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Effects of hot-air and infrared drying methods on drying performance and quality parameters of pumpkin (*Cucurbita moschata* Duch.) cubes

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Abstract

This study evaluated the drying behavior of pumpkin (*Cucurbita moschata* Duch.) cubes using hot-air and infrared drying at 50, 60, and 70 °C. Drying performance was assessed through yield, drying rate, effective moisture diffusivity, energy consumption, color variation, and rehydration capacity. Results showed that drying technology exerted a greater influence than temperature on process efficiency and product quality. Convective drying achieved higher yield, faster drying rates, greater effective diffusivity, shorter drying times, and lower color alteration compared with infrared drying. Although increasing temperature reduced drying time, convective drying at 50 °C provided the best balance between energy efficiency, drying performance, and quality retention. Rehydration analysis for convective dryings also demonstrated satisfactory water absorption capacity. Overall, convective drying at 50 °C was identified as the most suitable condition for producing high-quality dried pumpkin cubes with reduced energy demand.

Keywords: *pumpkin, Cucurbita moschata, convective drying, infrared drying, color properties, drying parameters, energy efficiency*

1.INTRODUCTION

Drying is one of the principal methods used for the preservation of agricultural products (Radojčin et al., 2021). It is a complex operation that involves simultaneous heat and mass transfer between the product surface and the surrounding medium, as well as within the internal structure of the product itself. The growing popularity of dried fruits and vegetables is largely associated with their prolonged shelf life, reduced storage and transportation requirements due to volume reduction, and the diversification of value-added products (Reis et al., 2022). Further expansion of this market could be achieved through improvements in product quality and drying technologies, thereby increasing consumer acceptance of dehydrated food products. Among the various drying applications, the production of dried fruit cubes represents a particularly advantageous approach because it avoids many of the previously mentioned limitations while offering additional technological and commercial benefits.

Pumpkin is a traditionally cultivated crop grown worldwide for agricultural, commercial, and ornamental purposes. It belongs to the family Cucurbitaceae, which includes several species such as *Cucurbita maxima*, *C. pepo*, *C. moschata*, and *C. mixta*. In Cuba, the traditional pumpkin corresponds primarily to the species *C. moschata* Duch. This fruit is recognized as an important source of carotenoids and is particularly rich in carotene (Adelerin et al., 2024; Altaf et al., 2025). However, its highly perishable nature restricts its utilization and shelf life. To enhance its preservation and consumption, pumpkin has been processed through various drying methods for human dietary use (Chikpah et al., 2022; Mkhize et al., 2023; Ortiz-Jerez et al., 2024; Grassino et al., 2024). Given these limitations, effective postharvest preservation strategies, particularly drying technologies, have gained increasing attention as practical solutions for reducing losses and improving product stability. Cost-effective and hygienic food preservation methods are of considerable importance in light of the persistent global challenges associated with food insecurity. The implementation of drying technologies in developing countries can substantially reduce postharvest crop losses and significantly enhance the quality of dried products compared with traditional preservation practices, such as sun or shade drying.

Although several studies have investigated the drying of pumpkin using different technologies, most have focused on drying kinetics or quality attributes separately, while comprehensive comparisons of drying performance, energy consumption, moisture diffusivity, and quality characteristics under both hot-air and infrared drying remain limited, particularly for *Cucurbita moschata* cubes. Moreover, information identifying drying conditions that simultaneously maximize process efficiency, minimize energy demand, and preserve product quality is still scarce. Therefore, a systematic evaluation integrating drying kinetics, energy efficiency, color retention, and rehydration behavior is needed to support the selection of appropriate drying conditions for industrial and small-scale applications.

Accordingly, this study evaluated the drying behavior of pumpkin (*Cucurbita moschata* Duch.) cubes using hot-air and infrared drying at 50, 60, and 70 °C. Drying performance was assessed through drying yield, drying rate, effective moisture diffusivity, energy consumption, color variation, and rehydration capacity to identify the drying conditions that provide the best balance between process efficiency and product quality.

2. MATERIAL and METHODS

2.1 Materials

Fresh pumpkins were sourced from a commercial agricultural supplier in Havana, Cuba, in January 2026 (dry season). For each experimental run, five pumpkins were used. The fruits were thoroughly washed under running water, peeled, deseeded, and cut into 1 cm cubes using a SAMMIC S.L. chopper (model 20720, Azkoitia, Spain).

2.2 Characterization of fresh pumpkin

Initial moisture and dry solids content were determined from the fresh pulp using the method of progressive heating infrared scale (Sartorius AG, MA35 model, Göttingen, Germany) at 105 °C, and the concentration of total soluble solids, by using a refractometer (Milton Roy Co., LR 45227 model, USA), expressing data as Brix degrees (Ortiz-Jerez et al., 2024). The characteristics of fresh pumpkin are shown in Table 1.
Color measurements were performed using a UV–Visible spectrophotometer (UV-2600, Shimadzu Corp., Kyoto, Japan). A large sample compartment equipped with an integrating sphere was employed, with measurements recorded over the 380–780 nm wavelength range at medium scan speed, using an 8 nm slit width and photometric detection in percent reflectance mode.

***Table 1**. Characteristics of the raw material used*

Characteristic	Mean (standard deviation)
Moisture (% m/m)	87.37 (1.07)
Soluble solids (°Brix)	4.5 (0.5)
L*	39.24 (0.4)
a*	6.98 (0.37)
b*	42.1 (0.15)

Samples were placed in 2 cm diameter cells covered with a glass plate. The color was measured on the samples surface and was expressed in the CIELAB system using UVPC Color Analysis software (version 3.12, Shimadzu Corp.). All analyses were conducted in triplicate.

2.3 Drying methods

Hot air and infrared oven equipment were used to dry the fresh pumpkin samples at different drying temperatures (50 °C, 60 °C and 70 °C). A standard hot air oven B5050E (Heraeus, Hanaus, Germany) with at air velocity of 1.5 m/s was used for the convective drying experiments. Pumpkin cubes (100 g) were evenly distributed on a stainless-steel mesh tray to allow air circulation, forming a single layer.

The samples were dried using infrared radiation in a Sartorius moisture analyzer (model MA35, Göttingen, Germany). Uniform heating was provided by a 400 W infrared dark radiator (metal tubular heating elements) located within and above the drying chamber. Pumpkin cubes (30 g) were evenly distributed on a metal tray.

All experimental runs were continued until the cubes reached a final moisture content of 5% (w/w). The relative humidity of the ambient air ranged between 70 and 75%. All experiments were performed in triplicate

2.4. Characterization of dehydrated pumpkin

The samples dried at the different temperatures were analyzed for moisture content using the same method applied to the fresh samples (Ortiz-Jerez et al., 2024). Color was measured under the same conditions as for fresh pumpkin, except that the powders were reconstituted beforehand to match the refractometric solids content (Monteiro et al., 2018). For the dehydrated samples, total color difference (ΔE) was also determined according to equation 1.

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \quad \text{(Eq. 1)}$$

where ΔL, Δa, and Δb are the differences between the powder and the fresh sample for each respective parameter.

2.5 Determination of rehydration behavior

This examination was only done for cubes from convective drying. Analyses were carried out in distilled water at 100 °C and the solid-to-liquid ratio was adjusted to 1:100 (w:w). The procedure was done according to Caliskan and Dirim (2017). The sample was removed from the water, drained, and was then weighed using an analytical balance (Sartorious, TE214S model, Göttingen, Germany). This procedure was performed every 1 min during the first 5 min, every 10 min for the subsequent 30 min, and every 30 min thereafter until completing 2 h. Three replicates of the rehydration process were conducted. Rehydration ratio was calculated using equation 2.

$$Rehydration\ rate = \frac{Weight_{rehydrated\ sample}}{Weight_{dried\ sample}} \quad \text{(Eq. 2)}$$

Rehydration data were modeled using the Peleg's equation, which can be expressed in its linearized form as shown in equation 3.

$$\frac{t}{M_t - M_0} = k_1 + k_2 t \quad \text{(Eq. 3)}$$

where M_t is the moisture content (kg H_2O/kg dm) at time *t*, M_0 is the initial moisture content (kg H_2O/kg dm), *t* is the rehydration time (min), k_1 is the kinetic constant [min (kg dm/kg H_2O)] and k_2 is characteristic constant for each product (kg dm/kg H_2O).

2.6 Calculation of drying parameters

Drying yield refers to the ratio between the mass of the obtained dried product (m_f) and the initial mass of the fresh product (m_i), expressed as a percentage (equation 4).

$$Yield\ (\%) = \frac{m_f}{m_i} \times 100 \quad \text{(Eq. 4)}$$

Drying rate at 15 min was calculated from equation 5, while total drying time (min) was measured at the time where the dried cubes reached 5% moisture content (Chikpah et al., 2022).

$$DR = \frac{M_{t+dt} - M_t}{dt} \quad \text{(Eq. 5)}$$

where *DR* is the drying rate (g water/g dry matter), M_t is the moisture content at drying time *t* (d.b.), M_{t+dt} is moisture content at time t + dt (d.b.), and dt is the small increase in time t (min).

The effective diffusivity (D_{eff}) was determined from Fick's second law of diffusion (equation 6) by plotting a graph of ln *MR* against drying time followed by calculation of the effective diffusivity by the slope method using equation 7 (Chikpah et al., 2022).

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} e^{-(2n+1)^2} \pi^2 D_{eff} \frac{t}{4L^2} \quad \text{(Eq. 6)}$$

$$Slope = \frac{\pi^2 D_{eff}}{4L^2} \quad \text{(Eq. 7)}$$

The energy consumption per unit volume (ECv) was calculated according to equation 8 (Lin et al., 2023).

$$EC_v = \frac{E_{total}}{V_{eff}} \quad \text{(Eq. 8)}$$

where EC_v is the energy consumption per unit volume (MJ/m³), E_{total} is the total energy consumed in the process (MJ) and V_{eff} is the effective product volume (m³).

Since the samples were cut into cubes, the effective volume was calculated using equation 9.

$$V_{eff} = n \times 1 \times 10^{-6}\ \text{m}^3 \quad \text{(Eq. 9)}$$

where *n* is the number of 1 cm³ cubes.

2.7 Statistical analysis

The results were subjected to analysis of variance, followed by Fisher's least significant difference (LSD) test to discriminate among means. Statistical analyses were performed using Statgraphics Centurion XV, version 15.2.05 (StatPoint, Inc., Warrenton, VA, USA).

3. RESULT and DISCUSSION

In this work, the effects of two different drying methods (convective drying, CD and infrared drying, IR) and drying temperatures (Table 2) were investigated to find suitable drying conditions to obtain the best technological parameters and color profiles of the dried pumpkin cube samples. In this context, product yield, drying rate at 15 min, total drying time, effective moisture diffusivity (D_{eff}) of dried pumpkin cubes, and total color difference (*ΔE*) were compared to highlight the efficiency of drying.

The analysis of variance applied to quality and efficiency indicators showed statistically significant differences among the six evaluated drying conditions ($F = 8.48$; $p = 0.001$) at $p \leq 0.05$, indicating that at least one of the compared means differs (Table 3).

Table 2. *Comparison between the two drying technologies*

Parameter	IR 50 °C	IR 60 °C	IR 70 °C	CD 50 °C	CD 60 °C	CD 70 °C
Yield (%)	9.8 (0.5) a	10.0 (0.5) a	10.3 (0.4) a	11.8 (0.6) b	11.3 (0.6) b	11.5 (0.5) b
Drying rate at 15 min (g water/g dry matter)	0.065 (0.01) c	0.254 (0.02) c	0.270 (0.03) c	0.286 (0.08) d	0.321 (0.03) d	0.368 (0.03) d
Total drying time (min)	480 (12.2) e	330 (12.0) e	270 (17.3) e	300 (17.6) f	180 (9.9) f	165 (16.7) f
D_{eff} (m^2/s)	1.013×10^{-9} g	2.026×10^{-9} g	3.039×10^{-9} g	1.216×10^{-8} h	1.621×10^{-8} h	2.026×10^{-8} h
ΔE	27.80 (0.20) i	27.96 (0.39) i	30.74 (0.35) i	15.65 (0.27) j	18.38 (0.54) j	21.64 (0.39) j
L*	69.84 (0.00) k	66.81 (0.66) k	66.31 (0.41) k	65.90 (1.4) l	59.09 (1.7) l	51.72 (1.6) l
a*	8.90 (0.00) m	9.77 (0.03) n	12.36 (0.02) o	12.45 (0.07) o	12.89 (0.15) p	15.11 (0.64) q
b*	44.32 (0.01) r	39.82 (0.12) s	37.61 (0.55) t	50.24 (1.1) u	44.48 (0.7) v	41.22 (1.3) w

IR: Infrared drying, CD: Convective drying, *ΔE*: Total color difference. Mean value (standard deviation). Values in the same row followed by different letters are significantly different ($p \leq 0.05$).

This confirms that the combination of technology and temperature has a decisive influence on the behavior of the pumpkin cube drying process.

The multiple range test LSD, at 95% confidence, allowed discrimination among treatments, identifying two homogeneous groups: one formed by the three infrared drying conditions (IR50, IR60, and IR70) and another formed by the three convective drying conditions (CD50, CD60, and CD70). Within each group, no significant differences were observed, whereas between groups the differences were consistent and statistically significant. This confirms that drying technology exerts a dominant effect on the evaluated indicators, outweighing the effect of temperature within each technology.

The comparison results show that convective drying outperformed infrared drying at all temperature levels. Yield was higher in convective drying (11.3–11.8%) than in infrared drying (9.8–10.3%), likely because the continuous flow of heated air promoted more uniform heat transfer and moisture removal throughout the sample, thereby reducing localized overheating and thermal degradation of the pumpkin tissue. In contrast, infrared drying may have caused rapid surface heating and partial crust formation, which hindered internal moisture migration and resulted in greater solid losses.

The drying rate at 15 min was also higher under convective drying (0.286–0.368 g water/g dry matter) than under infrared drying (0.065–0.270 g water/g dry matter). This difference can be attributed to the greater convective heat transfer coefficient and the continuous removal of water vapor from the product surface by the

Table 3. Least significant difference at 95% for comparison among treatments

Groups	Contrasts	Differences (rank)	Limit LSD	Significance
IR internal	IR50 - IR60 IR50 - IR70 IR60 - IR70	-0.002 to -0.005	0.009	NS
CD internal	CD50 - CD60 CD50 - CD70 CD60 - CD70	-0.002 to 0.005	0.009	NS
IR50 – CD	IR50 - CD50 IR50 - CD60 IR50 - CD70	-0.015 to -0.02	0.009	*
IR60 – CD	IR60 - CD50 IR60 - CD60 IR60 - CD70	-0.013 to -0.018	0.009	*
IR70 - CD	IR70 - CD50 IR70 - CD60 IR70 - CD70	-0.010 to -0.015	0.009	*

Limit: minimum difference required to declare significance.
NS: not significant; * significant ($p \leq 0.05$).
The difference ranges represent the minimum and maximum values obtained within each group of comparisons.

airflow, which maintained a high vapor pressure gradient and enhanced moisture diffusion. As expected, increasing the drying temperature increased the drying rate in both methods because higher temperatures increased the vapor pressure difference between the product and the surrounding air, reduced water viscosity, and accelerated internal moisture diffusion. Consequently, the total drying time decreased with increasing temperature, reaching 165 min for convective drying and 270 min for infrared drying at 70 °C. The shorter drying time achieved by convective drying is consistent with its higher drying rate and more efficient heat and mass transfer, which facilitated faster moisture removal from the pumpkin cubes.

The effective water diffusivity (D_{eff}) is a physical parameter that describes the rate at which water moves or diffuses within a food product (or any porous material) during processes such as drying (Wang et al., 2023). D_{eff} was also higher in convective drying (up to 2.026×10^{-8} m²/s) than in infrared drying (maximum 3.039×10^{-9} m²/s), reflecting greater mass transfer efficiency.

Regarding product quality, evaluated through ΔE, an inverse trend was observed compared with the drying efficiency indicators. ΔE values were lower in convective drying (15.65–21.64) than in infrared drying (27.80–30.74), indicating less chromatic alteration and therefore better preservation of the original pumpkin color. This result is particularly relevant, as ΔE is a key indicator of the visual quality of dehydrated products. The lower color variation observed during convective drying may be attributed to the more uniform distribution of heat within the drying chamber and the continuous removal of moisture by the airflow, which reduced localized overheating of the product surface. In contrast, infrared drying transfers energy directly to the product by radiation, producing rapid surface heating and higher surface temperatures. This can accelerate the degradation of carotenoids, promote non-enzymatic browning reactions such as the Maillard reaction and caramelization, and increase pigment oxidation, all of which contribute to greater color changes. Furthermore, increasing the drying temperature generally intensified color variation in both drying methods because higher temperatures increased the rates of pigment degradation and browning reactions. Therefore, although convective drying exhibited higher drying efficiency, its more controlled heat transfer resulted in better preservation of the natural color of the pumpkin cubes.

The multiple range test showed that all convective drying conditions were significantly better than infrared drying conditions, while no statistically significant differences were found among temperatures within convective drying. From a statistical standpoint, the three convective temperatures are equivalent in performance. Under this framework, CD50 is identified as the most advantageous condition, since operating at a lower temperature requires less total energy while maintaining high yield and reduced color alteration. For CD50, the drying process was conducted at a power of 7.97 kW over a duration of 5.17 h. According to Eq. 8, the volumetric energy consumption (ECv) was calculated to be 148 MJ/m^3. Although CD70 showed shorter drying times, the higher temperature implies greater energy consumption. Therefore, from an integrated efficiency and quality perspective, CD50 represents the most favorable option within the evaluated range.

The ECv value obtained for CD50 falls within the range reported for convective drying of vegetables, according to An et al. (2024). Comparative studies show that infrared drying tends to exhibit higher energy consumption due to greater heat losses and longer processing times (Sakare et al., 2020; Nurmawati et al., 2023). Likewise, recent evaluations of energy efficiency in fruit and vegetable drying techniques confirm that the values obtained in this study are consistent with those reported in the literature (Kaveh et al., 2023).

The infrared-dried samples were excluded from the rehydration analysis because preliminary observations showed that they developed pronounced surface hardening and structural collapse during drying, resulting in non-uniform water absorption and poor reproducibility of the rehydration measurements. Under these conditions, the rehydration ratio would not provide a reliable basis for comparison with the convectively dried samples. The rehydration behavior assessment showed that samples air-dried at 60 °C (CD60) exhibited the highest water absorption capacity, with more favorable k_1 and k_2 values and superior statistical fit (Table 4).

Table 4. *Values of the Peleg model parameters for convective drying*

	k_1	k_2	R^2	SE
CD50	2.021	0.262	0.959	0.243
CD60	2.325	0.152	0.996	0.130
CD70	1.457	0.294	0.981	0.141

k1 y k2: model parameters. R2: coefficient of determination. SE: regression standard error.

However, samples air-dried at 50 °C (CD50) also met the expected rehydration standard, reaching the initial volume of fresh product and showing adequate kinetics. Although the rehydration capacity of CD50 was lower than that of CD60, this difference does not compromise the functional quality of the product. Considering that CD50 operates at a lower temperature and therefore requires less total process energy; while maintaining good yield and lower color alteration (*ΔE*), it remains a highly competitive condition.

4. CONCLUSION

This study compared convective and infrared drying of *Cucurbita moschata* Duch. cubes at different temperatures in terms of efficiency, energy consumption, and product quality. Results showed that drying technology had a stronger influence than temperature on the evaluated responses. Convective drying outperformed infrared drying by achieving higher yield, faster drying rates, greater effective moisture diffusivity, and shorter processing times. It also better preserved the product color, indicating reduced pigment degradation. Although higher temperatures reduced drying time, the most favorable overall condition was convective drying at 50 °C, which balanced energy efficiency, process performance, and product quality. Overall, effective drying optimization requires a trade-off between energy use, drying time, and quality retention, with convective drying at 50 °C being the more recommended condition.

The results of this study have practical implications for the optimization of pumpkin drying processes at pilot and industrial scales. The higher drying rates, shorter drying times, and better color preservation achieved under convective drying indicate that this technique can improve process productivity while maintaining product quality. These findings may support the selection of appropriate drying conditions for the production of dehydrated pumpkin cubes used in powdered food formulations. Furthermore, the drying kinetics and effective moisture diffusivity values obtained in this work provide useful input parameters for process modeling, equipment design, and scale-up of drying operations.

DECLARATION OF CONFLICTING INTERESTS

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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