

Optimization of Different Drying Systems for Lavender Leaves Applying Response Surface Methodology

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ABSTRACT

Lavender leaves, widely used as flavors for foods and beverages, are a rich source of phenol components and antioxidant. Drying method is of vital importance for keeping these compounds. In this study, lavender leaves were dried by means of Atmospheric Freeze (AF), Multi-Stage Semi-Industrial Continuous (MSSIC), and Near Infrared-Vacuum (NIR-Vacuum) dryers and optimized by Response Surface Methodology (RSM) for the highest drying rate, total phenol content, antioxidant capacity, and the lowest color indicators change. Lavender leaves were also dried under natural conditions as the traditional method. Multi-stage drying caused tempering phenomenon and, consequently, drying rate increased obviously. Near infrared-vacuum dryer had suitable performance on keeping the active ingredients of lavender leaves. Optimum point to dry lavender leaves in atmospheric freeze dryer was found to be -5°C. The optimum temperature points in the multi-stage semi-industrial continuous dryer were achieved to be 60, 40, and 60°C for the first, second, and third stages, respectively. The optimum point in near infrared-vacuum dryer was 60°C and 20 kPa for air temperature and pressure, respectively. Based on the results, among several drying methods, near infrared-vacuum dryer was the more suitable for drying lavender leaves.

Keywords: Atmospheric freeze dryer, *Lavandula officinalis*, Multi-stage drying, RSM, Tempering.

INTRODUCTION

Lavandula officinalis, recognized as lavender around the world, is one of the famous plants for relaxation and meditation. This plant is widely used as flavors for foods, beverages, and chewing gum (Da Porto *et al.*, 2009). Lavender with the different components of Flavonoids and Anthocyanin is one of the rich sources of phenolic components (Harborne and Williams, 2002). The leaves of this plant contain hydroxycinnamic acid esters,

rosmarinic acid, and chlorogenic acid (Lis-Balchin, 2012).

Keeping active ingredients of lavender leaves is one of the important quality factors for drying because aromatic plants such as lavender are so sensitive to heat during drying and they should be dried in controlled conditions (Krempski-Smejda *et al.*, 2015).

Study on drying behavior of lavender leaves is necessary prior to drying them at industrial scales. For this purpose, lavender leaves are dried through Atmosphere Freeze (AF) as a high-technology dryer, Multi-Stage Semi-Industrial Continuous (MSSIC) as a prevalent dryer, and Near Infrared-

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Vacuum (NIR-Vacuum) as a modern dryer compared to open sun and shade drying as traditional drying systems.

Vacuum drying is a process through which moisture content is lost at a low atmospheric pressure and water molecules diffuse into surface and dehydrated in the vacuum chamber. Vacuum reduces water vapor concentration of the product and creates a vapor pressure gradient (Dev and Raghavan, 2012). The near-infrared lamp is one of the heat sources in this regard (Alaei and Chayjan, 2015).

Hot air drying is one of the most popular drying techniques in the industry such that more than 85% of the industrial dryers use hot air with electronic or combustion heat source. An effective method to improve efficiency in high-energy consumption dryers is to utilize multi-stage dryer at different temperatures (Jangam *et al.*, 2011).

Vacuum freeze dryer is one of the expensive dryers, because the vacuum is always associated with high costs (Fissore *et al.*, 2014). In order to decrease production costs, AF drying was developed. Experiments showed that the diffusion of water vapor from drying boundary depends on vapor pressure gradient rather than absolute pressure in drying chamber, making the freeze-drying possible at atmospheric pressure. An important point for AF drying is convection heat transfer at temperatures below the freezing point while this temperature is higher than vacuum freeze drying (Claussen *et al.*, 2007).

Today, AF dryer is considered as a novel system with an important role in reducing production costs and environmental pollution. In this method, a product is dehydrated in air atmosphere instead of vacuum pressure while chamber temperature is below zero (Rahman and Mujumdar, 2008; Moses *et al.*, 2014).

Open sun and shade drying, as traditional processing methods, are still widely used in drying applications; however, these methods have some shortcomings such as a low hygiene, long drying time, and larger required space. Most of the time, industrial

drying methods could be compared with sun and shade drying as control samples (Borah *et al.*, 2017).

Response surface methodology (RSM) is a toolbox for the collection of statistical and mathematical techniques for the development, improvement, and optimization of various processes (Sumic *et al.*, 2016). Nowadays, RSM is one of the best, simplest, and easiest methods to optimize engineering processes (Fealekari and Chayjan, 2014). To the best of our knowledge, there is no report about drying optimization of lavender leaves with considering the importance of active ingredients.

In this study, we aimed to dry lavender leaves using AF, MSSIC, and NIR Vacuum dryers, and subsequently optimize the process by RSM for the highest Drying Rate (DR), Total Phenolic Content (TPC), Antioxidant Capacity (AC), and the lowest Color Index (CI) change. Another objective was to compare the obtained results with those of open sun and shade drying methods.

MATERIALS AND METHODS

Atmospheric Freeze Dryer

A schematic view of a fabricated Atmospheric Freeze (AF) dryer is shown in Figure 1. For this purpose, a closed cycle of cool air at a negative temperature ($^{\circ}\text{C}$) was supplied by a laboratory freezer (Arminco, -60°C and 100 L, made in Iran). A silica gel bed was used to absorb air humidity. It was replaced with the fresh gel every 12 hours. A radiant heat source (NIR lamp) was placed over the sample to accelerate Drying Rate (DR) and lamp power was controlled by a digital dimmer. After primary drying (sublimation of surface moisture) without product movement, air temperature was increased to 40°C by steps of 10°C /hand drying conditions shift to convection. For this purpose, condenser of the freeze was turned off and the system was let to increase

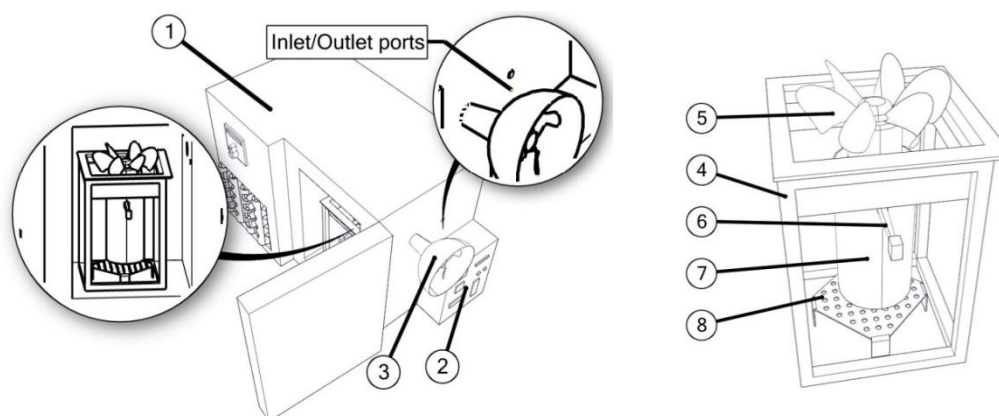


Figure 1. Schematic view of Atmospheric Freeze (AF) dryer: (1) Freezer, (2) Electrical panel, (3) Outlet fan, (4) Internal frame, (5) Internal fan, (6) NIR lamp, (7) Air flow channel, (8) Sample place.

the air temperature. An axial fan was employed to remove the humidity of the air.

To dry lavender leaves by AF drying, the leaves were placed in a freezer at -20°C for 20 hours, then frozen leaves were dried under AF conditions (-5 , -10 , and -15°C) for 48 hours as primary drying. Subsequently, the chamber temperature was increased to 40°C at a rate of $10^{\circ}\text{C h}^{-1}$ as secondary drying. The secondary drying process continued until the sample moisture content reached the Equilibrium Moisture Content (EMC). When the chamber temperature was over zero, inlet and outlet ports were opened to remove the air from inside the chamber using a fan controlled by a hygrometer (20% RH).

Multi-Stage Semi-Industrial Continuous Dryer

This dryer was designed and fabricated in the Department of Biosystems Engineering, Bu-Ali Sina University, Hamedan, Iran. The Multi-Stage Semi-Industrial Continuous (MSSIC) dryer was designed as three stages, and air temperature for every stage was set separately. One cycle was done after the sample passed all stages and the cycle was repeated until moisture content reached an equilibrium state (Figure 2-A). Air temperature of every stage was set to be 40,

50, and 60°C , respectively. Air velocity and belt speed were set at 1 m s^{-1} and 0.1 m min^{-1} , respectively. To avoid long drying time of lavender leaves under MSSIC dryer, microwave pretreatment was applied at set times with a power of 450W for 10 seconds.

Near Infrared-Vacuum Dryer

A schematic view of Near Infrared-Vacuum (NIR-Vacuum) dryer is shown in Figure 2-B. In this experiment, the air temperature and vacuum pressure were set at three levels of 40, 50, and 60°C and 20, 40, and 60 kPa, respectively.

Natural Drying

Lavender leaves were dried under two different conditions: Open sun and shade drying. Through open sun drying, lavender leaves were exposed to solar radiation and to shade drying and then placed in the laboratory environment with the average air temperature and humidity of $30\pm 3^{\circ}\text{C}$ and $25\pm 5\%$, respectively. Relative humidity, air temperature, and solar power during open sun drying were recorded.

Moisture Ratio

Moisture Ratio (MR) of lavender leaves was calculated as follows:

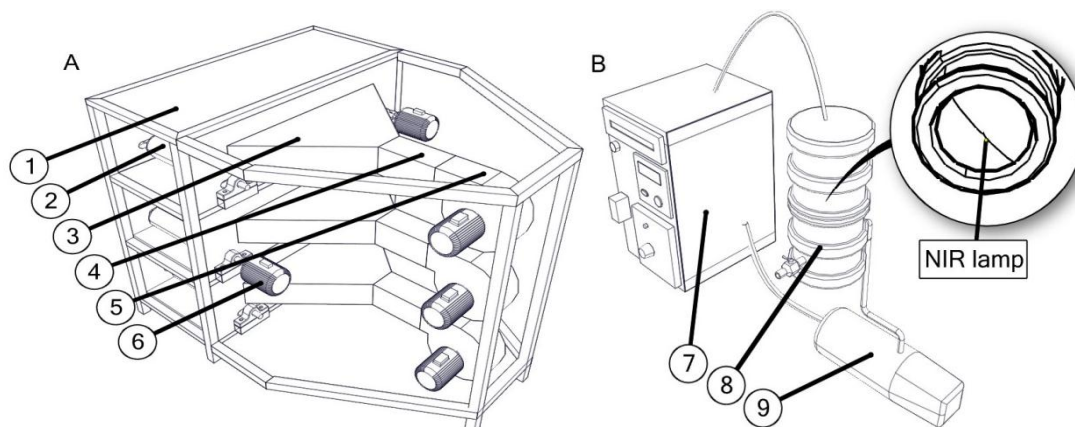


Figure 2. (A) Schematic view of Multi-Stage Semi-Industrial Continuous (MSSIC) dryer: (1) Polyurethane wall, (2) Belt, (3) Air flow channel, (4) Heater, (5) Centrifuge fan, (6) Belt's electrical motor. (B) Schematic of Near Infrared-Vacuum (NIR-Vacuum) dryer: (7) Electrical panel, (8) Vacuum chamber, (9) Vacuum pump.

$$MR = \frac{M - M_e}{M_0 - M_e} \quad (1)$$

Where, M , M_e , and M_0 are the instantaneous, equilibrium, and initial Moisture contents ($\text{kg}_{\text{water}} \text{kg}^{-1}_{\text{dry matter}}$), respectively (Sousa *et al.*, 2017).

Drying Rate

Drying Rate (DR) of lavender leaves was calculated as follows:

$$DR = \frac{\Delta MC}{\Delta t} \quad (2)$$

Where, ΔMC and Δt were Moisture Content changes ($\text{kg}_{\text{water}} \text{kg}^{-1}_{\text{dry matter}}$) and time variation (sec), respectively (Chayjan and Kaveh, 2016).

Preparation of Extracts from Dried Lavender Leaves

In this step, extraction solution was prepared based on the method of Oniszczuk *et al.* (2014) with modification, i.e. 0.1 g of dried lavender leaves was grounded by mortar and then dissolved in 85% methanol. Next, the solution was put in centrifuge at 3,000 rpm for 7 minutes. The prepared

extraction was kept at -20°C for the next experiments.

Determination of Total Phenolic Content

Folin-Ciocalteu method was applied to measure Total Phenolic Content (TPC). Also, 300 μL of the prepared extraction solution was mixed with 1,500 μL of 10% Folin solution. After 3 minutes, 1,200 μL of a molar solution of sodium carbonate was added and mixed together. Finally, the solution was put on a shaker for one hour with 140 cycle min^{-1} . The absorbance of the solution was measured at 735 nm by a spectrophotometer (Cary, 1000, Australia). About 100% methanol was used to calibrate the device (Singleton and Rossi, 1965). The total phenolic content of the samples was calculated by dividing the Gallic Acid Equivalents (GAE) by the Dry Weight (DW) of the sample (g).

Determination of Antioxidant Capacity

Antioxidant Capacity (AC) of the extract was evaluated by Radical Scavenging Capacity (RSC) method through 1,1-

DiPhenyl- 2-PicrylHydrazyl (DPPH). About 500 µL of extract was mixed with the 500 µL of distilled water and put in centrifuge at 3,000 rpm for 10 minutes. Then, 75 µL of the prepared solution was mixed with 2,925 µL of DPPH solution. Subsequently, the absorbance of the prepared solution and control solution was measured at 517 nm by a spectrophotometer. The radical scavenging capacity was calculated as follows (Brand-Williams *et al.*, 1995):

$$RSC(\%) = \left(\frac{A_{\text{blank}} - A_{\text{sample}}}{A_{\text{blank}}} \right) \times 100 \quad (3)$$

Where, A_{sample} and A_{blank} are Absorbance of sample and control solutions, respectively.

Color Index Change

Color Index (CI) was evaluated by a simple image processing method (Alaei and Chayjan, 2015). The dried lavender leaves were scanned after calibrating the scanner (Hp Scan Jet) by black and white cards. Indicators L^* , a^* , and b^* were processed by Matlab 2013b. Finally, CI change was calculated as follows (Jha, 2010):

$$\Delta L^* = (L^*_{\text{standard}} - L^*_{\text{sample}}) \quad (4)$$

$$\Delta a^* = (a^*_{\text{standard}} - a^*_{\text{sample}}) \quad (5)$$

$$\Delta b^* = (b^*_{\text{standard}} - b^*_{\text{sample}}) \quad (6)$$

Where, L^* is darkness (0) to brightness (100), a^* is redness (+120) to greenness (-120), and b^* is yellowness (+120) to blueness (-120).

Optimization

The process of drying lavender leaves under AF, MSSIC, and NIR-Vacuum dryers were optimized by RSM. To optimize MSSIC, NIR-Vacuum, and AF dryers, independent variables were air temperature of the chamber (-15 to -5) for AF, inlet air temperature of the first, second, and third stages (40 to 60°C) for MSSIC, and air temperature (40 to 60°C) and air pressure (20 to 60 kPa) for NIR-Vacuum (Table 1). Besides, dependent variables (response) were TPC, AC, CI, and DR.

Central Composite Design (CCD) was applied to fit a second-order polynomial (y) equation for the experimental data and three codes level for each variable were selected as follows: -1, 0, and +1 for the low, medium, and high levels of each independent variable, respectively. In addition, AF dryer was optimized as one numerical factor. The optimization was carried out using Design Expert 10.

The results of optimization were compared with those of natural drying as control samples (Fealekari and Chayjan, 2014).

$$y = \beta_0 + \sum_{j=1}^k \beta_j x_j + \sum_{i < j} \beta_{ij} x_i x_j + \sum_{j=1}^k \beta_{jj} x_j^2 \quad (7)$$

Where, y is the response calculated by the model, β_0 , β_j , β_{ij} , and β_{jj} are constant, linear, squared, and interaction coefficients, respectively.

RESULT AND DISCUSSION

Response ranges for all the dryers and

Table 1. Experimental domain with natural and coded values of independent variables.

Dryer	Independent variable	Coded values		
		-1	0	+1
Multi-stage semi-industrial continuous	Inlet air temperature of first stage (°C)	40	50	60
	Inlet air temperature of second stage (°C)	40	50	60
	Inlet air temperature of third stage (°C)	40	50	60
Near infrared-vacuum	Air temperature (°C)	40	50	60
	Air pressure (kPa)	20	40	60
Atmospheric freeze	Air temperature of chamber	-15	-10	-5

drying conditions are presented in Table 2. Maximum Drying Rate (DR) belonged to Near Infrared-Vacuum (NIR-vacuum) dryer, while the minimum belonged to shade drying, which was even longer than AF dryer at primary drying level.

AF dryer had a positive effect (1.5-9 %) on Antioxidant Capacity (AC) while the value of AC was minimum for the shade drying (~0). Open sun drying had a better effect (0.1-0.2 %) on AC compared to shade drying. The results showed that, in addition to temperature, drying time had a significant effect on AC. Moreover, the maximum value of Total Phenolic Content (TPC) was achieved in NIR-Vacuum dryer [1.9-4.3 mg GAE g⁻¹ dry matter (dm)] and minimum value of TPC occurred in AF dryer [0.3 mg GAE g⁻¹ (dm)].

Color Index (CI) changes were maximum for lavender leaves dried under shade condition and the lowest belonged to NIR-Vacuum dryer, where the ΔL^* had the widest variation.

Drying Kinetics by AF Dryer

Lavender leaves were dried by AF dryer in two steps. The first one was primary drying in which the sample was dehydrated by sublimation. DR of lavender leaves increased with increase in air temperature and there was a significant difference between -10 and -5°C. In the second drying step, the lavender leaves were dried under convection drying with the temperature of 40°C. Since this condition was applied to all the experiments, the rate of secondary drying section was similar for all cases (Figure 3).

Optimization of AF Dryer for Lavender Leaves

The optimum performance of AF dryer for drying of lavender leaves was at -5°C air temperature with the desirability of 0.60 (Figure 4). The values of responses for this

Table 2. Range of response values in lavender leaves drying by different apparatuses.^a

Responses	Range of values	Type				
		AF	MSSIC	NIR-Vacuum	Open sun drying	Shade drying
Drying rate (kg _{water} kg ⁻¹ dry matter)	Max	1.12×10 ⁻⁵	2.24×10 ⁻⁴	9.62×10 ⁻⁴	1.621×10 ⁻⁴	5.08×10 ⁻⁶
	Min	1.73×10 ⁻⁶	1.61×10 ⁻⁴	2.01×10 ⁻⁴	1.187×10 ⁻⁴	4.39×10 ⁻⁶
	Std. Dev.	4.07×10 ⁻⁶	1.97×10 ⁻⁵	2.15×10 ⁻⁴	2.45×10 ⁻⁵	3.44×10 ⁻⁷
Antioxidant capacity (%)	Max	9.032	0.9700	4.9454	0.2301	0.0776
	Min	1.519	0.0500	0.2249	0.1016	0.0057
	Std. Dev.	0.1711	0.2203	1.4404	0.0706	0.0390
Total phenol content (GAE g ⁻¹ dry matter)	Max	3.7432	3.4300	4.3479	2.3529	2.9461
	Min	0.3027	1.7700	1.9137	2.0826	2.4760
	Std. Dev.	0.0846	0.4943	0.8467	0.1547	0.2667
ΔL^*	Max	16.6568	2.2000	3.35493	14.0060	17.531
	Min	11.6379	0.0800	0.655284	12.0908	12.642
	Std. Dev.	2.0843	0.6213	0.7774	0.9647	2.6254
Δa^*	Max	0.4990	2.7400	1.7836	3.3483	2.8000
	Min	0.1760	0.3000	1.0598	3.1989	2.1648
	Std. Dev.	1.4941	0.77821	0.2363	0.0795	0.3624
Δb^*	Max	1.9717	6.8000	0.8282	4.6941	9.0395
	Min	2.9896	2.1700	0.4600	4.1944	6.6917
	Std. Dev.	2.4496	1.3899	0.1015	0.2717	1.3392

^a AF: Atmospheric Freeze, MSSIC: Multi-Stage Semi-Industrial Continuous, NIR-Vacuum: Near Infrared-Vacuum ΔL^* : Color change for L* index, Δa^* : Color change for a* index, Δb^* : Color change for b* index.

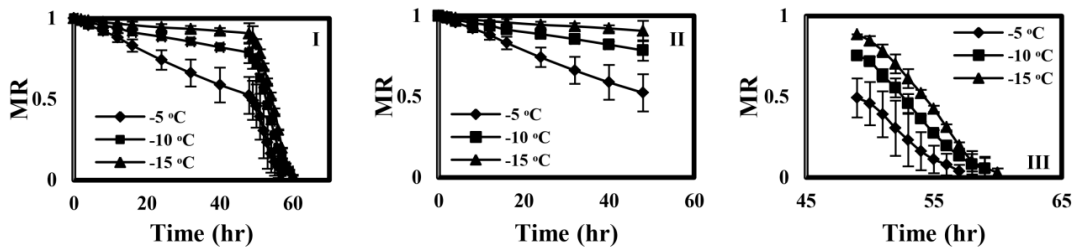


Figure 3. Change of Moisture Ratio (MR) versus time for drying of lavender leaves by Atmospheric Freeze (AF) dryer.

temperature were 1.812 mg GAE g^{-1}_{dm} for TPC, 0.442% for AC, 14.81 for ΔL^* , 0.75 for Δa^* , 8.47 for Δb^* , and $9.03 \times 10^{-6} kg_{water} kg^{-1}_{dm}$ for DR.

Under primary drying at $-5^{\circ}C$, frozen water needs a lower energy than temperatures -10 and $-15^{\circ}C$; consequently, a strong moisture gradient is developed. Therefore, moisture reduction rate at $-5^{\circ}C$ was more than the other temperatures. Also, DR in primary drying level increased strongly by the higher temperature. Reyes *et al.* (2011) reached similar results for DR when apple slices were dried by an AF dryer.

According to the importance of the factors, air temperature of $-5^{\circ}C$ under primary drying was suggested as the optimum point. Note that the risk of melting the sample was high at this temperature and caution should be taken. Perhaps, this is why Stawczyk *et al.* (2006) suggested a temperature of $-10^{\circ}C$ for

drying of apple cubes.

Although more research is needed to apply AF dryer as a high-technology and novel dryer in industry, considering the recent studies and the less energy consumption of AF dryer rather than vacuum freeze dryer, quality of this types of dryers is not significant (Claussen *et al.*, 2007; Rahman and Mujumdar, 2008; Colucci *et al.*, 2017). Hence, AF dryer is expected to be a matter of interest for drying experts.

Drying Kinetics by MSSIC Dryer

Figure 5 presents the changes in Moisture Ratio (MR) versus time for drying of lavender leaves by MSSIC dryer. Using the charts presented based on the variations of the first-floor temperature, the effect of first-floor temperature on DR was found to be statistically significant at 0.05.

Dwivedy *et al.* (2012) studied the drying of borage by a microwave dryer and found that the best performance for keeping TPC and AC was at the power of 540W. The power of 450W was selected as microwave pretreatment considering the adjustment point of the microwave oven. Also, Shi *et al.* (2017) suggested microwave drying to keep the higher content of flavone, vitamin C, and soluble sugar for chrysanthemum flower.

With an increase in air temperature, DR of lavender leaves was also increased. The most important phenomenon in multi-stage lavender leaves drying was tempering. Tempering caused moisture content transfer from the center to surface at the low-

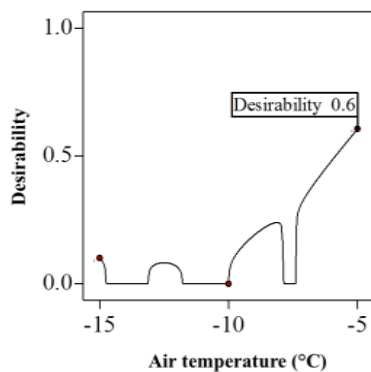


Figure 4. Desirability chart for drying of lavender leaves by atmospheric freeze dryer.

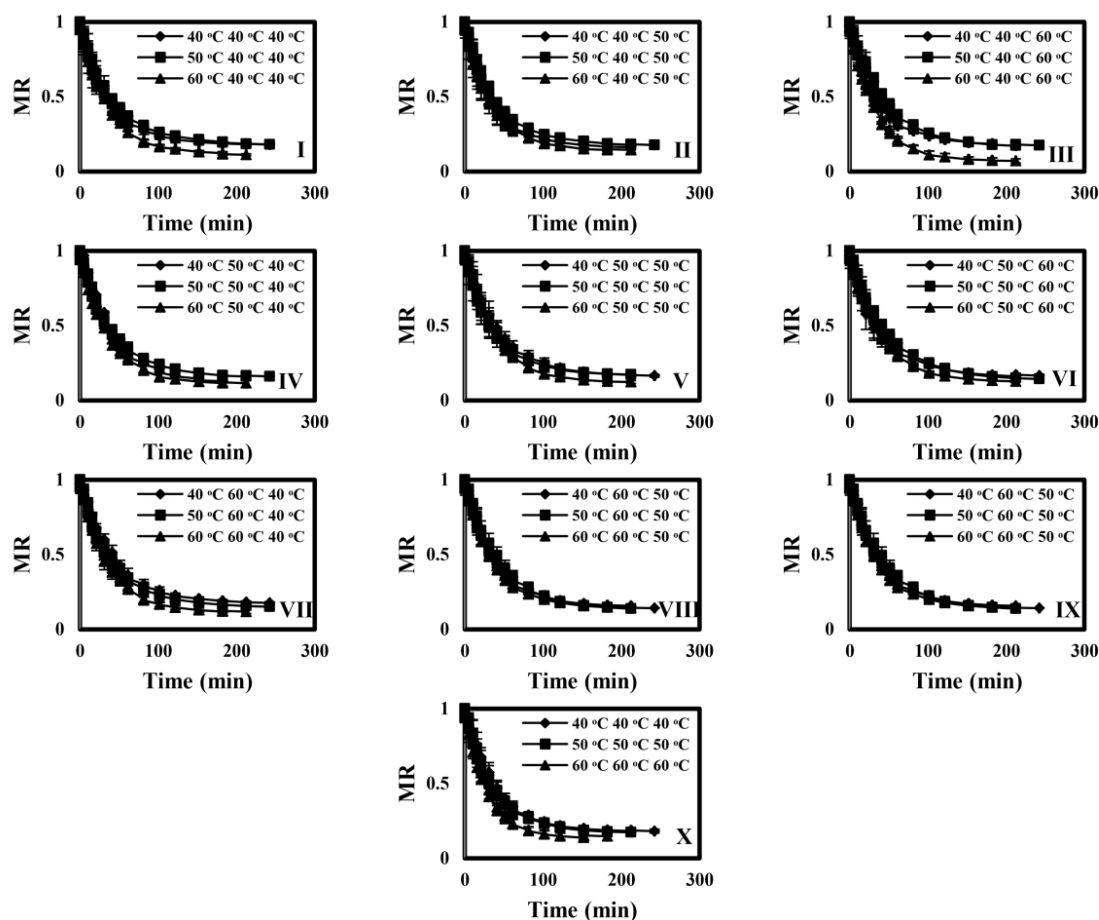


Figure 5. Change of Moisture Ratio (MR) versus time for drying of lavender leaves by Multi-Stage Semi-Industrial Continuous (MSSIC) dryer.

temperature condition. Besides, a decrease in drying time resulted in lower energy consumption (Figure 5-c). The result indicated that the kinetics of lavender leaves drying by MSSIC dryer contains two different sections because of microwave pre-treatment effect at every set-time. At the first level, all the drying kinetics was the same, but there were some differences between them in the second level (Figure 5). At the beginning of the drying process, the moisture content of lavender leaves was high and, consequently, the microwave could dehydrate moisture. When moisture content was reduced, microwave pre-treatment with the same power and time could not dehydrate moisture as previously and the effect of hot air drying was more visible than before.

Effect of drying on the chemical constituents is different for aromatic plants such as lavender. For example, for drying of basil leaves by the fluidized and vibro-fluidized dryer, a significant drop in the eugenol content was observed after drying under temperatures of 45 and 60°C, while linalool, 1,8-cineole, and camphor were kept under 30°C and strongly increased under temperatures of 45 and 60°C (Lima-Corrêa *et al.*, 2017). In addition, a study on the drying of peppermint leaves showed that microwave drying improved the quantity of some bioactive components in the essential oil (Torki-Harchegani *et al.*, 2018).

Generally, at higher temperatures, active ingredients of aromatic leaves are destroyed and more oil molecules may be evaporated from the leaves surface with moisture. In

this regard, however, the multi-stage strategy could be of great assistance to reduce the evaporation of active ingredients by letting moisture diffuse from the core to surface in lower temperature and then moisture evaporated at the higher temperature. In addition, more oil glands may be destroyed during long drying time (Nozad *et al.*, 2016). Thus, it is very important to create a balance between drying time and drying temperature.

The mixture of two different components, chlorophyll-a and chlorophyll-b, which are dependent on Mg^{2+} , creates the green color. High temperature accelerated the process of substituting magnesium with hydrogen in chlorophyll, which is called pheophytin (Salarikia *et al.*, 2017). Significant destruction in chlorophyll and carotenoids content at the higher temperature was reported in the study on drying of mint leaves under the effect of hot-air drying (Beigi, 2019).

Optimization of MSSIC Dryer for Lavender Leaves

For lavender leaves drying by MSSIC dryer, the optimum condition suggested 60-40-60 °C for temperature of the first, second and third stages, respectively, with the response values being 0.391 mg GAE g^{-1}_{dm} for TPC, 2.695% for AC, 0.51 for ΔL^* , 1.73 for Δa^* , 4.17 for Δb^* , and 2.1218×10^{-4} $kg_{water} kg^{-1}_{dm}$ for DR (Figure 6).

According to a study conducted on the variations of essential oil content during convective drying of lemon balm, the highest losses of essential oil content occurred at the beginning of drying processes (Argyropoulos and Müller, 2014). Thus, considering the effect of constant microwaves pretreatment, it could be assumed that most of the change of active ingredients was under the effect of constant microwave pretreatment. Accordingly, the effect of MSSIC drying was insignificant on TPC and AC variations. Nevertheless, our results showed that the multi-stage drying

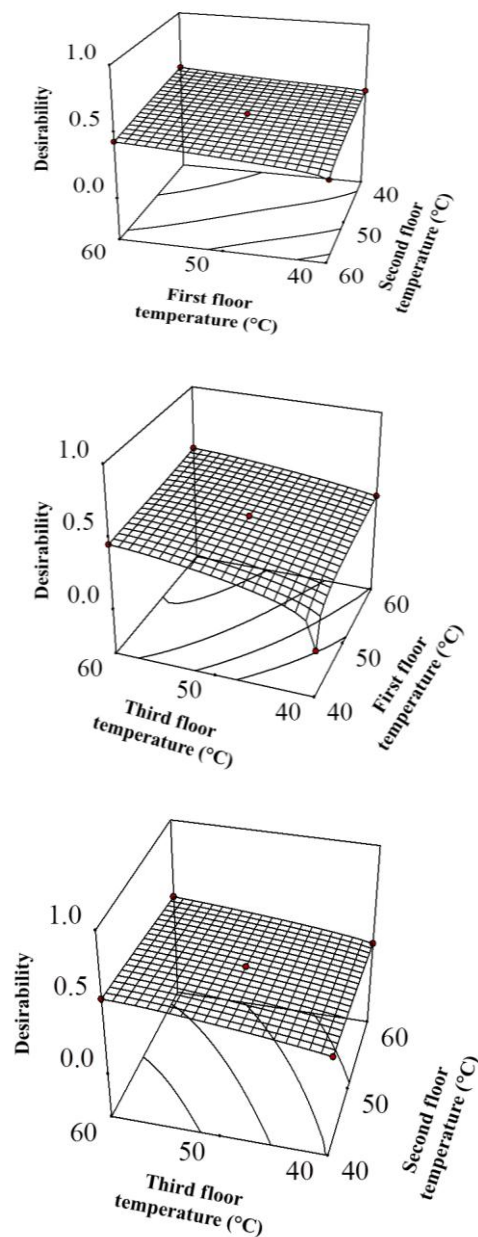


Figure 6. Desirability chart of lavender leaves drying by Multi-Stage Semi-Industrial Continuous (MSSIC) dryer.

had insignificant effects on active ingredient (at the range of 40-60°C), for which the optimum point was suggested as a multi-stage.

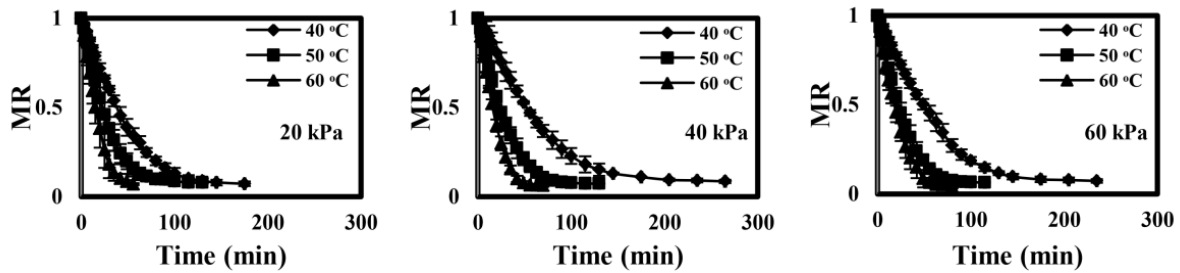


Figure 8. Change of Moisture Ratio (MR) versus time for drying of lavender leaves by Near Infrared-Vacuum (NIR-Vacuum) dryer.

Drying Kinetics of NIR-Vacuum Dryer

Figure 7 shows the variations in the moisture ratio versus time for drying of lavender leaves using NIR-Vacuum dryer. The results showed that the drying time (about 60 to 115 minutes) decreased with increasing of air temperature (40 to 60°C) and air temperature variation was significant on drying rate at the level of 0.01. Since TPC and AC were decomposed mainly by oxidation reactions, a lower pressure caused less oxygen around the sample and, consequently, oxidation reactions decreased. Vacuum level variation was statistically significant versus TPC and AC variations.

Quality of green vegetable is extremely dependent on chlorophyll retention, and more chlorophyll means less color change from green to red (Sledz and Witrowa-Rajchert, 2012). Chlorophyll degradation is limited by vacuum dryer because during the vacuum drying both oxygen and light were at their lowest level within the system. As a result, chlorophyll degradation is prevented and thus the main cause of color change might be attributed to Maillard reaction rather than chlorophyll's degradation (Uribe *et al.*, 2016).

Optimization of NIR-Vacuum Dryer for Lavender Leaves

Results showed that the best performance was 20 kPa for air pressure and 60 °C for air

temperature with response values of 0.754 mg GAE g⁻¹_{dm} for TPC, 1.648% for AC, 1.31 for ΔL^* , 1.80 for Δa^* , 4.13 for Δb^* , and 9.08×10^{-4} kg_{water} kg⁻¹_{dm} for DR (Figure 8). Under such conditions, beside reducing the drying time, decomposition and destruction of the phenolic structure, antioxidant, and some pigments such as chlorophyll are limited by reducing oxygen and hydrogen through reducing air pressure. However, by drying the sample at high-temperature conditions, active ingredients were less damaged due to the shorter drying time.

Drying Kinetics of Solar Drying

Figure 9-A shows sun radiation, relative humidity, and air temperature change during drying, while drying kinetics change under

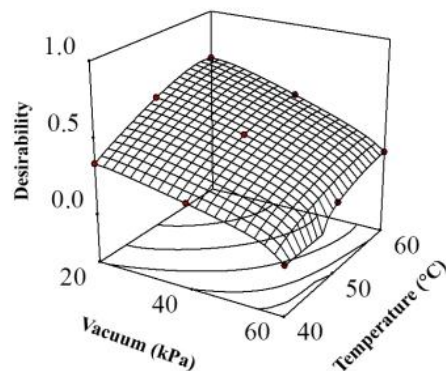


Figure 7. Desirability chart of drying lavender leaves by Near Infrared-Vacuum (NIR-Vacuum) dryer.

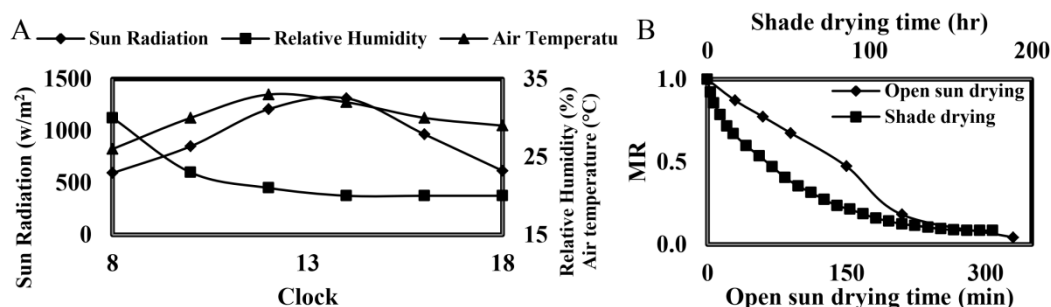


Figure 9. (A) Air condition when lavender leaves dried in the open sun and shade conditions, and (B) Change of Moisture Ratio (MR) versus time for drying of lavender leaves at open sun and shade condition.

open sun and shade conditions. With increasing sun radiation power, air temperature increased and, consequently, relative humidity decreased. Lavender leaves were dried about 200 hours under shade condition and 300 minutes in open sun condition.

Drying the lavender leaves under solar radiation caused relative humidity to decrease with increasing temperature and vapor pressure gradient increase (Hassanain, 2011). Results showed that drying rate suddenly increased at 12:00, which was because solar radiation was maximum at this time (Figure 9-B).

Drying the lavender leaves through solar radiation was much faster and shorter than shade drying. Apart from sun radiation, wind blow caused open sun drying (drying in 300 minutes), which was faster than shade drying (drying in 200 h).

Comparison between Open Sun and Shade Drying

Shade drying was more effective to keep TPC ($2.638 \text{ mg GAE g}^{-1}_{\text{dm}}$) rather than open sun drying ($2.261 \text{ mg GAE g}^{-1}_{\text{dm}}$), while the result of AC was opposite to those of TPC. The AC for open sun drying was about 0.14 % more than shade drying.

Although shade drying of lavender leaves had a statistically insignificant effect on active ingredients, open sun drying was faster compared to shade drying.

Furthermore, shade drying caused more color change compared to open sun drying. The color of lavender leaves dried at shade conditions was changed to yellow-red, probably because of a longer drying time.

In some study, a dryer was recommended just based on the drying time, energy consumption or drying kinetic (Altay *et al.*, 2019), while keeping active ingredients are so important in the process of drying aromatic plants. Therefore, in terms of comparison, MSSIC drying with microwave pretreatment had insignificant effects on the qualitative factors. However, AF drying, which was successful in keeping active ingredients, needs more study before industrial application, due to having low DR. Natural condition, in addition to the hygiene issue, CI change, and active ingredient had better performance related to MSSIC and AF drying methods. Finally, in this study, NIR-Vacuum dryer method was suggested for drying lavender leaves because of the higher DR and keeping TPC and AC better than the other methods.

CONCLUSIONS

This research was performed to figure out how different drying methods affect the drying characteristics such as Drying Rate (DR) and selected physicochemical parameters of Color Index (CI), Total Phenol Content (TPC), and Antioxidant Capacity (AC) during drying of lavender

leaves. Lavender leaves were dried under three different AF (Atmosphere Freeze), Multi-Stage Semi-industrial Continuous (MSSIC), and Near Infrared-Vacuum (NIR-Vacuum) dryers and optimized by Response Surface Methodology (RSM). The results showed that an increase in air temperature at primary drying level is accompanied by an increase in the drying rate and -5°C is the optimum temperature. Multi-stage drying through tempering phenomenon increased drying rate remarkably and optimum point for MSSIC dryer suggested a cycle at which the temperature of the first, second, and third stages were $60-40-60^{\circ}\text{C}$, respectively. Results indicated that the multi-stage drying had no significant effect on the variation of the material since microwave pretreatment was applied to all the similar experiments. Because oxygen and hydrogen entry was limited by NIR-Vacuum dryer, this dryer kept active ingredients better than the others. The result showed that the optimum conditions for drying of lavender leaves under NIR-Vacuum dryer were 20 kPa and 60°C . The longest drying time belonged to shade drying. Moreover, the highest Color Index (CI) change also occurred in shade drying condition. The green color of lavender leaves changed to yellow for all the dryers, suggesting that chlorophyll was degraded and other pigments such as carotenoid could be obviously more than before.

Eventually, NIR-Vacuum drying compared with other methods was the best dryer for lavender leaves drying with $\text{TPC}=0.754 \text{ mg GAE g}^{-1} \text{ dried matter}$, $\text{AC}=1.648\%$, $\Delta\text{L}^*=1.31$, $\Delta\text{a}^*=1.80$, $\Delta\text{b}^*=4.13$, and $\text{DR}=9.08 \times 10^{-4} \text{ kg}_{\text{water}} \text{ kg}^{-1} \text{ dm}$, because of the low degradation of ingredients and suitable drying rate.

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بهینه‌سازی تجهیزات مختلف خشک کردن برای برگ‌های اسطوخودوس با روش سطح پاسخ

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چکیده

برگ اسطوخودوس به‌عنوان طعم دهنده به غذاها، نوشیدنی‌ها در سطح گسترده‌ای استفاده می‌شود و یک منبع غنی از ترکیبات فنولی و آنتی‌اکسیدانی است. روش خشک کردن برای نگهداری این ترکیبات بسیار حیاتی است. در این مطالعه، برگ اسطوخودوس به‌وسیله خشک‌کن‌های اتمسفر انجمادی، چندمرحله‌ای نیمه‌صنعتی پیوسته و مادون‌قرمز خلأی خشک شد و به روش سطح پاسخ برای بالاترین نرخ خشک شدن، فنول کل بافت و ظرفیت آنتی‌اکسیدانی و کمترین تغییر شاخص‌های رنگی بهینه‌سازی شد. همچنین برگ اسطوخودوس در شرایط طبیعی به‌عنوان یک روش سنتی خشک شد. خشک کردن چندمرحله‌ای موجب پدیده باز پخت شد که متعاقباً نرخ خشک شدن به‌صورت مشهود افزایش یافت. خشک‌کن مادون‌قرمز-خلأی عملکرد مناسبی بروی نگهداری مواد فعال برگ‌های اسطوخودوس داشت. نقطه بهینه برای خشک کردن برگ‌های اسطوخودوس در خشک‌کن اتمسفر انجمادی در دمای 5°C یافت شد. نقطه بهینه‌دما در خشک‌کن چندمرحله‌ای نیمه‌صنعتی پیوسته در $60-40-60$ به ترتیب برای دمای مرحله اول، دوم و سوم به دست آمد. نقطه بهینه در خشک‌کن مادون‌قرمز خلأی 60°C و 20kPa به ترتیب برای دمای هوای و فشار هوا بود. بر اساس نتایج، از میان چندین روش خشک کردن، خشک‌کن مادون‌قرمز خلأی برای خشک کردن برگ‌های اسطوخودوس مناسب‌تر بود.