Evaluation of convective drying with cold and hot air of mint 
(Mentha spicata) leaves

Avaliação da secagem convectiva com ar frio e quente de folhas de 
hortelã (Mentha spicata)

Evaluación del secado convectivo con aire frío y caliente de hojas de 
yerbabuena (Mentha spicata)

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ABSTRACT
*Mentha spicata*, commonly known as peppermint, is a medicinal herb that is used for its pharmacological properties, obtained from its extracts and essential oils that have different health benefits, such as antioxidants, anticancer, antiparasitic, antimicrobial, and antidiabetic effects. In Mexico, it is estimated that around 130 tons of this perishable product are wasted per year, mainly due to various marketing problems. To minimize this loss, it is proposed to dehydrate it and thus prolong its shelf life. Two methods were used: first, hot air at 50 °C and 1 m/s velocity; the second one, with air at room temperature and the same velocity for 90 min and then, raise of temperature to 50 °C and the same velocity of air. In the first case 220 min and a total energy of 1800 W were needed, and with the combination of ambient temperature and later with hot air, 1700 W were required, but 290 min were used in total. In this later case the energy saving was marginal, so it is necessary to make a valorization between both methods. With respect to the numerical model that best simulates the behavior, the Henderson-Pabis model was suitable in both cases. Also, the color variation was very small, so both drying methods render similar results in the quality of the dried product.

Keywords: *Mentha spicata* drying, convective drying, cold and hot air, color change.

RESUMO
*Mentha spicata*, comumente conhecida como hortelã-pimenta, é uma erva medicinal que é usada por suas propriedades farmacológicas, obtidas a partir de seus extratos e óleos essenciais que têm diferentes benefícios para a saúde, tais como antioxidantes, anticâncer, antiparasitários, antimicrobianos e efeitos antidiabéticos. No México, estima-se que cerca de 130 toneladas desse produto perecível são desperdiçadas por ano, principalmente devido a vários problemas de comercialização. Para minimizar essa perda, propõe-se desidratá-la e, assim, prolongar sua vida útil. Dois métodos foram utilizados: primeiro, ar quente a 50 °C e velocidade de 1 m/s; a segunda, com o ar em temperatura ambiente e a mesma velocidade por 90 min e, em seguida, elevação da temperatura para 50 °C e a mesma velocidade do ar. No primeiro caso, foram necessários 220 min e uma energia total de 1800 W, e com a combinação da temperatura ambiente e posteriormente com o ar quente, foram necessários 1700 W, mas 290 min foram usados no total. Neste último caso a economia de energia foi marginal, por isso é necessário fazer uma valorização entre os dois métodos. Com relação ao modelo numérico que melhor simula o comportamento, o modelo de Henderson-Pabis mostrou-se adequado em ambos os casos. Além disso, a variação de cor foi muito pequena, de modo que ambos os métodos de secagem produziram resultados semelhantes na qualidade do produto seco.

Palavras-chave: secagem de *Mentha spicata*, secagem por convecção, ar frio e quente, mudança de cor.

RESUMEN
La *Mentha spicata*, comúnmente conocida como yerbabuena, es una hierba medicinal que se utiliza por sus propiedades farmacológicas, obtenidas de sus extractos y aceites
esenciales que tienen diferentes beneficios para la salud, como antioxidantes, efectos anticancerígenos, antiparasitarios, antimicrobianos y antidiabéticos. En México, se estima que alrededor de 130 toneladas de este producto perecedero se desperdician al año, principalmente debido a diversos problemas de comercialización. Para minimizar esta pérdida, se propone deshidratarlo y así prolongar su vida útil. Se utilizaron dos métodos: primero, aire caliente a 50 °C y velocidad de 1 m/s; el segundo, con aire a temperatura ambiente y a la misma velocidad durante 90 min y luego, aumento de temperatura a 50 °C y la misma velocidad de aire. En el primer caso se necesitaron 220 min y una energía total de 1800 W, y con la combinación de temperatura ambiente y posteriormente con aire caliente, se requirieron 1700 W, pero se utilizaron 290 min en total. En este último caso el ahorro energético fue marginal, por lo que es necesario realizar una valorización entre ambos métodos. Con respecto al modelo numérico que mejor simula el comportamiento, el modelo de Henderson-Pabis fue adecuado en ambos casos. Además, la variación de color era muy pequeña, por lo que ambos métodos de secado dan resultados similares en el producto seco.

Palabras clave: secado de Mentha spicata, secado convectivo, aire frío y caliente, cambio de color

1 INTRODUCTION

*Mentha spicata*, commonly known as peppermint, is a medicinal plant of the *Lamiaceae* family, characterized by its potential to synthesize and secrete secondary metabolites, mainly essential oils. It is used in different parts of the world for the preparation of tea, which has shown several beneficial effects, according to ethnopharmacological studies [1, 2]. Its pharmacological properties obtained from extracts and essential oils offer different health benefits, such as antioxidant, anticancer, antiparasitic, antimicrobial and antidiabetic effects [2]. The annual production of *Mentha spicata* in Mexico is 650 tons, of which it is estimated that 20% is not marketed due to various problems, including decay of the product quality. It would be very convenient to achieve its drying in an efficient way and thus produce a greater income for growers [3]. Since ancient époques, the drying process has had an important role in the conservation of some necessary foods, it aims to eliminate moisture that could damage different products, and therefore, promotes their proper preservation for later consumption. However, the amount of energy required to achieve the dry state is very high, so it is necessary to make its thermal consumption more efficient, and, in this way, reduce its costs considering the least possible damage to the environment, and maintaining the quality of the dehydrated product [4]. In the drying of the leaves of peppermint several variables and parameters represent a drawback in the modeling of the process using
phenomenological equations, for this reason most studies are based on empirical approaches, such as the fitting of experimental data to kinetic empirical models. Recently, alternative modeling approaches have been proposed in the literature to describe these processes [4]. In this work we evaluated the energy consumed when dehydrating peppermint leaves in two conditions: first with air at room temperature and then with hot air. The energy consumed, the kinetic model of the process, the diffusion coefficient, and the activation energy, using color as a quality variable, were separately obtained.

Mathematical modelling

The mathematical model assumes the following considerations:

a) the heat flow is one-dimensional in the direction parallel to the air flow;
b) the temperature of the environment is considered constant throughout the test;
c) there is no shrinkage of the product during drying;
d) there are no chemical reactions during drying;
e) the thermal properties of the product, air and its moisture content, are constant;
f) all the leaves of the product to be dried are at the same temperature.

The diffusion of moisture in solids during the drying process is a complex process that can involve molecular diffusion, capillary flow, Knudsen flow, hydrodynamic flow, or surface diffusion, all these phenomena are combined into one, the effective diffusivity, which can be defined from Fick’s second law, given by

\[ \frac{\partial X}{\partial t} = D \nabla^2 X \quad (1) \]

in which \( D \) is the effective diffusivity, \( X \) is the moisture content of the material and \( t \) is the time. The humidity ratio is:

\[ MR = \frac{M_t - M}{M_0 - M} = \frac{M}{M_0} \quad (2) \]

The solution of equation (1) and using equation (2), with a single term, [5,6] is:

\[ \frac{M}{M_0} = \frac{8}{\pi^2} e^{-Dt\left(\frac{\pi^2}{4}\right)} \quad (3) \]

This moisture ratio is a linear equation, [7,8], given by:
\[ \ln MR = \ln \left( \frac{8}{\pi^2} \right) - \left[ \frac{\pi^2 D_{\text{eff}} t}{4L^2} \right] \] (4)

whose slope is obtained from its graph,

\[ \text{slope} = \frac{\pi^2 D_{\text{eff}} t}{4L^2} \] (5)

Finally, in these \( D_{\text{eff}} \) is the effective diffusivity, which is related to the activation energy in the Arrhenius equation, [9]:

\[ D_{\text{eff}} = D_0 \exp \left[ -\frac{E_a}{RT} \right] \] (6)

where \( R \) is the universal constant of gases, \( T \) is the absolute temperature; \( E_a \) is the activation energy, which is defined as the minimum energy per mole per second required to affect the diffusivity of moisture, in this case, peppermint.

Again, obtaining the antilogarithm on both sides of the equation and plotting \( \ln D_{\text{eff}} \) against \( 1/T \) we would have that the slope would be \(-E_a/R\), from which the value of the activation energy \( E_a \) would be obtained. [10].

The drying velocity of peppermint leaves is obtained with [11]:

\[ DR = \frac{M_t - dt}{-M_t} \] (7)

Equation (2) is also the same as any empirical model, for example: Page, [12]; Newton, [13]; Henderson and Pabis, [14]; Logarithmic, [15], and several more. The criteria followed to select the most appropriate model were derived from the regression analysis: the value closest to the unit of the correlation coefficient \( R^2 \), and the lowest that corresponds to \( \chi^2 \) [16].

Finally, for the analysis of the color change during the drying process, the Hunter method (CIELAB) was used. It is based on the determination of the following proportions: black/white, (0/100), \( L \), red/green, (negative/positive), \( a \); and yellow/blue, (positive/negative), \( b \); also, the total color change \( \Delta E \) and the \textit{Chroma}, which indicate color saturation, [16]. These are calculated as:
\[ \Delta E = \sqrt{(L_0 - L_t)^2 + (a - a_t)^2 + (b_0 - b_t)^2} \quad (8) \]

where the subscript 0 corresponds to the initial value, \( t \) is the evaluation time, and

\[ Chroma = \sqrt{a_t^2 + b_t^2} \quad (9) \]

2 EXPERIMENTAL APPARATUS

The scheme of the drying tunnel used in this study is presented in figure 1. Air is conducted by means of an axial-flow fan, (a). The velocity of air can be varied between 1.0 and 4.0 m/s; in this study the velocity applied was 1.0 m/s. There is a panel of two electrical resistances of 1750 W each, they are independently operated, which allows the selection of the energy to be provided, in this case only one was turned on, (b). The test chamber (c) is 20-cm width, 20-cm length, it has an air outlet designed as a vertical vent (d), and a control system (e). There are four infrared lamps of 500 W each, which are activated individually from the control panel, they were not used in this experiment.

![Figure 1](source: Own Authorship)

3 INSTRUMENTATION AND MEASUREMENT

Air and product-surface temperatures were measured using calibrated K-type thermocouples (0.5 °C exactitude); the relative humidity of the environment was determined using a model EA25 EXTECH digital hygro-thermometer, with 0.1 % resolution. Mass was quantified using a model BL1505 SARTORIUS scale, with a 0.001 g span. Data acquisition was programmed using LABVIEW software. For the
measurement of the electrical power supplied to the lamps, a model EX655 EXTECH
digital hook multimeter, of 700 V and 600 A alternate current, (with 2.5% resolution) was
used. The infrared lamps are ISW-01 MIGSA model, 0.20 m long and 220 V AC.

4 EXPERIMENTAL PROCEDURE

The peppermint leaves used in this work were obtained directly in the Supplies
Central (Central de Abastos) of Mexico City, which is the place where producers directly
market their products with the suppliers of small markets in the city, aiming to guarantee
their freshness and quality. In this case, peppermint harvested in the State of Tlaxcala,
Mexico, was used. The plants were washed and disinfected to avoid any damage; the
leaves were separated from the stems. 10 samples of 0.020 kg each were chosen, were
placed in vacuum-sealed bags and frozen for preservation. To determine their physical
dimensions, five leaves were photographed and processed with the "Boundary Tracing in
Images" tool, included in the MATLAB software, this same operation was performed
with the dehydrated products.

Each sample was taken out of the freezer and left for two hours at room
temperature; it was then placed inside the drying tunnel. The venter, and the electrical
resistance were activated so that the air conditions were 1 m/s speed and a temperature of
50 ° C; this was done for five samples. The other five were first subjected to an air flow
of 1 m/s speed and ambient temperature for 90 min, then at this time the electrical
resistance was activated so that the temperature increased up to 50 °C, and it was
maintained until the experimentation ended. The mass of the samples was measured every
10 min, the electrical energy consumption was recorded every 5 min, and all
measurements were recorded with the help of the program prepared with LAB VIEW
software.

5 RESULTS AND DISCUSSION

Initially, the experimentation was carried out for the five samples of peppermint
with an air flow of $1 \frac{m}{s}$ and 50 °C temperature, for which it was necessary to activate one
of the electrical resistances. The initial mass of the samples was 0.020 kg and ended at
0.004 kg approximately. In terms of the moisture ratio, it went from 0.90 to 0.14. The
The average time required was 220 min. For the other five samples at the beginning of the test, air was used at the same speed, but at room temperature during 90 min and then the electrical resistance was activated so that the temperature rose to 50 °C, the time it took to reach a humidity ratio of 0.14 was 290 min in total. The results obtained are shown in Figure 2. The graph of the moisture ratio versus drying provides very similar results between both drying methods, in most points they coincide, except when using air only. It is clearly observed that the drying velocity presents very small and almost constant values, on average it is \(0.003 \frac{kg_{dm}}{min}\).

The model that best represents the kinetics of drying is the Henderson-Pabis model for both methods of dehydration, its equation is:

\[ MR = A \exp(kt) \] (10)
For the hot air experiment the values of $R^2 = 0.9988$ and $\chi^2 = 0.0000579$ meet the conditions imposed by the regression analysis, and for the combination of air at room temperature and subsequently at 50 °C the results are: $R^2 = 0.9831$ and $\chi^2 = 0.00114$, which are also within the acceptable values. The values of the constants $A$ and $k$, are included in table 1 and the graph of both models are presented in figure 4.

Figure 4.- Numeric model Henderson-Pabis

![Graph](Image)

Table 1. Numeric values of the model

<table>
<thead>
<tr>
<th>Process</th>
<th>$A$</th>
<th>$k$</th>
<th>$R^2$</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot air</td>
<td>0.826</td>
<td>94.208</td>
<td>0.9988</td>
<td>0.0000579</td>
</tr>
<tr>
<td>Cold air + Hot air</td>
<td>1.996</td>
<td>522.88</td>
<td>0.9831</td>
<td>0.00114</td>
</tr>
</tbody>
</table>

Source: Own Authorship

With respect to the color change, the difference between the two drying methods is very small, the photographs of the product at the beginning and end of each process can be observed in table 2, the average values were obtained using MATLAB software for color analysis. Using equations [8] and [9] described above, for the hot air process it resulted: $\Delta E = 19.93$ and $Chroma = 13.7$; for the combined method these values were: $\Delta E = 19.51$ and $Chroma = 13.4$, the difference between them is only about 2%.

Table 2.- Color analysis of the Mentha spicata

<table>
<thead>
<tr>
<th>Process</th>
<th>Initial</th>
<th>Average</th>
<th>$Lab$</th>
<th>Final</th>
<th>Average</th>
<th>$Lab$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot air</td>
<td>![Image]</td>
<td>![Image]</td>
<td>$L= 42.32$</td>
<td>$a = -15.29$</td>
<td>$b= 26.93$</td>
<td>![Image]</td>
</tr>
</tbody>
</table>

Source: Own Authorship
The constant power consumption used by the fan was $37 \frac{W}{h}$. The total energy used in the process with air at $50 \, ^\circ C$ was $1800 \, W$. For the case in which air was first used at room temperature for 90 min and subsequently heated to the same temperature, approximately $1700 \, W$ were required, the difference between the two methods is less than 6%. Therefore, it must be decided which drying process is more convenient: the one where the drying of the product lasts 220 min or else, the other in which 290 min are required, with an energy saving of 100 W.

6 CONCLUSIONS

*Mentha spicata* is a medicinal herb that is used in different parts of the world for its pharmacological properties, extracts and essential oils obtained from it have different health benefits, such as antioxidant, anticancer, antiparasitic, antimicrobial and antidiabetic effects. In Mexico it is estimated that around 130 tons are wasted per year mainly due to loss of product quality during various marketing processes. In order to minimize these losses, it is proposed to dehydrate the herb and thus preserve its shelf life. The analyzed methods consisted of hot air at $50 \, ^\circ C$, and $1 \, m/s$ velocity and alternatively, air at room temperature and the same velocity for 90 min and then elevation of the temperature to $50 \, ^\circ C$ and the same velocity. In the first case a total energy of $1800 \, W$ and $220 \, min$ were required; in the second process only $1700 \, W$ were needed, but $290 \, min$ were used in total. The energy saving was very small, so it can be considered that both methods are equivalent. The numerical model that best simulates the behavior in both cases was the Henderson-Pabis one, according to the conditions of the analysis of regression used. Also, the color variation between both cases was very small.
REFERENCES


