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# Thin layer forced convective solar drying characteristics of *artemisia herba-alba*

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## Abstract
*Artemisia herba-alba* is a characteristic plant of the steppes of the Middle East North Africa and Spain and *has* been used as a medicinal plant since ancient time. In Morocco this plant is used in diabetes treatment. The solar drying is essential for preserving the agricultural products, so that it is necessary to know the process of drying and storage for *Artemisia herba-alba.* The drying behaviour of *Artemisia herba-alba* was investigated in the ranges of 28 to 39°C of ambient air temperature, 50 to 80°C of drying air temperature, 30 to 33.5%, of relative humidity and 0.056 $m^3$ $s^{-1}$ of drying air flow rate. Ten statistical models were tested for fitting the experimental drying curves. The Midilli-Kuck model was found to be the most suitable for describing the drying curves of *Artemisia herba-alba*. The drying parameters in this model were quantified as a function of the drying air temperature.The range of variation of the effective moisture diffusivity is between 9.75 $10^{-12}$ and 6.27 $10^{-11}$ $m^2$ $s^{-1}$. The activation energy was found to be 60.59 kJ $mol^{-1}$.

*Keywords*: Activation Energy, *Artemisia herba alba*, Convective solar drying, Effective diffusivity.

**Nomenclature**

| | |
|---|---|
| $a, b, c, g, k, k_0, k_1, n$ | Model coefficients |
| CDC | Characteristic drying curve |
| d.b | Dry basis |
| $D_{eff}$ | Effective diffusivity ( $m^2.s^{-1}$ ) |
| $D_v$ | Drying air flow rate ( $m^3.s^{-1}$ ) |
| $E_a$ | Activation energy ( $kJ.mol^{-1}$ ) |
| exp | Experimental |
| f | Dimenssionless drying rate (-) |
| H | Half thickness (m) |
| M | Moisture content (% d.b) |
| $M_0$ | Initial moisture content (% d.b) |
| MBE | mean bias error |
| $M_e$ | Equilibrium moisture content (% d.b) |
| $M_f$ | final moisture content (% d.b) |
| MR | Moisture ratio (-) |
| N | Number of observations |
| pre | predicted |
| r | Correlation coefficient |
| R | Universal gas constant (8.3145 $J.mol^{-1}.K^{-1}$ ) |
| Rh | Relative humidity (%) |
| SE | Square error |
| t | Drying time (min) |
| T | Absolute temperature (K) |
| $\chi^2$ | reduced chi-square |
| $\theta$ | Temperature (°C) |

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## 1. Introduction

*Artemisia herba-alba* is known for its therapeutic and medicinal properties. It is used in both traditional and modern medicine. *Artemisia herba-alba* is a characteristic plant of the steppes of the Middle East, North Africa and Spain. In Morocco it is widespread in the South Desert and the Atlas Mountains. *Artemisia herba-alba* («shih») has a wide use in traditional medicine, for treatment of gastric disturbances, such as diarrhea and abdominal cramps. In Morocco, this plant is used in diabetes treatment. Its pharmacology and toxicity has not received as much attention as the related species of *Artemisia herba-alba* [1].

The solar drying is essential for preserving the agricultural products, so it can be concluded that is necessary to know the process of drying and storage for *Artemisia herba-alba*. Using solar dryer, the drying time can be shortened by 65% as compared to sun drying because inside the dryer it is warmer than outside, the quality of the dried products can be improved in terms of hygiene, cleanliness, safe moisture content, colour and taste, the product is also completely protected from rain, dust, insects and its payback period ranges from 2-4 years depending on the rate of utilization. The most important feature of solar dryers is that the product does not include any kind of conservators or other added chemical stuffs, which allows using it for people suffering from various allergic reactions from chemical conservators and other added stuffs. Further more products are not exposed to any kind of harmful electromagnetic radiation or electromagnetic poles [2].

Many papers on the mathematical modelling and experimental drying kinetics have of various vegetables and fruits such as apricots [3], green pepper [4], Eucalyptus Globulus [5], pistachio [2] and prickly pear fruit [6]. There is no literature on drying process of *Artemisia herba-alba.*

This study was mainly concerned with the:

- determination of the effect of drying air temperature and air flow rate on the drying kinetics of *Artemisia herba-alba*;
- fitting of the drying curves with thirteen mathematical models and determination of the characteristic drying curve (CDC);
- calculation of effective diffusivity and the activation energy of *Artemisia herba-alba.*

## 2. Material and methods

### *2.1. Drying experiments*

The experimental set up, shown in figure 1, mainly consists of an indirect forced convection solar dryer with a solar air collector, an auxiliary heater, a circulation fan and a drying cabinet. It was described in detail in references [5-7].

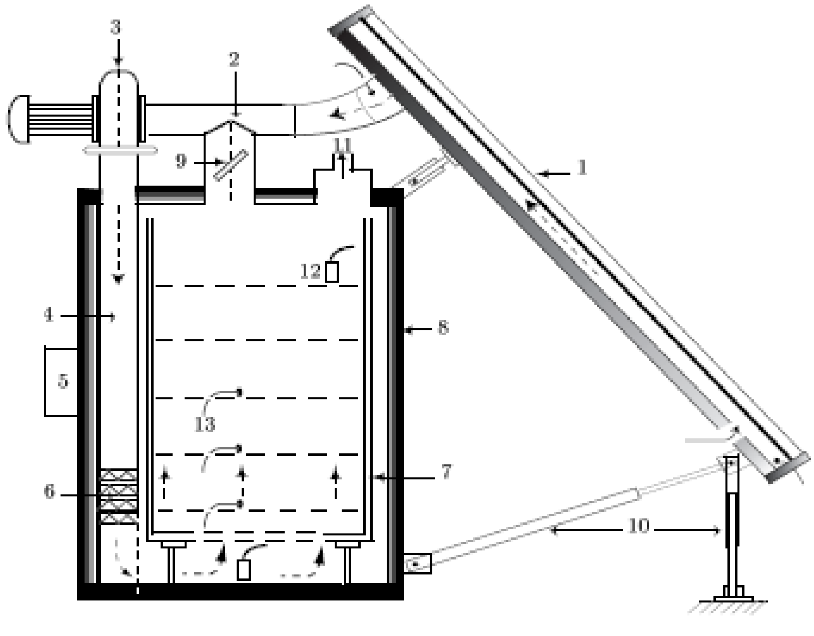


**Figure 1:** Schematic representation of the convective solar dryer.

(1) solar collector; (2) circulation fan;(3) fan; (4) air flow direction; (5) control box;
(6) auxiliary heating system; (7) shelves; (8) drying cabinet; (9) recycling air; (10) control foot; (11) exit of air; (12) humidity probes; (13) thermocouples

Experiments were performed to determine the effect of different drying air conditions on the drying kinetics. Four drying air temperatures (50, 60, 70 and 80°C) at constant drying air flow rate ($0.056\,m^3.s^{-1}$), were selected to examine the influence of temperature on the drying kinetics. The mass of the product used in drying experiments was ($20.0 \pm 0.001$) g per tray. During all drying experiments, only the first shelve of the dryer was selected.
However, the samples were uniformly spread evenly on a drying tray that was then placed on the first shelf of the drying cabinet. The heated air enters the drying cabinet below the trays and flows upwards through the samples. In order to dry the product sufficiently, it was important to keep the drying air temperature constant. In solar drying processes, the drying air temperature can vary based on the magnitude of the solar radiation. However, the auxiliary heater was used for controlling the drying air temperature. Temperature measurements and recordings at different points in the solar dryer were made by Cr-Alumel thermocouples (0.2 mm diameter) connected to a data logger enabling ±0.1°C accuracy, and the outlet temperatures were measured with thermometers. A digital weighing balance (±0.001 g) measures the mass loss of the product during the drying process. During each drying experiment, the weight of the product on the tray was measured by removing it from the drying cabinet for approximately 15–20s. These measurements were undertaken each 10 min at the beginning of the experiment and at 60 min intervals at the end. The initial and final moisture contents of each sample were determined by a drying oven whose temperature was fixed at 105°C for 24h.

### *2.2. Mathematical modelling of drying curves*

Several authors [5, 8, 9], based on the Van Meel transformation [10], have used simply the initial moisture content ($M_0$) and the equilibrium moisture content ($M_e$) to obtain moisture ratio (MR) and initial drying rate $\left(\frac{-dM}{dt}\right)_0$ to normalize the drying rate as follows:

$$MR = \frac{M-M_e}{M_0-M_e} \tag{1}$$

The equilibrium moisture content $M_e$ is determined from the desorption isotherm.

$$f=\frac{\left(-\frac{dM}{dt}\right)_t}{\left(-\frac{dM}{dt}\right)_0} \tag{2}$$

Where f is the dimensionless drying rate.

The obtained solar drying curves were fitted with 10 different thin-layer drying models (Table 1). The correlation coefficient (r), the reduced chi-square ($\chi^2$) and the mean bias error (MBE) were the statistical parameters used for selecting the best equation to describe the thin-layer drying curves of *Artemisia herba-alba*.

**Table 1**: Selected mathematical models applied to the drying curves

| Model name | Model expression | Reference |
|---|---|---|
| Lewis | $MR = \exp(-kt)$ | [11] |
| Page | $MR = \exp(-kt^n)$ | [12] |
| Henderson and Pabis | $MR = a\exp(-kt)$ | [13] |
| Logarithmic | $MR = a\exp(-kt) + c$ | [3] |
| Two term | $MR = a\exp(-k_0 t) + b\exp(-k_1 t)$ | [13] |
| Two term exponential | $MR = a\exp(-kt) + (1-a)\exp(-kat)$ | [14] |
| Midilli-Kucuk | $MR = a\exp(-kt^n) + bt$ | [2] |
| Wang and Singh | $MR = 1 + at + bt^2$ | [15] |
| Approximation of diffusion | $MR = a\exp(-kt) + (1-a)\exp(-kbt)$ | [4] |
| Verma et al. | $MR = a\exp(-kt) + (1-a)\exp(-gt)$ | [16] |

These parameters can be calculated as follows:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N-n} \tag{3}$$

$$MBE = \frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right) \tag{4}$$

Where $MR_{exp,i}$ is the ith experimental moisture ratio, $MR_{pre,i}$ the i$^{th}$ predicted moisture ratio, N the number of observations, and n the number of constants in models.

## 3. Results and discussion

### *3.1. Drying experiments*

The solar collector provided energy at the rate of 15.50 $kWh.m^{-2}/year$ [5]. During the experiments, the daily solar radiation varied between 250 and 980 $W.m^{-2}$ ; the ambient air temperature ranged from 28 to 39°C; the ambient air relative humidity ( $Rh$ ) ranged from 30 to 35% ; the drying air temperature ranged from 50 to 80°C; at the drying air flow rate (0.056 $m^3.s^{-1}$);. The initial moisture content of the *Artemisia herba-alba* ranged from 1.08 to 1.29% dry basis and was reduced to the final moisture content which varies from 0.13 to 0.22 % dry basis (Table 2).The fresh and dried at 60 °C is shown in Figure 2.

*A.Herba Alba* fresh | *A.Herba Alba* dried

**Figure 2:** *A.Herba Alba* fresh and dried

**Table 2:** Drying conditions during experiments in the solar dryer of *Artemisia herba-alba*

| Experiment number | Dv $(m^3.s^{-1})$ | θ± 0.1 (°C) | Rh± 2 (%) | $M_0$ (%d.b) | $M_e$ (%d.b) | $M_f$ (%d.b) | t (min) |
|---|---|---|---|---|---|---|---|
| 1 | 0.056 | 50 | 30.5 | 1.08 | 0.15 | 0.18 | 300 |
| 2 | 0.056 | 60 | 30 | 1.27 | 0.15 | 0.22 | 140 |
| 3 | 0.056 | 70 | 35 | 1.29 | 0.16 | 0.2 | 70 |
| 4 | 0.056 | 80 | 30.5 | 1.27 | 0.15 | 0.13 | 60 |

Figures 3 and 4 represent the moisture content versus drying time and the drying rate versus moisture content, respectively. These figures show that there is an absence of phase 0, the increasing drying rate period, where the temperature of the product is increased without any substantial loss of water, and phase 1, the constant drying rate period. There is only the presence of the falling drying rate period (phase 2). These results are in agreement with the literature [4, 6, 8].

The drying air conditions have an important influence on the rates of these curves. At constant drying air flow rate ( $0.056\ m^3.s^{-1}$ ), the changes in the drying rate versus moisture content are shown in figure 4. It is apparent that the drying rate decreases continuously with decreasing moisture content. The drying rate increases with the increase of the drying air temperature and the highest values of drying rate were obtained in experiment for $\theta = 80\ °C$.

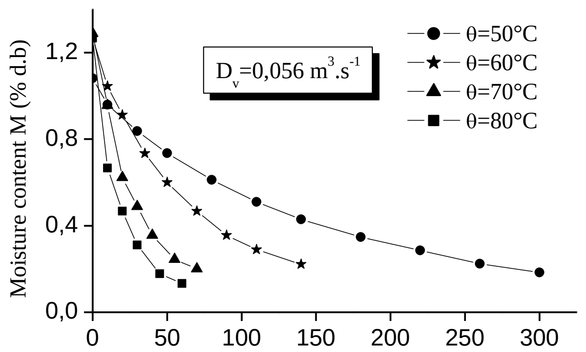


**Figure 3**: Variation of moisture content as a function of time for different drying air conditions of *Artemisia herba-alba*.

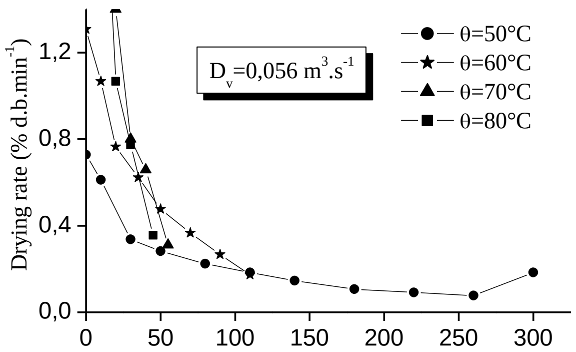


**Figure 4**: Influence of drying air temperature on drying rate during drying of *Artemisia herba-alba*.

### *3.2. Characteristic drying curve*

The Van Meel (1958) transformation is applied for determining the characteristic drying curve of *Artemisia herba-alba*. Experimental drying data are plotted in Figure 5 to represent $f = f(MR)$. This figure shows that all drying curves obtained with the moisture ratio and dimensionless drying rate, for the different tested conditions, fall into a tight band, indicating that the effect of variation in different conditions is small over the range tested.

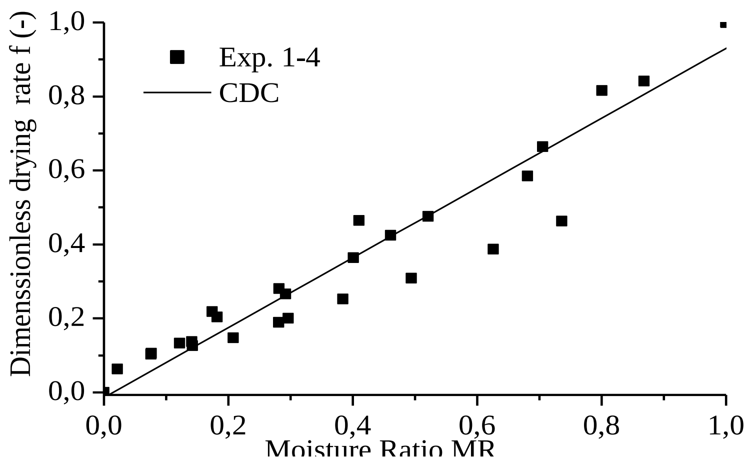


**Figure 5.** Characteristic drying curve of *Artemisia herba-alba*.

From the four drying tests, the correlation expressing the normalized drying rate of Artemisia herba-alba as a polynomial function of degree 1 (Figure 5) was determined. For this operation, the non-linear optimization method of Levenberg-Marquard has been used via the Origin 6.1 software by treating all experimental points. Then, the best fitting of these results is obtained by choosing high correlation coefficient value ($r=0.97$) and a minimum mean square error ($SE=0.079$) as an evaluation criteria. So,

$$f = 0.94\ MR \qquad (5)$$

*3.3. Fitting of the drying curves*

The drying data as moisture ratio MR versus drying time were fitted to thin layer drying models. The Midilli-Kucuk model was found to be the appropriate model describing the drying curves of *Artemisia herba-alba* with an r of 0.99; $\chi^2$ of $4.28\,10^{-5}$ and MBE of $4.61 10^{-4}$. These results can be proved consequently from figure 6 which plotted Midilli-Kucuk predicted moisture ratios versus drying time at 50, 60, 70 and 80 °C. Also from this figure, it can be concluded that the predicted moisture ratio decreased with the increasing in the drying air temperature and consequently the drying time decreased.

*3.4. Calculation of effective diffusivity*

In this study, the coefficients of each model, the most suitable model for drying of *Artemisia herba-alba*, the relationship between the drying air temperature and the coefficients of the best suitable model were also determined.

The experimental results obtained have shown that internal mass transfer resistance due to the presence of falling rate drying period controls drying time. The drying data in the falling rate period are usually analysed by Fick's diffusion equation. The solution of this equation and the form of Eq. (9) can be applicable for slab geometry by assuming uniform initial moisture distribution, constant diffusivity and negligible shrinkage:

$$MR=\frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)^2\pi^2 D_{eff}\,t}{4H^2}\right) \tag{6}$$

Where $D_{eff}$ is the effective diffusivity; $H$ is the half thickness of the slab in samples; and n is a positive integer constant. In practice, only the first term of Eq. (9) is used yielding:

$$MR=\frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}\,t}{4H^2}\right) \tag{7}$$

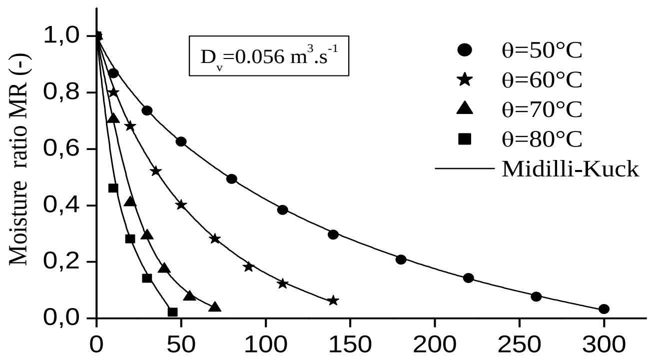


**Figure 6.** Experimental and predicted moisture ratio obtained using the Midilli-Kuck model.

The effective diffusivity is also typically obtained by plotting $\ln(MR)$ vs t : as seen from Eq. (7), a linear dependence is expected, with the slope :

$$Slope=\frac{\pi^2 D_{eff}}{4H^2} \tag{8}$$

The slope of Eq. (8) is the measure of the diffusivity, Figure 7 shows the plot of experimental results of ln(MR) versus drying time for the studied range of temperatures. It is apparent at constant drying air flow rate, that $D_{eff}$ increases with the increase of drying air temperature. The diffusivity values for the runs are found to be $9.75\ 10^{-12}$, $2.12\ 10^{-11}$, $4.62\ 10^{-11}$ and $6.27\ 10^{-11}$ $m^2.s^{-1}$ at 50, 60, 70 and 80 °C, respectively. These values are almost equal to the energy of activation of different products [17-18-19].

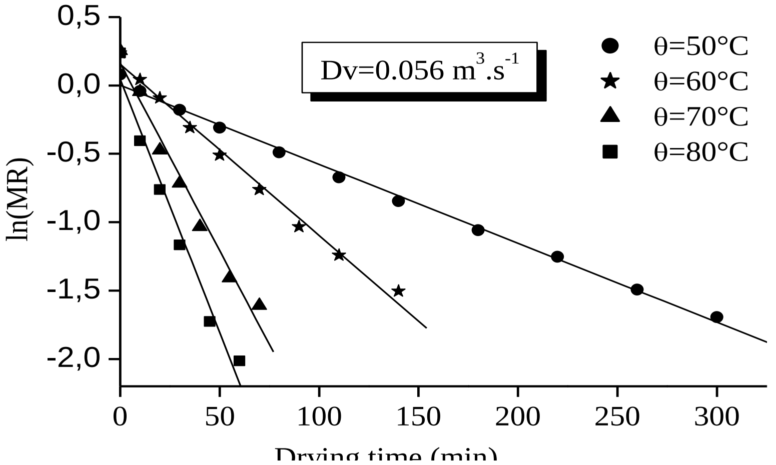


**Figure 7.** Plot of ln(MR) vs drying time for different drying air conditions

*3.5. Activation energy*

The correlation between the drying conditions and the determined values of the effective diffusivity can be expressed by using an Arrhenius type equation [8-19-20] such as:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \tag{9}$$

Where $D_0$ is the pre-exponential factor of the Arrhenius equation ($m^2.s^{-1}$), $E_a$ is the activation energy of the moisture diffusion ($kJ.mol^{-1}$), $T$ is the air temperature absolute and R is the universal gas constant ($J.mol^{-1}.K^{-1}$).

The activation energy ($E_a$) was calculated from the slope of the plot on $\ln(D_{eff})$ versus reciprocal of the absolute temperature as presented in Figure 8. The activation energy of *Artemisia herba-alba* was found to be $60.59$ $kJ.mol^{-1}$.

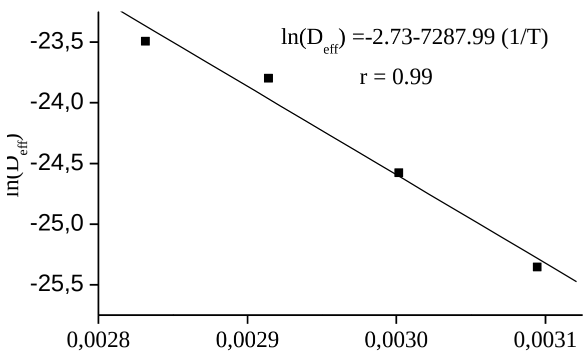


**Figure 8.** Influence of drying air temperature on the effective diffusivity

## 4. Conclusion

In this study, thin-layer convective drying experiments were conducted for *Artemisia herba-alba* in the temperature range of 50-80°C at constant drying air flow rate. Also, the drying air temperature was found to be the main factor influencing the drying kinetics.

From the results obtained, it was observed that only the falling drying rate period exists. The characteristic drying curve was obtained and the drying rate equation was calculated. The goodness of fit of the observed values with 10 thin layer drying equations was evaluated. The Midilli-Kuck model was the best model to fit the experimental data and was recommended as the thin layer model for *Artemisia herba-alba*. The drying parameters in this model were quantified as a function of the drying air temperature.

The effective diffusivity values changed from $9.75\ 10^{-12}$ to $62.68\ 10^{-12}\ m^2.s^{-1}$ within the given temperature range and increased as temperature increases. An Arrhenius relation with an activation energy value of $60.59\ kJ.mol^{-1}$ expressed the effect of temperature on the effective diffusivity.

## References

1. Marrif, H.I., Ali. B.H., Hassan, K.M. *J. Ethnopharmacology*. 49 (1995) 51-55.
2. Midilli, A., Kucuk, H. *Energy Conversion and Management*. 44(7) (2003) 1111-1122.
3. Togrul, T. I., Pehlivan, D. *J. Food Engineering*. 58 (2003) 23-32.
4. Kaya, A., Aydın, O. *Energy Conversion and Management*. 50 (2009) 118–124.
5. Kouhila M., Kechaou N., Otmani M., Fliyou M., Lahsasni S. *Drying Technology*. 20(10) (2002) 2027-2039.
6. Roberts J., Kidd D., Padilla-Zakour O. *J. Food Engineering*. 89 (2008) 460–465.
7. Hawlader M.N A., Khin M. M. *Stewart Postharvest Review*. 1(3) (2008) 1- 8
8. Lamharrar A., Idlimam A., Kane C. S. Ethmane, Jamali A., Abdenouri N., Kouhila M. *J. Agronomy*. 6(4) (2007) 488-498.
9. Lahsasni, S., Kouhila, M., Mahrouz, M., Idlimam, A., Jamali, A. *Energy*. 29 (2004) 211-224.
10. Van Meel D.A. *Chemical Engineering Science*. 9 (1958) 36-44.
11. Bruce, D. M. *J. Agricultural Engineering Research*. 32 (1985) 337–347.
12. Ghaly A.E., MacDonald K.N. *Am. J. Eng. Applied Sci*. 5 (2012) 136-150.
13. Henderson, S. M. *Transactions of the ASAE*. 17 (1974) 1167-1168.
14. Zlatanovi I., Komatina M., Antonijevi D. *Applied Thermal Eng*. 53 . (2013) 114-123.
15. Wang, C. Y., Singh, R. P. *Transactions of the ASAE*, 11 (1978) 668-672.
16. Verma, L. R., Bucklin, R. A., Endan, J. B., Wratten, F. T. *Transactions of the ASAE*, 85 (1985) 296-301.
17. Shackelford C.D., Moore S.M. *Eng. Geol*. 152 (2013). 133-147.
18. Madamba, P. S., Driscoll, R. H., Buckle, K. A. *J. Food Engineering*. 29 (1996) 75-97.
19. Doymaz, I. *J. Food Processing and Preservation*, 36(4) (2012) 310-319.
20. Idlimam A., Kane C.S.E., Kouhila M. *Revue des Energies Renouvelables*, 10(2) (2007) 191-203.

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