Effect of Ultrasound on Henna Leaves Drying and Extraction of Lawsone: Experimental and Modeling Study

Said Bennaceur 1, Abdelaziz Berreghioua 2, Lyes Bennamoun 3,*, Antonio Mulet 4, Belkacem Draoui 5, Mostafa Abid 6 and Juan A. Carcel 4

Abstract: The effect of drying temperature and the application of ultrasound on drying kinetics of Lawsonia inermis (henna) leaves and the extraction of lawsone from the dried samples was addressed. Indeed, henna leaves were dried with and without the application of ultrasound (21.7 kHz, 30.8 kW/m²) at 40, 50 and 60 °C with a constant air velocity (1 m/s). As expected, both the increase of temperature and the application of ultrasound decreased the drying time and increased the rate of extraction of the lawsone. The values of the effective diffusion coefficients obtained were used to quantify this influence showing the value increases with higher drying temperature and the application of ultrasound. Moreover, the influence of temperature was quantified by the estimation of the activation energy from an Arrhenius-type equation (46.25 kJ/mol in the case of drying without ultrasound application and 44.06 kJ/mol in the case of ultrasonically-assisted drying). Regarding the influence of studied variables on lawsone extraction yield, the higher is the temperature, the lower is the yield, probably linked with lawsone degradation reaction due to thermal treatment. On the contrary, the application of ultrasound improved the extraction yield mainly at the lower drying temperature tested of 40 °C.

Keywords: activation energy; effective diffusivity; lawsone; Lawsonia inermis; ultrasound

1. Introduction

The medicinal and aromatic plants of Algeria, in particular from the southwest of the country, have attracted the attention of several researchers and scientists from different areas, such as botany, biochemistry, agri-food, chemistry and pharmaceutical field. Most of the published studies [1,2] have been focused on the chromatographic determination of the essential oil content of these plants because of their therapeutic uses. In this sense, Lawsonia inermis L. is an important plant widely consumed in Algerian society and worldwide. This plant grows mostly in the southern region of Algeria and is known as henna. It is characterized by a height of up to 2–3 m at the end of plant life, consisting mainly of dark green oval leaves with a length of 2–4 cm (Figure 1) that remain greenish in color for eight months [3]. In general, henna is used as a cosmetic product and is considered as an exceptional source of natural components resulting from several drug developments. Thus, henna leaves are presented as a preventive agent for treating certain diseases of the...
skin, eyes and intestines [4]. More concretely, some studies showed that extracts from henna leaves have antimicrobial and antifungal actions [5] and have several industrial applications [6]. The main component identified in henna leaves extracts is the lawsone (2-hydroxy-1,4-naphthoquinone) [7,8] (Figure 2). Lawsone is used to dye the hair, fingernails, leather, silk and wool [6]. To extract this active substance, the fresh leaves of henna have to be previously dried. Traditionally, the leaves of henna are dried using solar energy. This methodology involves very long drying time and depends on the weather conditions, resulting in an important loss in the quality of the final product. Nowadays, drying is carried out at industrial scale mainly using convective hot air drying.

![Figure 1. (a) Lawsonia inermis fresh leaves; and (b) leaves powder.](image1)

![Figure 2. Structure of the Lawsone molecule.](image2)

This allows the standardization of the production and avoids problems, such as contamination by dust particles or insects [9]. As the drying process takes a long time, the conventional way to reduce this factor is to use high drying temperatures. However, this can influence the quality of the dried product and affect other characteristics such as color, texture, ascorbic acid content (AA), total carotenoids content, antioxidant properties, shrinkage and rehydration capacity [9–11].

The low efficiency of convective drying and its relatively high operating cost have made this process a subject of research to improve its results. Consequently, different of alternative technologies, such as microwaves or infrared, have been tested [11,12] with the aim of improving both the kinetics of the drying process and the quality of the final product. In this sense, high-intensity ultrasound has been found to be an efficient way to intensify convective drying of different food products and plants [13,14]. These high intensity ultrasonic waves can cause a rapid series of alternating compressions and expansions in the same way as a sponge when it is compressed and released several times (sponge effect). The sponge effect caused by the application of ultrasound may be responsible for the creation of microscopic channels in porous materials. In addition, ultrasound produces cavitation in liquid media, which can be useful in removing strongly bound moisture. At the interphases, ultrasound can generate so-called sonic wind, which reduces the diffusion boundary layer and increases the convective mass transfer [9,15]. All these effects could allow decreasing the drying time and contribute to an improvement in the quality of the product [9,16,17]. Thus, as a general rule, it can be stated that the application of ultrasound
at moderate temperatures does not produce negative effects on the quality of the product and contributes to an improvement in some quality characteristics [9,16,17]. However, this fact strongly depends on the product under consideration [9,18].

Thus, the aim of this study was to address the influence of the application of ultrasound on the drying kinetics of henna leaves and the properties of the main active component, lawsone, extracted from the henna leaves.

2. Materials and Methods

2.1. Drying Experiment

Henna leaves were cultivated in the wilaya of Bechar (southwestern region of Algeria). After the harvest, the leaves were transported from Algeria to Spain under ambient conditions; the temperature did not exceed 25 °C and there was low humidity during the travelling day. In the Agri-Food Process Analysis and Simulation Laboratory (ASPA) of the Food Technology Department, Universitat Politècnica de València, Spain, the samples were stored in plastic bags (Ziploc) at 5 ± 1 °C until the drying experiments were performed.

Drying was carried out in an ultrasonically-assisted convective dryer previously described [10,11]. This equipment is a laboratory-scale dryer modified to apply power ultrasound, with automatic control of the air temperature and velocity and provided with an automatic sample weighing system. This device includes a cylindrical vibrating radiator driven by a piezoelectric transducer (21.7 kHz), which generates a high-intensity ultrasonic field in the air medium, where the samples are placed. A high-power ultrasound generator, an impedance matching unit and a digital power meter (WT210, Yokogawa Electric Corporation, Japan) regulate and measure the electrical parameters of the acoustic signal (voltage, intensity, phase, frequency and power). The air parameters (velocity and temperature) were controlled through a PID algorithm, and a PC supervised the entire drying process. [19] The drying experiments were carried out at different air temperatures (40, 50 and 60 °C) without (Air) and with ultrasound application (Air + us; 21.7 kHz, 20.5 kW/m³). In every run, a constant air velocity of 1 m/s was applied, and the process was stopped when the samples lost 75% of their initial weight. Each drying condition was tested at least in triplicate.

2.2. Drying Kinetics

The evolution of the moisture content of the samples during drying was determined by weighing the henna leaves at different drying times and the determination of the initial moisture content of fresh samples [20]. The equilibrium moisture content of the henna leaves was experimentally obtained by placing the henna samples in the drying conditions for a very long time. This time was enough to have no difference in sample weight for 2 h. The obtained value was compared with that previously reported by Bennaceur et al. [8]. The moisture content of the samples was then expressed in a non-dimensional way using Equation (1) [20]

\[
MR = \frac{X(t) - X_{eq}}{X_0 - X_{eq}}
\]  

(1)

The drying rate (Dr) of henna leaves was calculated using the following equation [21]:

\[
Dr = \frac{X_{t+dt} - X_t}{dt}
\]

(2)

where \(MR\) is the dimensionless moisture content, \(X(t)\) is the moisture content after a drying time \(t\) (kg water/kg dry matter, d.m.), \(X_0\) is the initial moisture content of samples (kg water/kg d.m.) and \(X_{eq}\) (kg water/kg d.m.) is the equilibrium moisture content.

2.3. Lawsone Extraction and Separation

The leaves of henna, which were dried at different temperatures (40, 50 and 60 °C) with and without ultrasound application, were vacuum packaged and stored in the darkness
until processing. Each sample was extracted with methanol using a Soxhlet apparatus (laboratory of Chemistry, University of Béchar. The extraction was completed after 10 h [22]. High-performance liquid chromatography (HPLC) experiments were carried out. We employed an i-series LC-2030 (Shimadzu, Tokyo, Japan), equipped with an automatic injector of 1–100 µL sample loop and double pump system with a vacuum degassing unit. Chromatographic data were acquired, stored and analyzed by the LC Lab solution software. All parameters were deeply explored to optimise the HPLC separation.

The extraction yield ($R_e$) was calculated according to Equation (3):

$$R_e = \frac{M_L}{M} \times 100$$

(3)

where $R_e$ is the extraction yield and $M_L$ is the weight.

3. Mathematical modeling
3.1. Determination of Effective Moisture Diffusivity

The second diffusion Fick law (Equation (4)) has been widely and successfully used to describe the drying process of most biological products [23] which present a unidimensional moisture transport. In this case, it is considered that the transfer of moisture during drying is controlled only by internal diffusion.

$$\frac{\partial X}{\partial t} = D_{eff} \frac{\partial^2 X}{\partial x^2}$$

(4)

where $D_{eff}$ is the effective diffusion coefficient ($m^2/s$), $t$ is the drying time (s) and $x$ is the moisture transport direction. To integrate this equation, the following boundary and initial conditions were assumed:

- Uniform initial moisture content: $X(x, 0) = X_0$
- Symmetry of moisture transport: $\frac{\partial X}{\partial x} / x=0 = 0$
- External resistance to mass transport negligible, which means that the equilibrium moisture content at the surface is only achieved at the beginning of the drying process: $X(L, t) = X_{eq}$

$L$ represents the half thickness of the henna leaves. With these assumptions, the integrated solution for the whole volume of sample of Equation (4) is the one proposed by Crank [24] (Equation (5)):

$$MR = \frac{X(t) - X_{eq}}{X_0 - X_{eq}} = \left[ \sum_{n=0}^{\infty} \frac{8}{\pi^2 (2n+1)^2} e^{-\frac{(2n+1)^2 \pi^2 D_{eff} t}{4L^2}} \right]$$

(5)

$$MR = \frac{X(t) - X_{eq}}{X_0 - X_{eq}} = \frac{8}{\pi^2} e^{-\frac{\pi^2 D_{eff} t}{4L^2}}$$

(6)

Equation (6) can be expressed in logarithmic form as:

$$\ln MR = \ln \left( \frac{8}{\pi^2} \right) - \frac{\pi^2 D_{eff} t}{4L^2}$$

(7)

Then, $D_{eff}$ can be easily calculated from the slope of the relationship between $MR$ and drying time (Equation (8)):

$$\text{slope} = \frac{\pi^2 D_{eff}}{4L^2}$$

(8)
3.2. Activation Energy

The influence of the drying temperature on the \( D_{\text{eff}} \) can be quantified by the activation energy \( (E_a) \) which can be calculated by using an Arrhenius-type equation \[25\] as follows:

\[
D_{\text{eff}} = D_0 \cdot e^{\left(-\frac{E_a}{RT}\right)}
\]

(9)

where \( D_0 \) is a pre-exponential factor of the Arrhenius equation \((m^2/s)\), \( E_a \) is the activation energy \((kJ/mol)\), \( T \) is the drying temperature \((K)\) and \( R \) is the constant of ideal gases \((kJ/molK)\).

4. Results and Discussion

4.1. Experimental Drying Kinetics

The initial moisture content of henna leaves was 2.33 kg water/kg d.m. The drying air temperature affected the experimental drying kinetics (Figure 3a). As expected, it was observed that the increase of the air temperature allowed decreasing the drying time. Thus, the time needed to achieve a moisture content of 1 kg water/kg d.m. was 3.47 ± 0.63 h at 40 °C, 1.97 ± 0.05 h at 50 °C and 1.19 ± 0.05 h at 60 °C. Thus, increasing the drying temperature from 40 to 60 °C reduced the drying time by 35%.

![Figure 3. Experimental drying kinetics of the henna leaves determined at different temperatures (40, 50 and 60 °C): (a) without ultrasound application (Air); and (b) with ultrasound application (Air + us; 20.5 kW/m³; 21.7 kHz).](image)

The application of ultrasound during convective drying significantly increased the drying kinetics of the henna leaves (Figure 3b). For example, at 40 °C, the drying time in experiments carried out with ultrasound was 40% lower than those carried out without ultrasound (Table 1). Ultrasound can improve moisture removal by affecting both the internal movement of water inside henna leaves producing the “sponge effect” and the transport to moisture from the henna leaves surface to the drying air by the micro-stirring at interfaces generated by the so-called ultrasonic wind \[13\].
Table 1. Drying of henna leaves (1 m/s) at different temperatures, without and with ultrasound (21.7 kHz, 20.5 kW/m³). Drying time needed to reach a final moisture content of 0.1 kg of water/kg of dry matter (mean ± SD).

| Temperature (°C) | Ultrasound Application | Time (h)    |
|------------------|------------------------|-------------|
| 40               | No                     | 3.47 ± 0.63 |
| 50               | No                     | 1.97 ± 0.05 |
| 60               | No                     | 1.19 ± 0.05 |
| 40               | Yes                    | 2.64 ± 0.13 |
| 50               | Yes                    | 1.64 ± 0.17 |
| 60               | Yes                    | 1.11 ± 0.19 |

In drying operations, it is interesting the study of the variation of drying rate versus the moisture content evolution, which called the Krischer’s curve (Figure 4).

Figure 4. Drying rate curves of leaves henna vs. moisture content at different temperatures (40, 50 and 60 °C): (a) without ultrasound application (Air); and (b) with ultrasound application (Air + us; 20.5 kW/m³; 21.7 kHz).

In this case, only the falling rate period was observed in all the experiments. The drying rate increased with increasing temperature. During the drying process of fresh henna leaves, the ratios between drying speeds without the application of ultrasound (AIR) for temperatures 50 and 60 °C and temperature 40 °C at moisture content of 1 kg water/kg d.m were 20,052% and 386%, respectively. This indicates the thermal effect observed on the drying rate. In the case of experiments carried out without ultrasound application, two stages were observed: the slope of the relation between drying rate and moisture content above a specific moisture content was significantly larger than the one below this moisture content (Figure 4a). This is because, at the beginning of drying, the free moisture content is eliminated. In this stage, the decrease of drying rate with the decrease of moisture content is fast. This specific moisture content depended on the drying temperature applied, being lower at higher drying temperature (1.9 kg water/kg d.m. at 40 °C, 1.6 kg water/kg d.m. at 50 °C and 1.2 kg water/kg d.m. at 60 °C). The higher is the temperature, the greater is the energy in the system, which makes the water movement easy. Below the specific moisture content, the remaining moisture is bound to the henna matrix. In this situation, the decrease of the drying rate with the reduction of moisture slowed down.

The application of ultrasound affected the evolution of drying rate with the moisture content. The drying experiments carried out with ultrasound showed an increase in the
drying rate compared with those performed without ultrasound. Thus, the ratios between drying speeds of the two drying methods (Air + us/Air) were 180.60%, 127.50% and 121.64% for 40, 50 and 60 °C, respectively, at moisture content of 1 kg water/kg d.m.

Regarding the evolution of drying rate, in the case of ultrasonic-assisted drying experiments, the evolution was continuous in the whole range of moisture content, and only at the drying temperature of 50 °C it was possible to identify the two stages identified in the drying carried out without ultrasound (Figure 4b). This could be due to the ultrasound effects can making the movement of water inside the samples easy and thus no difference in bounded and unbounded water removal appeared.

4.2. Effective Diffusivity and Activation Energy

To quantify the influence of temperature and ultrasound application on the drying kinetics, experimental moisture content evolution was modeled using Equation (5). The values of the identified effective diffusion coefficient \( D_{\text{eff}} \) and the correlation coefficient at different temperatures (40, 50 and 60 °C), with and without the application of ultrasound, are shown in Table 2. The correlation coefficient was above 0.98 in every experiment, which indicates that the model adequately fit the experimental data. The \( D_{\text{eff}} \) values obtained ranged between \( 0.7094 \times 10^{-9} \) and \( 2.5547 \times 10^{-9} \) m²/s in the case of conventional drying experiments and \( 1.0234 \times 10^{-9} \) and \( 2.8164 \times 10^{-9} \) m²/s in the case of ultrasonically-assisted ones. These values are in the same range as others given in the literature [26,27].

| Temp (°C) | Air \( D_{\text{eff}} \) (m²/s) \( 10^{-9} \) | r    | Air + us \( D_{\text{eff}} \) (m²/s) \( 10^{-9} \) | r    |
|-----------|-----------------------------|------|-----------------------------|------|
| 40        | 0.7094 ± 0.2253             | 0.9835 | 1.0234 ± 0.0398             | 0.9929 |
| 50        | 1.5933 ± 0.1218             | 0.9920 | 2.0882 ± 0.9859             | 0.9887 |
| 60        | 2.5547 ± 0.4922             | 0.9930 | 2.8164 ± 0.3576             | 0.9834 |

The application of ultrasound increased the \( D_{\text{eff}} \) identified at the temperature tested. The ultrasound effects could contribute to accelerate the water movement and removal from the henna leaves. Regarding the temperature, it was observed than the the \( D_{\text{eff}} \) increased with the drying temperature. To evaluate the influence of drying temperature in drying kinetics, an Arrhenius-type equation was used to calculate the activation energy. Thus, the natural logarithm of the identified values of \( D_{\text{eff}} \) was represented as a function of the temperature inverse, and, from the slope of this relation, the activation energy was calculated.

The values obtained were 62.23 ± 1.78 and 43.83 ± 1.42 kJ/mol for drying without and with the application of ultrasound, respectively (correlation coefficients of 0.9840 and 0.9906, respectively). These values are similar to those reported in the literature [26,27]. Therefore, the influence of drying temperature in drying kinetics was slightly lower in the experiments carried with ultrasound application.

4.3. Influence of Drying in Lawsone Content

To confirm the presence of lawsone in our samples, we used the results obtained from the analysis by HPLC [28]. The chromatograms were developed at 293 nm and then compared with that of pure lawsone. As shown in Figure 5a,b, the peak obtained at 4.404 min (retention time) for the pure lawsone corresponds with the peak obtained at 4.413 min for the extract obtained from henna leaves dried at 40 °C without ultrasound application.
As shown in Figure 6, the drying temperature highly affected the extraction yield (Re). Thus, Re decreased with the increase of drying temperature. The higher is the air temperature, the greater is the amount of energy supplied, and this likely produces a greater degradation of the product. Therefore, the drying at low temperature of henna leaves permits obtaining a greater yield of lawsone extracts.

Figure 5. HPLC analysis for: (a) pure Lawsone; and (b) samples of dried leaves without ultrasound (Air) at 40 °C.

Figure 6. The extraction yield of lawsone extracted from henna leaves at 40, 50 and 60 °C without (Air) and with (Air + us; 20.5 kW/m²; 21.7 kHz) ultrasound application.
Regarding the effect of the ultrasound application during drying, it was observed that, for all drying temperatures (40, 50 and 60 °C), the lawsone extraction yields were significantly higher in the ultrasonically-assisted dried henna leaves (Air + us) than in the conventionally dried ones (Air). This could be related with the shortening of the drying process when ultrasound is applied. Thus, the extraction yield differences were obtained in samples dried at 40 and 60 °C. In the first case, the slow drying kinetics could increase the degradation of lawsone by oxidation reactions. In this case, application of ultrasound reduced drying time and the time of exposure to the drying air, limiting oxidation reactions. In the second case, the higher drying temperature applied (60 °C) could affect the lawsone integrity. The shortening of drying process produced by ultrasound application reduced the exposure time to high temperature and, therefore, the thermal damage.

Moreover, it is known that the application of ultrasound during drying can produce some effects in the microstructure of products. Thus, the sequential compressions and expansions induced by ultrasonic waves can affect the integrity of cell walls or produce the generation of micro-channels in the material [13]. These effects can improve the extraction of lawsone from henna leaves and increase the yield.

5. Conclusions

The influence of drying temperature and ultrasound application in the drying kinetics of henna leaves was addressed. In the range of temperature tested, the higher is the temperature, the faster is the drying. The impact of the temperature and application of the ultrasound on the diffusivity coefficient temperature followed the same trend. However, the relationship between temperature and extraction yield of lawsone, the most interesting compound of henna leaves, was the opposite: the greater is the temperature, the lower is the extraction yield, likely because of thermal degradation. The application of ultrasound increased the drying kinetics as well as the extraction yield of lawsone. Therefore, ultrasonically-assisted drying of henna leaves can be considered to both reduce drying temperature to save energy and increase the yield of the extraction of lawsone. Ultrasonic-assisted drying provided a good effect on the drying process, but the extent of ultrasonic improvement depended largely on process variables, such as air velocity and range of ultrasound frequencies. The application of ultrasound technology will in some way affect the quality of food, including physical and chemical attributes. In general, the application of ultrasound can decrease water activity and improve product quality.

Author Contributions: Conceptualization, S.B.; L.B. and J.A.C.; methodology, S.B.; L.B. and J.A.C.; software, S.B., J.A.C. and A.M.; validation, S.B., A.B. and M.A.; formal analysis, S.B.; A.B. and M.A.; investigation, S.B.; L.B., J.A.C. and A.M.; resources, J.A.C., A.M., A.B. and M.A.; writing—original draft preparation, S.B.; writing—review and editing, L.B., J.A.C., A.M. and B.D.; visualization, L.B.; and J.A.C.; A.M. and B.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Science and Innovation Ministry of Spain, grant number PID2019-106148RRC42.

Data Availability Statement: Not applicable.

Acknowledgments: S. Bennaceur would like to thank the Algerian research direction DGRSDT for supporting this research.

Conflicts of Interest: The authors declare no conflict of interest.
Abbreviations

\[ \text{D}_0 \] Pre-exponential factor of the Arrhenius equation \([\text{m}^2/\text{s}]\)

\[ \text{D}_{\text{eff}} \] Effective diffusivity \([\text{m}^2/\text{s}]\)

\[ \text{E}_a \] Activation energy \([\text{kJ/mol}]\)

\( L \) Half-thickness of el Henna’s leaves \([\text{m}]\)

\( M \) Mass of the dry sample \([\text{g}]\)

\( \text{MR} \) Dimensionless moisture content \([-\text{]}\)

\( M_L \) Lawsone mass \([\text{g}]\)

\( \text{Re} \) Yields of lawsone \([-\text{]}\)

\( r \) Correlation coefficient \([-\text{]}\)

\( t \) Time

\( T \) Temperature \([\degree\text{C or K}]\)

\( x \) Mass transport direction \([\text{m}]\)

\( X \) Moisture content

\( X_{\text{eq}} \) Equilibrium moisture content \([\text{kg/kg % d.b}]\)

References

1. Cheriti, A.; Rouissat, A.; Sekkoum, K.; Balansard, G. Plantes de la pharmacopée traditionnelle dans la région d’El-Bayadh (Algérie). *Fytoter* 1995, 66, 525–538.

2. Saad, A.; Touati, B.; Draoui, B.; Tabti, B.; Abdenebi, A.; Benaceur, S. Mathematical Modeling of moisture sorption isotherms and determination of isosteric heats of sorption of *Ziziphus* Leaves. *Model. Simul. Eng.* 2014, 16. [CrossRef]

3. Fortin, D.; Lô, M.; Maynart, G.; Arseneault, C. *Plantes Médicinales du Sahel*; Occasional paper: Dakar, Senegal, 1990.

4. Chetty, K.M. *Flowering Plants of Chitterling*. 1st ed.; Students Offset Printers: Andhra Pradesh, India, 2008; p. 132.

5. Rahmouni, N.M.; Boucherit-Atmani, Z.; Benabdallah, M.; Boucherit, K.; Villemin, D.; Choukchou-Braham, N. Antimicrobial activities of the henna extract and some synthetic naphthoquinones derivatives. *Am. J. Med. Biol. Res.* 2013, 1, 16–22. [CrossRef]

6. Kamal, M.; Jawaid, T. *Pharmaceutical Activities of Lawsonia inermis* Linn.: A Review. *Int. J. Biomed. Res.* 2010, 1, 37–43. [CrossRef]

7. Jan, H.U.; Shinwari, Z.K.; Khan, A.A. Staining effect of dye extracted from dry leaves of *Opuntia ficus indica*. *L. (Prickly pear peel)*. *LWT-Food Sci. Technol.* 2014, 47, 789–795. [CrossRef]

8. Bennaceur, S.; Draoui, B.; Bennamoun, L.; Touati, B. Experimental study and modeling of moisture sorption isotherms of Leaves (Waronia saharae). *Phys. Energy*. 2017, 37. Available online: https://www.semanticscholar.org/paper/Experimental-study-and-modeling-of-moisture-of-Ziziphus-Draoui/d931cc1044d5662041037798df280a137480a16e (accessed on 28 February 2021).

9. Cárcel, J.A.; Castillo, D.; Simal, S.; Mulet, A. Influence of temperature and ultrasound on drying kinetics and antioxidant properties of red pepper. *Dry. Technol.* 2019, 37, 486–493. [CrossRef]

10. Di Scala, K.; Crapiste, G. Drying kinetics and quality changes during drying of red pepper. *LWT-Food Sci. Technol.* 2008, 41, 789–795. [CrossRef]

11. Zhou, L.; Cao, Z.; Bi, J.; Yi, J.; Chen, Q.; Wu, X.; Zhou, M. Degradation kinetics of total phenolic Compounds, capsaicinoids and energy considerations. *Trends Food Sci. Technol.* 2016, 51, 842–853. [CrossRef]

12. Lechtańska, J.M.; Szadzińska, J.; Kowalski, S.J. Microwave-assisted convective drying of green pepper: Quality and energy considerations. *Chem. Eng. Process.* 2016, 98, 155–164. [CrossRef]

13. Cárcel, J.A.; Garcia-Perez, J.V.; Riera, E.; Rossello, C.; Mulet, A. Ultrasonically assisted drying. In *Ultrason in Food Processing*; Villamiel, M., Garcia-Perez, J.V., Montilla, A., Carcel, J.A., Benedito, J., Eds.; John Wiley & Sons Ltd.: Hoboken, NJ, USA, 2017; pp. 371–391.

14. Musielak, G.; Mierzwa, D.; Kroehnke, J. Food Drying Enhancement by Ultrasound—A Review. *Trends Food Sci. Technol.* 2016, 56, 126–141. [CrossRef]

15. De la Fuente-Blanco, S.; De Sarabia, E.R.-F.; Acosta-Aparicio, V.M.; Blanco-Blanco, A.; Gallego-Juárez, J.A. Food drying process by power ultrasound. *Ultrasonomics*. 2006, 44, e525–e527. [CrossRef] [PubMed]

16. Do Nascimento, E.M.G.C.; Mulet, A.; Ascheri, J.L.R.; de Carvalho, C.W.P.; Cárcel, J.A. Effects of high-intensity ultrasound on drying kinetics and antioxidant properties of passion fruit peel. *J. Food Eng.* 2016, 170, 108–118. [CrossRef]

17. Fan, K.; Zhang, M.; Mujumdar, A.S. Application of airborne ultrasound in the convective drying of fruits and vegetables: A Review. *Ultrason. Sonochem.* 2017, 39, 47–57. [CrossRef]

18. Villamiel, M.; Garcia-Perez, J.V.; Montilla, A.; Carcel, J.A.; Benedito, J. *Ultrasonic in Food Processing: Recent Advances*; John Wiley & Sons: Hoboken, NJ, USA, 2017.

19. Gamboa-Santos, J.; Montilla, A.; Cárcel, J.A.; Villamiel, M.; Garcia-Perez, J.V. Air-borne ultrasound application in the convective drying of strawberry. *J. Food Eng.* 2014, 128, 132–139. [CrossRef]

20. Lahsasni, S.; Khouila, M.; Mahrouz, M.; Idrimam, A.; Jamal, A. Thin layer convective solar drying and mathematical modeling of prickly pear peel (*Opuntia ficus indica*). *Energy* 2004, 29, 211–224. [CrossRef]

21. Celma, A.R.; López-Rodriguez, F.; Blázquez, F.C. Experimental modelling of infrared solar drying of industrial grape by-products. *Food Bioprod. Process.* 2009, 87, 247–253. [CrossRef]
22. Ashnagar, A.; Shiri, A. isolation and characterization of 2-Hydroxy-1, 4-Naphthoquinone (Lawson) from the powdered leaves of henna plant marketed in ahwaz city of Iran. If Chemtech. Res. 2011, 3, 1941–1944.
23. Srikiatden, J.; Roberts, J.S. Measuring moisture diffusivity of potato and carrot (core and cortex) during convective hot air and isothermal drying. J. Food Eng. 2006, 74, 143–152. [CrossRef]
24. Crank, J. The Mathematics of Diffusion, 2nd ed.; Oxford Science Publication: Oxford, UK, 1975; p. 32.
25. Nourhène, B.; Mohammed, K.; Nabil, K. Experimental and mathematical investigations of convective solar drying of four varieties of olive Leaves. Food Bioprod. Process. 2008, 86, 176–184. [CrossRef]
26. Kane, C.S.E.; Jamali, A.; Kouhila, M.; Mimet, A.; Ahachad, M. Single-layer drying behavior of mexican tea leaves (Chenopodium ambrosioides) in a convective solar dryer and mathematical modeling. Chem. Eng. Commun. 2008, 195, 787–802. [CrossRef]
27. Lamharrar, A.; Idlimam, A.; Alouani, A.; Kouhila, M. Modelling of thin layer solar drying kinetics and effective diffusivity of Urtica doica leaves. J. Eng. Sci. Technol. 2017, 12, 2141–2153.
28. Dhiman, A.; Sharma, K.; Goyal, J.; Garg, M.; Sharma, A. Determination of lawson content in fresh and dried leaves of Lawsonia inermis Linn. And its quantitative analysis by HPTLC. J. Pharm. Sci. Innov. 2012, 1, 17–20.