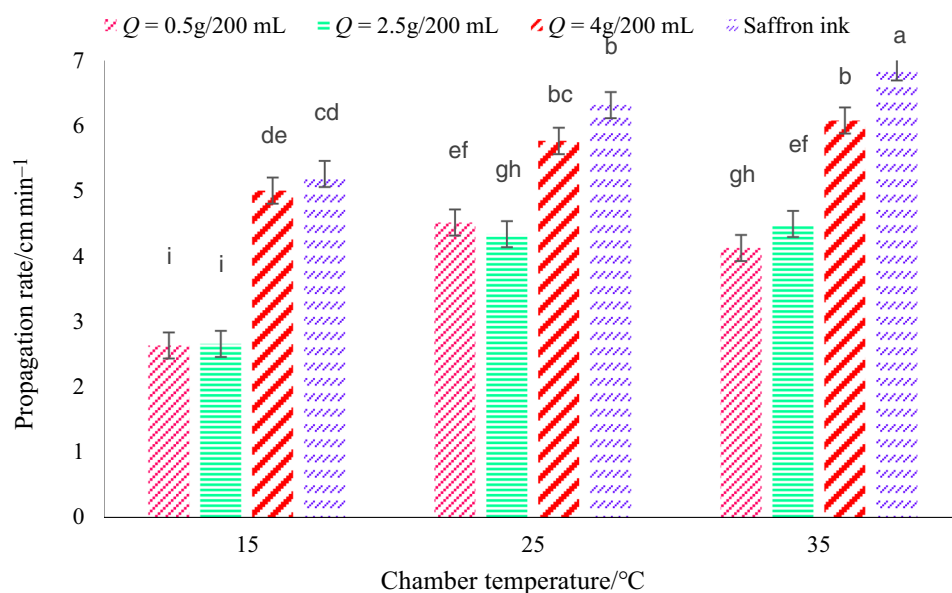


Fig. 8 The effect of the concentration and the chamber temperature on the propagation rate of the pseudo yellow zone, representing the temperature span of 31–33 °C



chamber temperature at which this difference was observed for each pseudo color zone are listed in Table 2. This discrepancy strongly indicates the difference between the compounds involved in pure saffron solutions and saffron inkTM.

Thermal diffusion refers to the process of heat transfer from regions of higher temperature to regions of lower temperature within a medium. The rate at which this heat transfer occurs, or the speed of heat propagation, is influenced by several factors, including the temperature gradient and thermal properties of the medium.

Figures 7–9 also reveal that the higher chamber temperatures lead to higher heat propagation rate values, indicating a faster heat transfer within the solution. This takes place

because the temperature rise results in greater internal thermal energy, which in turn, increases the motion and kinetic energy of the solute particles. As a result, the transfer of heat energy between the particles becomes more rapid, leading to a higher thermal diffusion rate.

In summary, the thermal imaging analysis sheds light on the intricate interaction between solution concentration, chamber temperature, and thermal diffusion characteristics within saffron-based solutions and saffron inkTM. The observed trends in the propagation rates of the pseudo colors of red, yellow, and green zones unveil valuable insights into the thermal properties of saffron compounds.

Fig. 9 The effect of the concentration and the chamber temperature on the propagation rate of in the green zone representing the temperature span of 29–3 °C

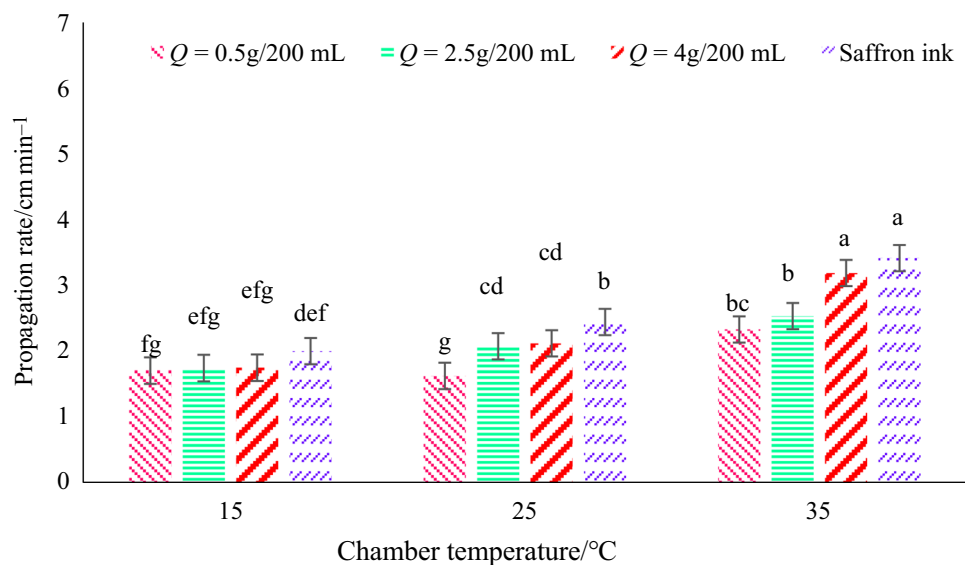


Table 2 The maximum propagation rate difference of pseudo color zones between pure saffron solutions and saffron ink™ and their corresponding chamber temperature

Corresponding chamber temperature / °C	The maximum propagation difference / %	Pseudo color
15	56.67	red
15	57.14	yellow
25	40	green

Conclusions

This study the possibility of distinguishing counterfeit saffron from the pure ones using thermal imaging was investigated. The main idea behind this proposed method came from the hypothesis that since counterfeit saffron differ with the pure saffron, thus their physical material properties, especially thermal properties are different too. To justify this hypothesis, a thermal imaging setup was developed in this study. The experiments were carried out at four different pure saffron solution concentrations and three imaging chamber temperatures. Furthermore, a commercial pseudo saffron solution, Saffron ink was also used as a counterfeit saffron because of its similar appearance characteristics to saffron solution. The propagation rate of pseudo color zones in the thermal images were measured to represent thermal diffusion within the solutions. The results revealed that increasing the saffron concentration from 2 to 4 g/200 mL increased thermal diffusion by approximately 33%. Similarly, an increment of ~48% observed when raising the chamber temperature from 15 °C to 35 °C. Since the thermal diffusion of the counterfeit saffron was higher than that of the pure saffron solutions at all chamber temperatures. The proposed

approach can be recommended as a reliable basic method to distinguish counterfeit saffron.

Authors contributions Sadegh Rashidi Kouchi-Conducting experiments; Hamid Morteza pour-Project supervisor; Zeinab Rezvani-Writing paper; Mohammadmehdi Maharlooei-Image processing; Kazem Jafarinaeimi-Advisor.

Declarations

Conflict of interest The authors declare no competing interests related to this research. **Saffron Ink™** (used for the counterfeit saffron in the study) is a product under investigation in this study. The authors confirm that there is no financial relationship or conflict of interest with the product or its distributors.

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