Chapter 17

Dehydration of saffron stigmas

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Chapter Outline

17.1 Introduction

Most foods are highly perishable, and therefore awareness of shelf-life is vital if products are to be stored in a warehouse or by the consumer for substantial periods. Drying is a traditional and useful method for keeping solid foods safe for long periods of time. When food products are exposed to drying conditions, the native physical state of the food product is altered, leading to changes in the quality and safety of the food product. Drying involves removal of excess water from the food matrix until a "safe" moisture level is achieved, at which minimal or no physical, chemical, or microbiological reactions occur.

Moisture content in saffron is a critical parameter for preservation of its characteristics (Alonso et al., 1993). To keep saffron preserved for a longer period of time, it should be dried. Postharvest processing, such as drying methods and storage conditions, determines the stability of saffron, which directly affects the market value of the product. Drying operations therefore need to be precisely controlled and optimized. This is necessary to produce a high-quality product that has the highest level of color and flavor, while maintaining microbiological safety. During the dehydration process, the stigmas lose ~80% of their weight. A lower moisture content, at least below 12%, maintains the quality of saffron for a longer time (International Standard ISO 3632).

Drying must be done in a proper way to achieve the right moisture content level. If the stigmas are not dried soon after picking, they are attacked by molds. On the other hand, if saffron is dried too much, it breaks easily, turns into powder, and loses weight to below the trade requirements. The equilibrium moisture content is dependent on the temperature and relative humidity of the environment as well as the species, variety, and maturity of the plant (Iglesias and Chirife, 1982; Rahman, 1995).

The dehydration process not only plays an important role in the preservation of saffron, but it is a critical step in development of the principal substance responsible for saffron's aroma, safranal (Del Campo et al., 2010). Fresh stigmas are not able to impart their organoleptic characteristics to food. A dehydration treatment, which is necessary to convert *Crocus sativus* L. stigmas into saffron spice, brings about the physical, biochemical, and chemical changes necessary to achieve the desired attributes of saffron (Carmona et al., 2005). The most obvious characteristic of saffron is its deep red color. The high gloss of fresh stigmas becomes dull upon drying, and a strong yellow extract passes into water upon wetting the dried stigmas.

Water activity (a_w) is an important parameter to assess the shelf-life of foods. Many desired and undesired physical changes in food can be correlated to the water activity of the system. Furthermore, water activity can have a major

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impact on the color, taste, and aroma of foods. The loss of saffron color is reduced at medium water activity of 0.43−0.53 (Tsimidou and Biliaderis, 1997) and the development of safranal is promoted.

17.2 Drying methods

Drying by any method requires considerable skill to ensure a high-quality spice. The main attributes that determine the market value and quality of saffron are color, aroma, and taste. The compounds responsible for these attributes are crocins, safranal, and picrocrocin, respectively. The quantities of these compounds in saffron depends mainly on the method by which the stigmas are dried. The drying process differs from country to country (Ordoudi and Tsimidou, 2004), and the different conditions of drying and aging affect the saffron constituents (Carmona et al., 2005). Low-temperature drying processes are favorable for maintaining high bioactivity of desired biocomponents in the final product. A minimal change in nutritional values is targeted during low-temperature processes.

Generally, there are two forms of saffron dehydration: traditional and industrial drying. Three different procedures are employed depending on the temperature used for dehydration: sundried or at room temperature with ventilation (India, Iran, and Morocco), mild temperature (Greece and Italy), and high temperature (Spain) (Carmona et al., 2005).

17.3 Traditional methods

The traditional method of drying saffron varies from country to country and depending on the availability of required equipment (Acar et al., 2011). Natural sun drying is considered to be the most common drying method for saffron worldwide. Solar drying, in sun or in shade, has been used for many years because of its simplicity and low investment cost although it results in a photochemical decrease in color intensity. Natural sun drying takes place outdoors, and the product is directly exposed to sunlight and open to risk of contamination. Therefore, the ultraviolet solar light can degrade or isomerize the carotenoids in saffron.

These drying methods are still used in Iran, India, and Morocco for drying of saffron stigmas. In Iran and Morocco, the stigmas are handled very gently and spread in a very thin layer on a large cloth. They are then exposed to the sun for several hours or placed in shade for 7−10 days. Drying is completed before the stigmas break or crumble. Air-dried saffron retains its purplish red color, its fragrance, and its aroma. In India, the stigmas are solar-dried for 3−5 days until their moisture content is reduced to 8%−10%. However, these methods raise some problems such as long drying time and microbial contamination of the dried materials (Gregory et al., 2005).

17.4 Artificial drying methods

Some modern drying methods have replaced the age-old drying method of fine mesh screens held over burning coals (Raines Ward, 1988). Artificial drying methods are carried out at higher temperatures and have been employed in saffron processing in some countries such as Spain, Greece, and Italy (Carmona et al., 2006). High-temperature drying processes require a strong heat supply for the removal of moisture from the food sample. The heat can be supplied in many ways such as microwave, radio frequency, hot gas stream including air, superheated steam, etc. The hot gas stream is the most frequently used heat source for large-scale commercial industries due to its increased availability, easier heat recovery, and cheaper cost compared to other heat sources. For this method the saffron is dried by means of hot air flow or by placing it on a heater. According to Carmona et al. (2005), the highest coloring strength was obtained when saffron was submitted to higher temperatures and shorter times. These findings may be supported by the fact that samples dehydrated at high temperature were more porous than those dehydrated at room temperature.

In Italy, the process is carried out by spreading the fresh stigmas on a sieve placed ∼20 cm above live oak-wood embers. Halfway through the process, the stigmas are turned over to ensure homogeneous drying. The process is considered finished when saffron stigmas retain between 5% and 20% moisture and possess a certain amount of elasticity when pressed between the fingers (Tammaro, 1999). Saffron dried over charcoal maintains its organoleptic qualities better; its purplish red color, its fragrance, and its aroma will be retained (Zanzucchi, 1987).

Drying saffron in Spain is accomplished by placing a layer of fresh stigmas less than 2 cm thick on a sieve with a silk bottom. The sieve is placed over the heating source, which can be a gas cooker, live vineshoot charcoal, or, less often, an electric coil. In Castile−La Mancha, in the central Spain the most used source is a gas cooker, followed by embers from kermes oak, or occassionally electrical sources (Alonso et al., 1998). The process is finished when the sample has lost between 85% and 95% of its moisture after being dried at 50°C−80°C for 30−60 minutes. At the halfway point of the process when 10–15 minutes have passed, the entire mass is turned over with the help of another sieve of the same type, which is again placed over the heating source to finish the drying process.

In Greece, when stamens and stigmas are dried together, the stamens' pollen pollutes and deteriorates the red saffron. It is therefore recommended to separate them before drying. The drying process starts by placing a thin layer of freshly harvested stigmas (4–5 mm) on 40 × 50 cm trays with fine silk screen. These trays are piled on frames with shelves 25–30 cm apart. The frames are then placed in a dark room or in a storage room with controlled temperature, which are then heated with a firewood stove. During the first few hours of the drying process, the temperature is maintained at 20°C and then raised to 30°C–35°C. The drying process is stopped when the moisture content of the product reduces to 10%–11% after 12 hours. If the red (stigmas and styles) and yellow (stamens) components of saffron are still together after drying, they can be separated at this stage. At the same time, all foreign substances (soil, hairs, threads, etc.) are removed from the dried saffron product. The pure dried saffron is kept in hermetically sealed glass vases or tin cans at 5°C–10°C.

In spite of some advantages of industrial dryers including achievement of hygienic conditions, quality control, reduction of product loss, and decreased process duration, the energy requirement of drying technology is one of the key problems that should be overcome. The drying process generally consumes large amounts of energy and releases carbon oxides into the environment. Therefore, it is crucial to assure not only good quality of the dried products but also high energy efficiency and low environmental impact (Aghbashlo et al., 2013).

17.5 Hybrid photovoltaic–thermal solar dryer

The energy required for drying, which is mostly for the production hot air, is mainly supplied by fossil fuels. The global demand for fossil fuels and the consequent increase in their prices, the insecurity of their supply, and environmental concerns have resulted in increasing interest in using renewable energies sources such as solar power.

Solar energy in its first form (sunlight) can be converted into heat by thermal solar collectors or into electricity by photovoltaic solar cells. A new technology has been developed to combine both types of conversions; this technology is called the solar photovoltaic/thermal collector (PV/T). Hybrid PV/T systems, or PVTs, are systems that convert solar radiation into thermal and electrical energy. These systems combine a solar cell, which converts sunlight into electricity, with a solar thermal collector, which captures the remaining energy and removes waste heat from the PV module (Fig. 17.1). Results of various studies have shown that such hybrid systems are more efficient than both individual photovoltaic and thermal systems.

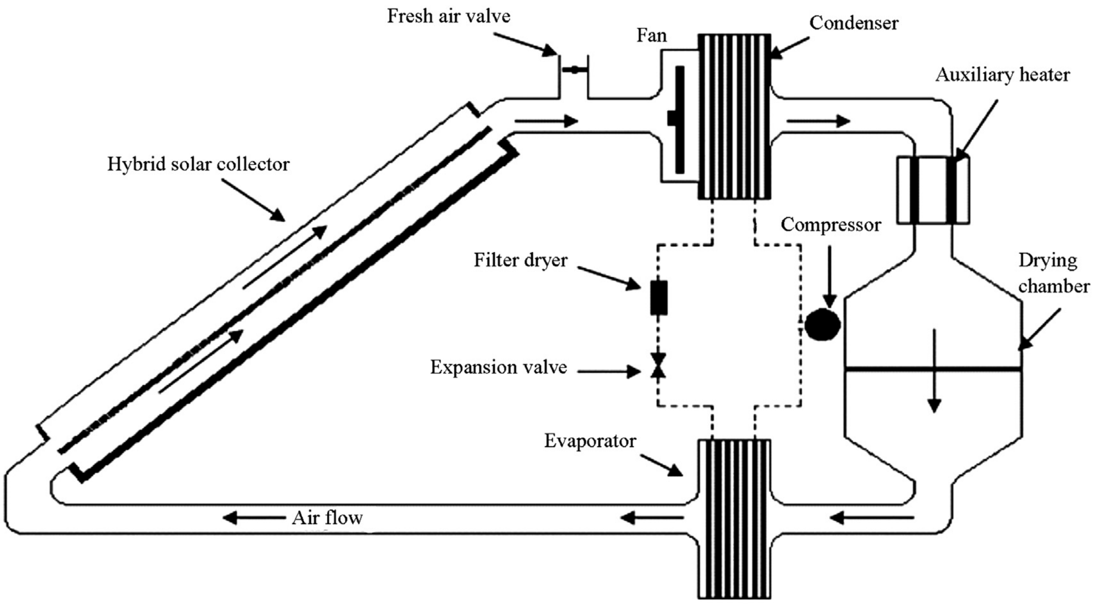

FIGURE 17.1 Schematic diagram of heat pump-assisted hybrid PV/T solar dryer. *From Mortezapour, H., Ghobadian, B., Khoshtaghaza, M.H., Minaei, S., 2014. Drying kinetics and quality characteristics of saffron dried with a heat pump assisted hybrid photovoltaic-thermal solar dryer. J. Agr. Sci. Tech. 16, 33–45.*

In a hybrid PV/T solar dryer, a photovoltaic panel provides the thermal energy required for both moisture removal from the products and electrical power for a fan to circulate air through the dryer. Mortezapour et al. (2012) used a hybrid PV/T system for drying saffron stigmas. To improve the quality of the final product, a heat pump was also added to the system, making it suitable for heat-sensitive materials such as saffron stigma. The sides and back wall of the solar air collector were constructed from wood and insulated by glass wool. A glass sheet was used as the transparent front cover of the solar collector, and a photovoltaic panel was fixed at the middle of the collector sides, with equal distances from the wooden back wall and the top glass cover, to work as the solar irradiance absorber plate. The arrangement of the dryer's components and the heat pump system, which were connected together by glass wool-insulated round ducts, created a system in which the drying air was circulated in a closed cycle through the evaporator, solar air collector, condenser, auxiliary heater, and drying chamber, respectively. A fresh air valve was deployed to allow ambient fresh air to enter the dryer's duct and mix with the drying air when temperature and relative humidity of the drying air were more than their desirable set values. Fresh saffron stigma (moisture content of 80% wb) were spread on a tray and placed inside the drying chamber.

Results showed that drying time decreased by 62% as the air temperature increased from 40°C to 60°C. Utilizing the heat pump system with the hybrid solar dryer improved drying rate and shortened the drying time by 60%. The color of saffron also improved when drying temperature increased and the heat pump system was applied. Saffron dried with heat pump-assisted hybrid PV/T had great aromatic properties with no significant changes in its bitterness.

As a result of these improvements, total drying time and energy consumption are decreased with use of a hybrid PV/T solar dryer. Applying a heat pump with the dryer leads to further reduction in the drying time and energy consumption and an increase in the electrical efficiency of the solar collector. The average total energy consumption is reduced by 33% when the dryer is equipped with a heat pump. Maximum values for electrical and thermal efficiency of the solar collector are 10.8% and 28%, respectively. A maximum dryer efficiency of 72% and a maximum specific moisture extraction rate were obtained at an air flow rate of 0.016 kg s^{-1} and air temperature of 60°C when using the heat pump (Mortezapour et al., 2014).

17.6 Infrared thin-layer drying

Infrared radiation (IR) is an increasingly popular method of supplying heat for drying of moist materials. Infrared drying involves heat transfer by radiation between a hot element and a material at lower temperature that needs to be dried. The peak wavelength of the radiation depends on the temperature of the heated element (Fig. 17.2). IR heating presents advantages such as decreased drying time, high energy efficiency, and lower environmental impact. The energy of radiated waves is transferred from the source to the sample product without heating surrounding air, which leads to higher temperatures in the inner layers of the samples compared to surrounding air and thus a high rate of heat transfer (Celma et al., 2008).

Akhondi et al. (2011) investigated the drying of saffron stigma with a laboratory infrared dryer. The influence of temperature on the drying rate of samples at various temperatures (60°C, 70°C, 110°C) was studied. The drying time

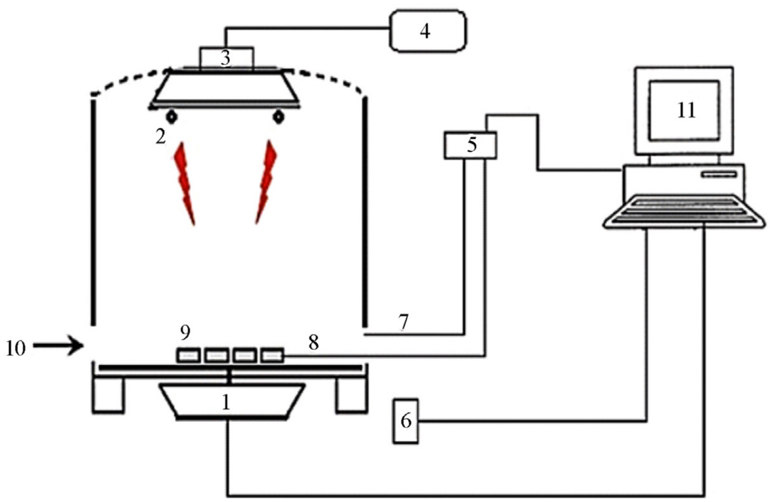

FIGURE 17.2 Infrared dryer setup schematic. *1*, digital balance; *2*, infrared heating tube; *3*, dimmer; *4*, fixed voltage power unit; *5*, data logger; *6*, hygrometer; *7*, k-type thermocouple; *8*, t-type thermocouple; *9*, samples; *10*, inlet cold air; *11*, PC. *From Ziaforoughi, A., Yousefi, A.R., Razavi, S.M.A., 2016. A comparative modeling study of quince infrared drying and evaluation of quality parameters. Int. J. Food Eng. 12, 1–9.*

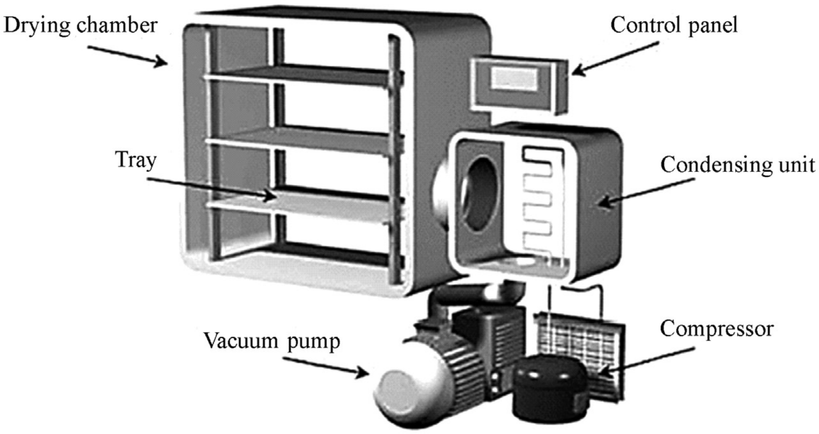

FIGURE 17.3 Schematic diagram freeze dryer used for saffron dehydration experiment. *From Acar, B., Sadikoglu, H., Doymaz, I., 2015. Freeze-drying kinetics and diffusion modeling of saffron (*Crocus sativus *L.). J. Food Process. Preserv. 39, 142–149.*

decreased with an increase in drying air temperature. According to Torki-Harchegani et al. (2017) the total crocin content increased when the IR dryer temperature increased to up to 90°C, but at higher temperatures the amount of crocin slightly decreased. The total safranal content of the samples decreased when the IR drying temperature increased from 60°C to 70°C and then continuously increased to up to 110°C. The amount of picrocrocin also increased as the IR drying temperature increased from 60°C to 100°C. As a result, the maximum values of crocin and safranal were obtained in the samples treated at the highest IR drying temperature.

17.7 Freeze drying

The freeze-drying process can be considered as a drying method for stigmas of the saffron flower (Acar et al., 2015). Freeze drying, also known as lyophilization, is a dehydration process typically used to preserve a perishable material or to make the material more convenient for transport. Freeze drying works by freezing the material and then reducing the surrounding pressure to allow the frozen water in the material to sublime directly from the solid phase to the gas phase (Fig. 17.3). Sublimation is when a solid (ice) changes directly to a vapor without first going through a liquid (water) phase. Controlled freeze drying keeps the product temperature low enough during the process to avoid changes in the dried product's appearance and characteristics. Therefore, heat-sensitive materials, fine chemicals, biotechnological products, and some pharmaceuticals, which might lose their quality (activity) in conventional evaporative drying, can be safely freeze-dried (Sadikoglu and Liapis, 1997; Sadikoglu et al., 2006). Compared with the other conventional dehydration processes, the highest quality dried product can be obtained by freeze drying.

The freeze-drying process is a multistage, relatively slow, and expensive (initial investment and operating costs are high) process.

Lyophilized saffron is a new product with a higher content of crocins, a consistent content of native compounds, and minimum water content (about 4%) in comparison to traditional dried saffron. For this reason it could be used as a standard substance to evaluate the quality and water content of saffron powder itself. At the same time the innovative method of lyophilization enables production of saffron with very low moisture content and consequently higher crocins content, longer shelf-life, greater stability, and higher coloring power.

In this method, stigmas are placed in the tray of the freeze dryer at a −40°C for 4 hours for complete freezing. The initial temperature of the freeze dryer is −30°C and increases gradually to 5°C without causing any melting or scorching of the stigmas. The drying chamber pressure should be kept at its minimum value (at least it should be well below the ice vapor pressure of the sample being freeze-dried). This increases water vapor mass flux through the pores of the dried material due to sublimation during the primary drying stage (Sadikoglu et al., 2003, 1998). The drying chamber pressure is set at 50 Pa and kept constant during drying.

Even though the initial investment and operation costs are high and the drying time is substantially longer than conventional drying methods, freeze drying is considered to be a good method for dehydration of saffron stigmas. The original shape and structure of the sample can be preserved during the freeze-drying process. Freeze-dried saffron not only contains high amounts of safranal and crocin but also has lower moisture compared with traditional and sun-dried saffron. Lower moisture content can prevent fading of the color of the saffron by limiting the degradation of crocin into crocetin during storage. The high cost of freeze drying saffron can be compensated for by keeping the safranal and crocin contents in the final product.

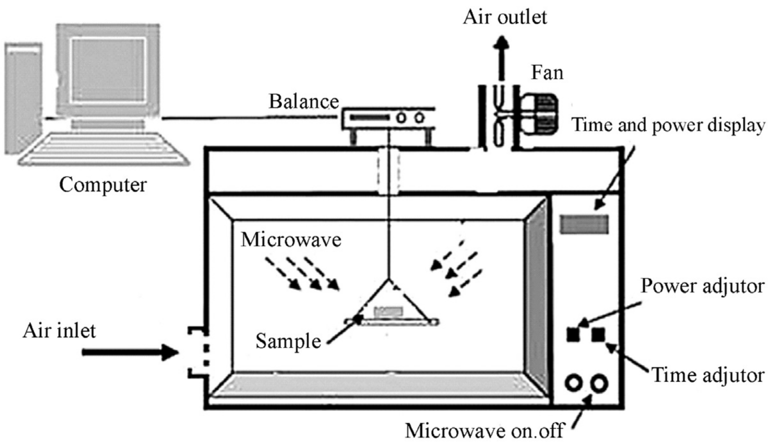

FIGURE 17.4 A schematic diagram of microwave−convective oven dryer. *From Zarein, M., Samadi, S. H., Ghobadian, B., 2015. Investigation of microwave dryer effect on energy efficiency during drying of apple slices. J. Saudi Soc. Agric. Sci. 14, 41−47.*

17.8 Microwave drying

The term "microwave" refers to electromagnetic radiation in the frequency range of 300 MHz to 300 GHz with a wavelength of 1 m^{-1} mm (Feng et al., 2012). Microwaves are not forms of heat but rather forms of energy that are manifested as heat through their interaction with materials. It is the propagation of electromagnetic energy through space by means of time-varying electric and magnetic fields (Fig. 17.4). Microwave energy makes it possible to control the drying process more precisely in order to obtain greater yields and better quality products in the shortest possible time.

The mechanism for drying with microwave energy is quite different from that of conventional drying. Microwaves initially excite the outer layers of molecules. The inner part of the material is warmed as heat travels from the outer layers inward. Most of the moisture is vaporized before leaving the material. This results in very rapid drying without the need to overheat the atmosphere and perhaps cause case hardening or other surface overheating phenomena. In microwave drying, energy is transferred through the material electromagnetically, not as a thermal heat flux. Therefore, the rate of heating is not limited and the uniformity of heat distribution is greatly improved. This results in a significant reduction in drying time, leading to significantly improved product quality (Schubert and Regie, 2006). In many cases microwaves are at least 50% more efficient than conventional systems, resulting in major cost savings.

Microwave drying can be used to improve the chemical profile of saffron in terms of safranal, which is responsible for its aroma. Microwave drying of saffron has a number of quantitative and qualitative advantages over conventional drying methods. In this method heat conductivities or heat transfer coefficients does not play such an important role. Therefore, saffron can be heated in a microwave dryer in a shorter time, with lower drying temperature, and with a more even temperature distribution. In microwave drying, treatments at lower microwave power and longer time benefit the quality of saffron. It only takes 3 minutes at 600 W to dry saffron when moisture is less than 12% and 6 minutes at 400 W. As a result, drying saffron stigma at moderate temperatures in a microwave oven results in saffron with better quality in terms of higher color strength, aroma, and taste.

17.9 Effects of drying on color, aroma, and taste

Postharvest processing such as drying methods and storage conditions determine the stability of saffron, which directly affects the market value of the product. The main active compounds in saffron are: crocins, a group of glycoside derivatives from the carotenoid crocetin; terpenic aldehydes known as safranal; and a glycoside terpenoid, picrocrocin. These compounds are responsible for saffron's coloring power, bitter taste, and aroma, respectively (Carmona et al., 2006). The quantities of these compounds in saffron are influenced by many factors. The dehydration treatment necessary to convert saffron stigmas into saffron spice is one of the most important factors (Carmona et al., 2006). The effect of temperature and other drying components on spice color and taste remain to be fully determined. There is some evidence that the three types of compounds (crocetin esters, picrocrocin and its related compounds, and volatiles) could be interrelated, as crocetin esters can generate as much picrocrocin as their analogues such as safranal and other volatile compounds (Carmona et al., 2007).

According to Raina et al. (1996), temperatures lower than 35°C−45°C are required for excessive enzymatic degradation of crocetin esters, the compounds responsible for saffron color. They found that crosin pigment content was highest in saffron dried between 35°C and 55°C either in solar or oven drying. Under these conditions safranal was at its peak value except for the vacuum oven dried samples.

On the other hand, using high temperature does not degrade the crocetin ester compounds. In fact, it increases the coloring strength and decreases other crocetin esters such as the trans-crocetin (β-D-glycosyl)-(β-D-gentibiosyl) ester and trans-crocetin (β-D-gentiobiosyl) ester (Carmona et al., 2005). According to Carmona et al. (2005), the highest coloring strength is obtained when saffron is submitted to higher temperatures and lower times. These findings were supported by the fact that samples dehydrated at high temperature were more porous than those dehydrated at room temperature. In addition there is evidence that high temperature promotes the production of compounds responsible for taste and aroma. Maghsoodi et al. (2012) also reported that higher amounts of safranal (aroma) and crocin (color) were obtained at high temperature. However, there was no significant difference between the amounts of picrocrocin at different temperatures.

Results by Gregory et al. (2005) showed that a brief (20 minutes) initial period at a relatively high temperature (80°C−92°C) followed by continued drying at a lower temperature (43°C) produced saffron with a safranal content up to 25 times more than that of saffron dried only at lower temperatures. Evidence was provided suggesting that drying with significant air flow reduced the safranal concentration. The results, moreover, indicated that high-temperature treatment had allowed greater retention of crocin pigments than in saffron dried at intermediate temperatures (46°C−58°C). The biochemical implications of the various treatments are discussed in relation to their potential for optimizing color and fragrance quality in the product.

The effect of mild temperature on the main components responsible for saffron quality during dehydration was studied by Del Campo et al. (2010). Based on their results, crocetin esters were not as labile as the bibliography mentioned before. Saffron coloring capability increased from 40°C, without finding significant differences with 55°C. A similar behavior was obtained for picrocrocin, that was higher at the highest temperature but without significant differences with the immediate inferior conditions. However, at higher temperatures (e.g., 55°C) more volatile compounds, especially safranal, were generated during the dehydration procedure.

The results of chromatographic analyses by Cossignani et al. (2014) also showed that samples dried in milder conditions had the lowest content of secondary metabolites such as crocins, picrocrocin, and safranal. Moreover, samples dried at 60°C for 55 minutes presented the highest contents of trans-crocin-4 and picrocrocin, while safranal was most prevalent compound in saffron dried at 55°C for 95 minutes. A detailed study by Tong et al. (2015) determined that the highest quality saffron is obtained when fresh saffron is treated at higher temperatures (no more than 70°C) for a long period by electric oven drying and vacuum oven drying.

As mentioned before, microwave radiation as a mild drying method is an efficient way for improving the chemical profile of saffron in terms of safranal. The total safranal content increases when saffron is dehydrated at moderate temperatures using microwaves (Muzaffar et al., 2015). Microwave drying retains the maximum concentration of safranal as compared with samples dried under shade. Therefore, microwave drying could be the best drying method for saffron stigmas in order to retain its aroma. According to Maghsoodi et al. (2012), among saffron drying methods, microwave drying obtained the highest amount of safranal at 1000 W. Under these conditions the amounts of crocin and picrocrocin were also high. Results by Tong et al. (2015) also showed that the chemical contents in saffron treated by microwave drying were higher than the other methods used and that the time spent in the drying process was also less. However, the antioxidant activity of these samples was not stronger, which means that other chemical compounds were formed in the samples treated by electric oven drying and vacuum oven drying processes.

The sarfanal content of the samples dried in a freeze dryer was found to be five times higher than the safranal content of the samples dried naturally under the sun. Crocin content of samples dried in a freeze dryer was about 40% higher than the crocin content of samples dried naturally under the sun. These results indicate that the safranal and crocin contents that define the quality and market value of commercial saffron were considerably higher in samples dried in a freeze dryer than in the samples dried traditionally under the sun (Acar et al., 2011).

17.10 Conclusion

Drying must be done in a proper way to achieve saffron with proper color, aroma, and taste. A dehydration treatment changes the physical and biochemical properties of saffron spice, which is necessary to achieve desired attributes. The quantities of crocins, safranal, and picrocrocin in saffron depend mainly on the method used for drying the stigmas. In traditional methods using solar and air drying, the carotenoids in saffron can be degraded. However, the purplish red color and aroma in saffron are retained when the air drying method is used. In artificial drying methods, such as drying over charcoal, the organoleptic qualities and its purplish red color are preserved. Due to environmental concerns, a solar photovoltaic/thermal collector dryer has been developed in order to decrease the total drying time and energy consumption for saffron drying. IR heating is another drying method, which has some advantages such as lower drying time, higher energy efficiency, and lower environmental impact. The maximum values of crocin and safranal were obtained in saffron dried at the highest IR temperature. In the microwave drying method, heat conductivity is not a critical factor, and saffron can be dried in a shorter time and at a lower temperature. Therefore, saffron will have higher color strength, aroma, and taste, with better quality. The total safranal content increases when saffron is dehydrated using microwave drying. Freeze-dried saffron has the highest quality when compared with other, conventionally dehydrated products. Saffron processed in this manner contains high amounts of safranal and crocin and also has lower moisture content. However, the initial investment and operational costs are high, and the drying time is substantially long.

References

Acar, B., Sadikoglu, H., Ozkaymak, M., 2011. Freeze drying of saffron (*Crocus sativus* L.). Dry. Technol. 14, 1622–1627.

Acar, B., Sadikoglu, H., Doymaz, I., 2015. Freeze-drying kinetics and diffusion modeling of saffron (*Crocus sativus* L.). J. Food Process. Preserv. 39, 142–149.

Aghbashlo, M., Mobli, H., Rafiee, S., Madadlou, A., 2013. A review on exergy analysis of drying processes and systems. Renew. Sustain. Energy Rev. 22, 1–22.

Akhondi, E., Kazemi, A., Maghsoodi, V., 2011. Determination of a suitable thin layer drying curve model for saffron (*Crocus sativus* L) stigmas in an infrared dryer. Sci. Iran. 18, 1397–1401.

Alonso, G.L., Varon, R., Salinas, M.R., Navarro, F., 1993. Auto-oxidation of crocetin and picrocrocin in saffron under different storage conditions. Boll. Chim. Farm. 132, 116–120.

Alonso, G.L., Salinas, M.R., Garijo, J., 1998. Method to determine the authenticity of aroma of saffron (*Crocus sativus* L.). J. Food Prot. 61, 1525–1528.

Carmona, M., Zalacain, A., Pardo, J.E., Alvarruiz, A., Alonso, G.L., 2005. Influence of different drying and aging conditions on saffron constituents. J. Agric. Food Chem. 53, 3974–3979.

Carmona, M., Zalacain, A., Alonso, G.L., 2006. The Chemical Composition of Saffron: Color, Taste and Aroma. Editorial Bomarzo SL, Albacete, Spain.

Carmona, M., Zalacain, A., Salinas, M.R., Alonso, G.L., 2007. A new approach of saffron aroma. Crit. Rev. Food Sci. Nutr. 47, 145–159.

Celma, A.R., Rojas, S., Lopez-Rodríguez, F., 2008. Mathematical modeling of thin-layer infrared drying of wet olive husk. Chem. Eng. Prog. 47, 1810–1818.

Cossignani, L., Urbani, E., Stella Simonetti, M., Maurizi, A., Chiesi, C., Blasi, F., 2014. Characterisation of secondary metabolites in saffron from central Italy (Cascia, Umbria). Food Chem. 143, 446–451.

Del Campo, C.P., Carmona, M., Maggi, L., Kanakis, C.D., Anastasaki, E.G., Tarantilis, P.A., et al., 2010. Effects of mild temperature conditions during dehydration procedures on saffron quality parameters. J. Sci. Food Agric. 90, 719–725.

Feng, H., Yin, Y., Tang, J., 2012. Microwave drying of food and agricultural materials: basics and heat and mass transfer modeling. Food Eng. Rev. 4, 89–106.

Gregory, M.J., Menary, R.C., Davies, N.W., 2005. Effect of drying temperature and air flow on the production and retention of secondary metabolites in saffron. J. Agric. Food Chem. 53, 5969–5975.

Iglesias, H.A., Chirife, J., 1982. Hand Book of Food Isotherms. Academic Press, New York, pp. 170–175.

Maghsoodi, V., Kazemi, A., Akhondi, E., 2012. Effect of different drying methods on saffron (*Crocus sativus* L.) quality. Iran. J. Chem. Chem. Eng. 31, 85–89.

Mortezapour, H., Ghobadian, B., Minaei, S., Khoshtaghaza, M.H., 2012. Saffron drying with a heat pump–assisted hybrid photovoltaic–thermal solar dryer. Dry. Technol. 30, 560–566.

Mortezapour, H., Ghobadian, B., Khoshtaghaza, M.H., Minaei, S., 2014. Drying kinetics and quality characteristics of saffron dried with a heat pump assisted hybrid photovoltaic-thermal solar dryer. J. Agr. Sci. Tech. 16, 33–45.

Muzaffar, S., Zaman Khan, K., Riaz, M., Mir, J.A., Ahmed, A., 2015. Aroma of Kashmir saffron (*Crocus sativus* L.) and variation of safranal content by different drying methods. J. Chem. Pharm. Res. 7, 111–115.

Ordoudi, E., Tsimidou, M., 2004. Saffron quality: effect of agricultural practices, processing and storage. In: Dris, R., Jain, S.M. (Eds.), Production Practices and Quality Assessment of Food Crops. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 209–260.

Rahman, M.D.S., 1995. Hand Book of Food Properties. CRC Press, New York, pp. 2–11.

Raina, B.L., Agarwal, S.G., Bhatia, A.K., Gaur, G.S., 1996. Changes in pigments and volatiles of saffron (*Crocus sativus* L.) during processing and storage. J. Sci. Food Agric. 71, 27–32.

Raines Ward, D., 1988. Flowers are a mine for a spice more precious than gold. Smithsonian 19, 105–110.

Sadikoglu, H., Liapis, A.I., 1997. Mathematical modelling of the primary and secondary drying stages of bulk solution freeze-drying in trays: parameter estimation and model discrimination by comparison of theoretical results with experimental data. Dry. Technol. 15, 791–810.

Sadikoglu, H., Liapis, A.I., Crosser, O.K., 1998. Optimal control of the primary and secondary drying stage of bulk solution freeze drying in trays. Dry. Technol. 16, 399−431.

Sadikoglu, H., Ozdemir, M., Seker, M., 2003. Optimal control of the primary drying stage of freeze drying process in vials using variational calculus. Dry. Technol. 21, 1307−1331.

Sadikoglu, H., Ozdemir, M., Seker, M., 2006. Freeze-drying of pharmaceutical products: research and development needs. Dry. Technol. 24, 849−861.

Schubert, H., Regie, M., 2006. Novel and traditional microwave applications in the food industry. In: Willert-Porada, M. (Ed.), Advances in Microwave and Radio Frequency Processing. Springer, New York, pp. 259−270.

Tammaro, F., 1999. Saffron (*Crocus sativus* L.) in Italy. In: Negbi, M. (Ed.), Saffron *Crocus sativus* L. Medicinal and Aromatic Plants Industrial Profiles. Harwood Academic Publishers, Amsterdam, pp. 53−61.

Tong, Y., Zhu, X., Yan, Y., Liu, R., Gong, F., Zhang, L., et al., 2015. The influence of different drying methods on constituents and antioxidant activity of saffron from China. Int. J. Anal. Chem. 2015, 1−8.

Torki-Harchegani, M., Ghanbarian, D., Maghsoodi, V., Moheb, A., 2017. Infrared thin layer drying of saffron (*Crocus sativus* L.) stigmas: mass transfer parameters and quality assessment. Chinese J. Chem. Eng. 25, 426−432.

Tsimidou, M., Biliaderis, C.G., 1997. Kinetic studies of saffron (*Crocus sativus* L.) quality deterioration. J. Agric. Food Chem. 45, 2890−2898.

Zanzucchi, C., 1987. La ricerca condotta dal consorzio comunale Parmaensi sullo zafferano (*Crocus sativus* L.). In: A. Bezzi (Ed.), Atti Convegno sulla coltivazione delle piante officinali, 9−10 ottobre, Istituto Sperimentale per l'Assestamento Forestale e per l'Alpicoltura, Villazzano (Trento), pp. 347−395 (in Italian).

Zarein, M., Samadi, S.H., Ghobadian, B., 2015. Investigation of microwave dryer effect on energy efficiency during drying of apple slices. J. Saudi Soc. Agric. Sci. 14, 41−47.

Ziaforoughi, A., Yousefi, A.R., Razavi, S.M.A., 2016. A comparative modeling study of quince infrared drying and evaluation of quality parameters. Int. J. Food Eng. 12, 1−9.