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Original article

CONVECTIVE DRYING PROCESSES FOR PLUMS USING SENSOR TECHNOLOGY

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Abstract

Purpose. This study aims to investigate the effects of convective drying on pitted plums using advanced sensor technology to monitor and optimize the drying kinetics.

Materials and methods. This study investigates convective drying processes applied to pitted plums utilizing advanced sensor technology to monitor and optimize convective drying kinetics. The average drying temperature was found 52.38 ± 9.45 °C throughout the drying process. A multidimensional 3D plate model (L_1, L_2, L_3) was employed to analyze the drying behavior. The effective diffusivity ($D_{eff} = 3.5338 \times 10^{-9}$ m^{2}s^{-1}), indicates efficient moisture transport within the plum tissue. The drying process lasted 62 hours, during which the plum samples underwent significant moisture reduction to about 50 %. Around 7.91 kWh of energy was needed to evaporate 1 kg of water from the plums over an estimated drying time.

Results. Around 7.91 kWh of energy was needed to evaporate 1 kg of water from the plums over an estimated drying time. These findings underscore the effectiveness of convective drying and sensor technology in understanding and optimizing drying kinetics for plums, paving the way for enhanced preservation and commercial processing strategies.

Conclusion. The study demonstrates the effectiveness of convective drying of seedless plums using advanced sensor technology for real-time monitoring and optimisation. This method produces high quality dried fruit with excellent preservation properties. Future scalability for industrial use can be explored and the sensor technology can be applied to other fruits and vegetables.

Keywords: convective drying; MEMS sensors; plum; sensor technology; drying system; relative humidity; moisture content

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Introduction

Drying is one of the oldest and most widely used methods for food preservation, offering a reliable means to extend the shelf life of perishable products by reducing the moisture content. Convective drying, in particular, is popular due to its simplicity, energy efficiency, and the ability to maintain dried products' nutritional and sensory quality. However, achieving optimal drying conditions for fruits like plums remains challenging due to balancing moisture removal with product quality. Recent advances in sensor technology have enabled more precise control and monitoring of the drying process, which can lead to improved drying kinetics and product quality. Integrating sensors into drying systems allows for real-time data collection on parameters such as temperature, humidity, and moisture content, facilitating the optimization of drying conditions [1; 10].

This study aims to investigate the effects of convective drying on pitted plums using advanced sensor technology to monitor and optimize the drying kinetics.

Materials and methods

Sample Preparation

The plums for this study were sourced from the local market and meticulously chosen for uniform size, ripeness, and lack of defects (mechanical or infected by moulds). Purchased plums were of cv. Stanley, harvested at appropriate maturity stage for fresh consumption, which made them finely suitable for processing too. After washing and pitting, the plums were prepared for drying. Before drying, the samples were blotted to eliminate any excess surface moisture and weighed.

Drying Process

The convective drying process was carried out in a laboratory-scale drying chamber (Figure 1) equipped with advanced sensor technology (Colossus CSS 5330 250W, PRC). The drying chamber maintained an average temperature of 52.38 ± 9.45 °C, with an air velocity of 3 ms^{-1}. The drying process lasted 62 hours, during which the moisture content of the plum samples was monitored at regular intervals.

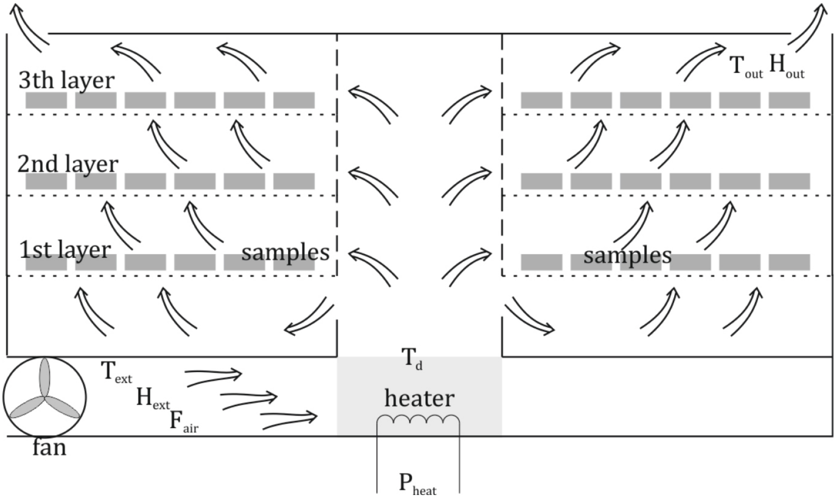


Fig. 1. Laboratory-scale drying chamber

Sensor Technology and Data Acquisition

The laboratory drying chamber was outfitted with an array of MEMS sensors, based on a BME280 sensor [3], capable of measuring temperature, relative humidity, and allows to calculate moisture content in real-time. These sensors were connected to a data acquisition system (Figure 2), based on IoT microcontroller ESP32 WROOM 32, that recorded measurements every minute and sent data via WiFi to Telegram cloud data storage. The use of this technology allowed continuous monitoring and control of the drying conditions, ensuring that the drying process was optimized for both energy efficiency and product quality.

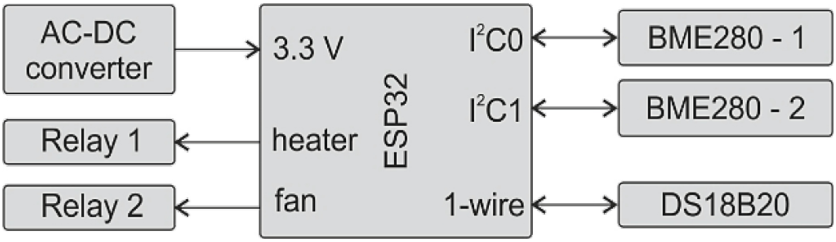
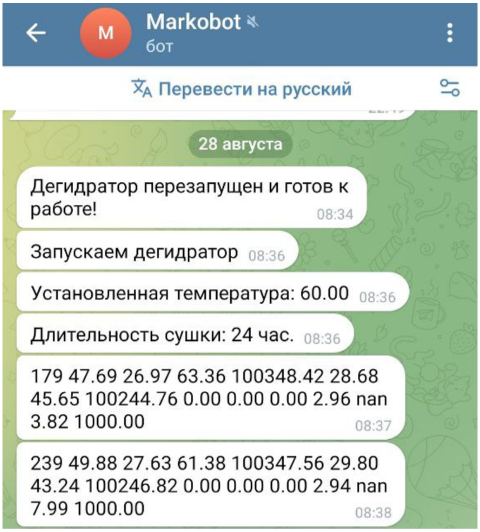


Fig. 2. Structural scheme of data acquisition system

A digital PID-controller (as a subroutine of a microcontroller program) was used to control hot air temperature. As a sensor to control hot air temperature, a digital thermometer DS18B20 is used. Relay 1 & Relay 2 are used to control the heater and fan respectively. For fan, only the on/off regime is used. A quasi-PWM regime was used for the heater solid state relay to maintain hot air temperature, with an actual control period of one second. That is enough because of the big heat inertia of the heating element.

For the aim of dehydration process monitoring, a Telegram bot is used which represents the data set in the mobile or computer Telegram application (Figure 3). Such applications allow entering commands to control and tune parameters of dehydration. In each data string next information represented (from left to right side): time in seconds, elapsed from the control system switched on; air temperature after heater (DS18B20); temperature, relative humidity and pressure of input air (BME280-1), temperature, relative humidity and pressure of input air (zero value, reserved for BME280-3), differential air moisture from 1st and 2nd sensors (Eqs. 1 – 3), differential air moisture from 3rd and 2nd sensors (not valid in this case), expended energy (cumulative), and mean heater duty (in ms.).



28 августа

Дегидратор перезапущен и готов к работе! 08:34

Запускаем дегидратор 08:36

Установленная температура: 60.00 08:36

Длительность сушки: 24 час. 08:36

179 47.69 26.97 63.36 100348.42 28.68 45.65 100244.76 0.00 0.00 0.00 2.96 nan 3.82 1000.00 08:37

239 49.88 27.63 61.38 100347.56 29.80 43.24 100246.82 0.00 0.00 0.00 2.94 nan 7.99 1000.00 08:38

Fig. 3. Screenshot of mobile Telegram bot screen

The Telegram bot is based on Alex Gyver's Telegram bot library "FastBot" for ESP32 microcontrollers and was created by the authors of the paper.

Differential air moisture calculated as differences between output air moisture d_{out} and output air moisture d_{inp}:

$$d = d_{out} - d_{inp} \tag{1}$$

Air moisture is calculated by the equation of air moisture:

$$d = 622 \cdot \frac{H \cdot P_s}{P_{atm} - H \cdot P_s} \tag{2}$$

where H is a relative humidity, P_s is a partial vapor pressure and P_{atm} is the atmospheric pressure.

Partial vapor pressure P_s is calculated by the Arden Buck equation:

$$P_s(\Theta) = 6.1121 \cdot e^{\left(18.678 - \frac{\Theta}{234.5}\right)\left(\frac{\Theta}{257.14 + \Theta}\right)} \tag{3}$$

This way we eliminate the influence of changing outside air humidity on the measurement of moisture loss.

One of the problems in analyzing moisture loss in convective dehydrators is calculating the actual moisture loss during the measurement process. In general, the cumulative moisture loss is calculated using the following formula:

$$W(t) = \int_0^t d(t) \cdot F_{air}(t)dt \tag{4}$$

where $F_{air}(t)$ is an air flow through the dehydrator. In turn, an airflow can be presented as:

$$F_{air}(t) = S \cdot V_{air}(t) \tag{5}$$

where $V_{air}(t)$ is a measured air velocity, and S is a cross-sectional area at the point of velocity measuring. It should be taken into account that this speed is different from the speed of blowing hot air over the dehydrated samples. If we assume that the air flow rate through the dryer is constant (which is not entirely true for the drying chamber under consideration), then equation (4) taking into account (5) can be represented as:

$$W(t) = S \cdot V_{air} \int_0^t d(t)dt \tag{6}$$

The reservation regarding the partial validity of the adoption of a constant air flow rate is related to the contact of the dehydrated product samples as moisture is absorbed, and, accordingly, to an increase in the flow area and a decrease in air resistance. As a result, by the end of drying, the airflow rate may increase. However, given the loose filling of the drying chamber trays with plum halves, we consider it possible to neglect this increase in this experiment.

In finishing the experiment, we can obtain a total water loss of the dehydrated product, by subtracting the mass of the dehydrated product from the mass of the original product. If the mass of moisture (water) is m_0 and the mass of dry matter is m_e, the removed water mass is:

$$\Delta m = m_0 - m_e \tag{7}$$

The final water loss at time T can represented as (6):

$$W(T) = S \cdot V_{air}\int_0^T d(t)dt \tag{8}$$

The Eq. 8 & 9 could be transformed:

$$\Delta m = W(T) = S \cdot V_{air}\int_0^T d(t)dt \tag{9}$$

In Eq. 9 we have not exactly defined values – product $S \cdot V_{air}$. It means, that we must calibrate the integral curve of $W(t)$ from the zero value at the start to the final value Δm at the end of the dehydration:

$$\widehat{W}(t) = ((W(t) - W(0))\frac{\Delta m}{W(T)} \tag{10}$$

At the next step, we can differentiate $\widehat{W}(t)$, and obtain a corrected sequence of instant water loss during dehydration:

$$S \cdot V_{air}\hat{d}(t) = \frac{d}{d(t)}\widehat{W}(t) = \frac{d}{d(t)}\left(S \cdot V_{air}\int_0^T d(t)dt - W(0)\right)\frac{\Delta m}{W(T)} =$$

$$= \frac{\Delta m}{W(T)} S \cdot V_{air} d(t) \tag{11}$$

$$\hat{d}(t) = \frac{\Delta m}{W(T)} d(t) \tag{12}$$

Eq. 12 is the final equation to correct measured data.

Mathematical Modeling

To analyze the drying behavior of the plum samples, a multidimensional 3D plate model (L_1, L_2, L_3, Figure 4) was employed. This model is based on Fick's second law of diffusion and was used to calculate the effective diffusivity (D_{eff}) of the plums during the drying process. The effective diffusivity provides insight into the rate at which moisture is transported within the plum tissue, which is critical for understanding and optimizing the drying process [4; 13].

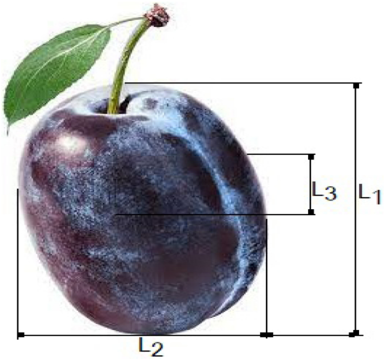


Fig. 4. 3D plate model

The moisture ratio (MR) is defined according to the Eq. 4 & 5 [6].

$$MR = \frac{M_t - M_e}{M_o - M_e} = \left(\frac{8}{\pi^2}\right)^3 \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} e^{\frac{-(2n+1)^2 \times \pi^2 \times D_{eff} \times t}{\frac{1}{L_1^2 + L_2^2 + L_3^2}}} = \left(\frac{8}{\pi^2}\right)^3 e^{\left(\frac{-\pi^2 \times D_{eff} \times t}{L_1^2 + L_2^2 + L_3^2}\right)} \quad (13)$$

$$lnMR = ln\left(\frac{8}{\pi^2}\right)^3 - \left(\frac{-\pi^2 \times D_{eff}}{L_1^2 + L_2^2 + L_3^2}\right) \times t \quad (14)$$

The moisture ratio (*MR*) is defined according to the Eq. 13 & 14 [6]. M_t, M_o, and M_e represent the moisture content at the time (t) during dehydration, the initial moisture content, and the equilibrium moisture content, respectively. Since the equilibrium moisture content (M_e) is typically very low, it can be omitted from Eq. (13), without significantly affecting the calculation of *MR*. When D_{eff} is constant and (t) approaches infinity, the earlier equations can be simplified to a linear form: $\ln(MR) = \ln(a) - k \times t$. In this equation, the slope corresponds to the constant drying rate *k*, which can then be used to calculate D_{eff} (as shown in Eq. 15).

$$k = \frac{-\pi^2 \times D_{eff}}{L_1^2 + L_2^2 + L_3^2} \quad (15)$$

The drying kinetics refer to the change in total mass loss ($M_{i-1} - M_i$) between two consecutive measurements ($t_{i-1} - t_i$) on a specific tray during the convective drying process, also known as the drying rate DR (Eq.16; Ramallo and Mascheroni, 2013).

$$DR = \frac{M_{i-1} - M_i}{t_{i-1} - t_i} \quad (16)$$

The Energy Usage During the Drying Process of Plums

The energy consumption (*E*) was recorded using a Prosto PM 001 device (230 V, 50 Hz, 0–16 A, 2–3680 W, 0–9999 kWh, −10 °C to +40 °C, relative humidity ≤ 85 %, maximum operating altitude 2000 m). A mathematical correlation was determined between the energy used and the CO_2 emissions during the drying process, with approximately 0.998 kg of CO_2 released per 1 kWh of energy consumed [21].

Results and discussion

Drying Kinetics

The data plums examined in this study had basic measurement values L_1 = 52.33 ± 1.53 mm, L_2 = 36.33 ± 1.15 mm, L_3 = 34.17 ± 1.26 mm. Dehydration was conducted in the dehydrator at atmospheric pressure, to the final percentage of dry matter after the plum dehydration of 50.55%. The average temperature range of drying process is show in

Figure 5. An amount of 273 g of plum was placed in each tray of 320 mm diameter with a mass load of 3.4 kgm^{-2} (5 trays, 1365 g of pitted plums).

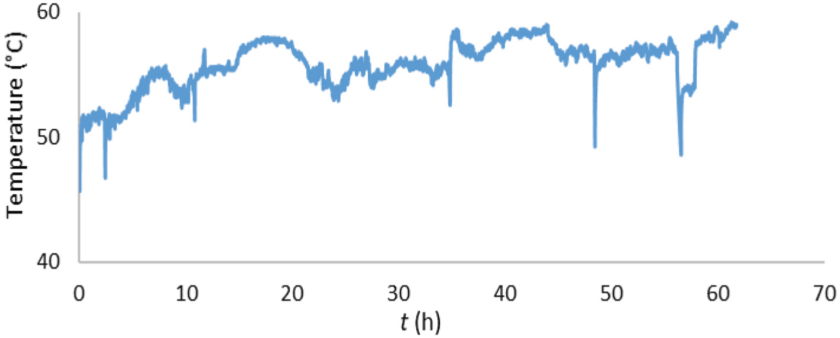


Fig. 5. The average temperature range of drying process

Figure 6 represents the process of convective drying of plums from the point of view of hot air and parameters registered by sensors (*WLS* – Water Loss Capacity), while Figures 7 and 8 from the point of view of plums and mass loss as a result of drying. The drying kinetics of the plum samples were characterized by an initial rapid loss of moisture, followed by a slower, diffusion-controlled drying phase. The sensor data revealed that th04/04/2026e moisture content decreased sharply during the first 10 hours of drying, which corresponds to the removal of free water from the surface of the plums (Fig. 6). After this initial phase, the rate of moisture loss slowed as the drying process became controlled by the diffusion of water from the interior of the plum tissue to the surface.

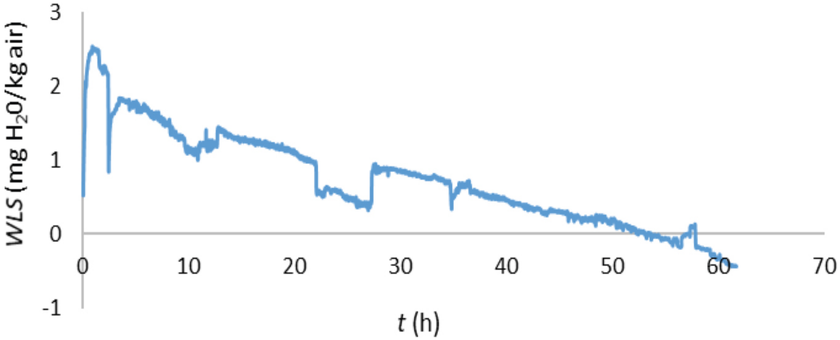


Fig. 6. Water loss speed during drying from the perspective of the drying air

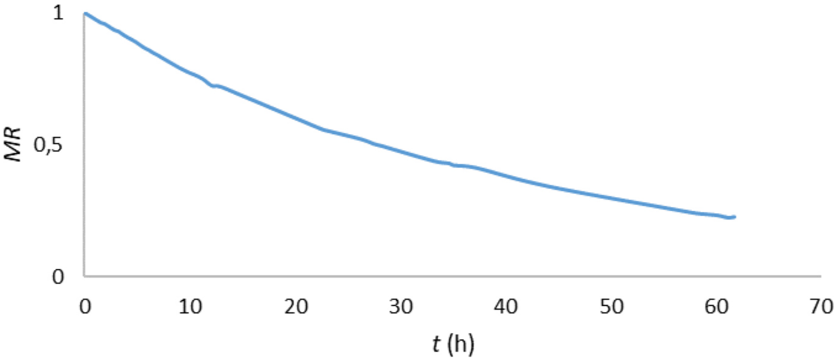


Fig. 7. Moisture ratio MR

The drying curve, presented in Figures 7 & 8, shows the relationship between moisture content and drying time, from the angle of the material (plum) being dried. The initial rapid decline in moisture content reflects the removal of surface water, while the subsequent plateau indicates the transition to the diffusion-controlled phase of drying. These results are consistent with findings from similar studies on the drying kinetics of fruits [2, 5]. The maximum *DR* was 109.5 gh^{-1} (after the 1.5 h of drying process).

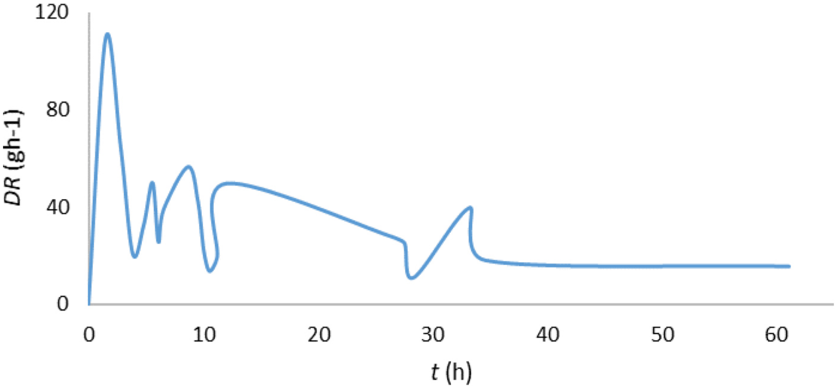


Fig. 8. Drying ratio DR

Effective Diffusivity

According to the multidimensional 3D plate model (L_1, L_2, L_3), the effective diffusivity (D_{eff}) of the plum samples was calculated to be 32.12×10^{-7} m^{2}min^{-1}

(3.53×10^{-9} m^2s^{-1}). This value suggests efficient moisture transport within the plum tissue, which is crucial for achieving uniform drying. The calculated effective diffusivity is within the range reported for similar fruits, indicating that the drying conditions used in this study were appropriate for plums [7]. Additionally, the plums were only pitted, not sliced, not cut in half or peeled; this drying method complicated the process because it made the moisture migration from various parts of the fruit more complex. For example, the D_{eff} values for the drying of plum (with kernel and pretreatments) at 50 °C were $2.66 - 3.75 \times 10^{-10}$ m^2s^{-1} [12], 5.6×10^{-9} for 55 °C (with kernel, [14]).

Moisture Reduction and Product Quality

By the end of the 62-hour drying period, the moisture content of the plum samples had been reduced to approximately 50% of their initial weight. This level of moisture reduction could be suitable for long-term storage and commercial distribution, as it effectively inhibits microbial growth while preserving the structural integrity of the fruit. The quality of the dried plums was evaluated based on their color, and texture. The convective drying process, when coupled with real-time monitoring through sensors, produced plums that retained their deep purple color and had a chewy, pliable texture. The integration of sensor technology into the drying process played a crucial role in ensuring that the plums were dried uniformly and that their quality was preserved throughout the drying process.

The Energy Usage During the Drying Process of Plums

The energy usage (E), as well as the CO_2 emission, is a linear (Figure 9).

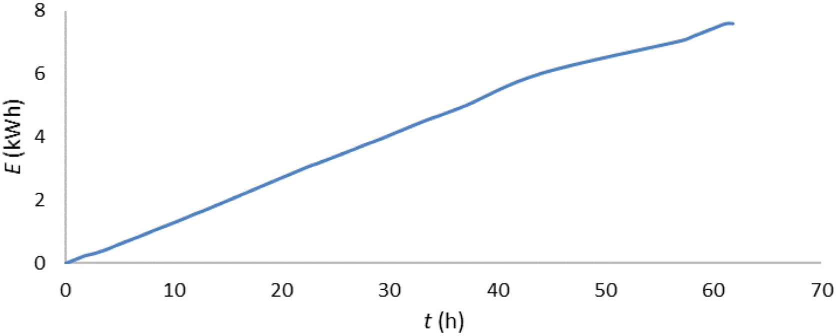


Fig. 9. The energy usage for the plums drying process

The experimental results indicate that approximately 7.91 kWh of energy was required to remove 1 kg of water from the plums during the estimated drying time of 62 hours. Over this period, around 7.9 kg of carbon dioxide was emitted. Given that this is a laboratory dehydrator, the data could be significant for evaluating energy efficiency in plum production "from the farm to the fork". For instance, Nadi and Hepbasli identified the drying process as the most energy-intensive stage with 46.67% [8].

Conclusion

This study demonstrates the effectiveness of convective drying processes for pitted plums, particularly when enhanced with advanced sensor technology. Integrating sensors into the drying process allowed for real-time monitoring and optimization of drying conditions, resulting in a high-quality dried product with efficient moisture transport, as indicated by the calculated effective diffusivity. The findings of this research suggest that convective drying, when carefully controlled and monitored, can produce dried fruits with excellent preservation qualities, suitable for both consumer markets and further processing. Future research could explore the scalability of this process for industrial applications, as well as the potential for sensor technology to be applied to the drying of other fruit and vegetable products.

Conflict of interest information. The authors declare no conflict of interest.

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