Kinetics modeling of the drying of sunflower stem (Helianthus annuus L.) in a forced convection tunnel

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Abstract. The sunflower is an annual plant native to the Americas. It possesses a large inflorescence (flowering head), and its name is derived from the flower's shape and image, which is often used to capture the sun. The plant has a rough, broad, hairy stem, coarsely toothed, with rough leaves, and circular flower heads. The sunflower seeds are appreciated for their oil, which has become a widespread cooking ingredient. Leaves of the sunflower can be used as cattle feed, while the stems contain a fiber that may be used in paper production. Recently this flower has been used in phytoremediation of soils, contaminated with heavy metals. Sunflower has been probed as an efficient phytoextractor of chromium, lead, aluminum, zinc, cadmium from soil.

In this work we present the experimental results of the drying of the sunflower stem, cut in 100 mm longitudinal sections, with diameters in the range of 11-18 mm. The aim was to obtain a dry and easy-to-handle final product, since these plants were originally cultivated in order to extract heavy metals from a polluted soil. The dried stems could then be easily confined or sent to recycle premises to concentrate the metals.

The drying process was done in forced convection within a hot air tunnel. The used temperature was 60 °C, the velocity of air was 3 m/s and the required times were 8 hours. The initial average wet mass was 28 g and the final value was 5 g, resulting in the aimed product.

1. Introduction
Traditionally, the oilseed sunflower plant is used to extract from its seeds oil and flour, the rest of the plant is used as fodder, namely animal feed. The kinetics of the flower drying has been studied. Syaref et al. [1], used hot air at 75 °C and 0.3 m/s to dry 200 g of sunflower seeds with initial humidity contents of 57%, to 12% on dry basis in 40 min. The structure, the morphology and the chemical composition are factors that influence the drying kinetics due to changes caused by the different moisture levels during this process [2]. According to Rovedo et al. [3], the complete sunflower seed is viewed as a spherical core, and the kernel is surrounded by a single hull. The solution of the Fick's second law for moisture diffusion from a sphere in terms of the average moisture contents was used to adjust the drying curves and to evaluate the diffusion coefficient at the same temperature of 75 °C. Gely and Santalla [4], found that the equation of Page was the one that better described the kinetics of drying, when they obtained a value of $r^2 = 0.99$ and a diffusion coefficient of $7.14 \times 10^{-8}$ cm$^2$/s. Kundu et al. [5], used a fluid bed dryer to dry sunflower seeds with air at 70 °C and 1.36 m/s velocity in 20 min, with initial and final moisture contents of 22% and 8%, respectively. The sorption characteristics of sunflower seeds were measured and analyzed to provide a means for evaluating stability conditions preventing microbial spoilage and oil acidification. Water activities $a_w$ were measured at three temperatures in a wide moisture content range and the data were interpreted with isotherm models [6]. Shanmugam et al. [7] used an oscillating-bed solar dryer with sunflower seeds to obtain in just 8 h an average moisture level of 7.9% which is in the...
acceptable level of moisture contents of less than 10%. The initial moisture contents were of 18%, the average thermal efficiency of the solar dryer was 30.1%. The possibility of using sunflower to produce biofuel has also been analyzed [8-11] and finally, some research has been done to use the plant in phytoremediation of soils contaminated with heavy metals [9, 12-17]. In this work we present the experimental results of the drying of the sunflower stem in a forced convection tunnel. The aim was to obtain a dry and easy-to-handle final product, since these plants were originally cultivated in order to extract heavy metals from a polluted soil. The dried stems could then be easily confined or sent to recycle premises to concentrate the metals.

2. Mathematical modeling
The moisture ratio was calculated using the equation:

\[ \frac{M_t - M_e}{M_0 - M_e} \]

which has been simplified to \( \frac{M_t}{M_0} \) by some researchers, including Kaymak-Ertekin [18], and Akpinar et al. [19], because of the continuous fluctuation of the relative humidity of the drying air during the process. Where \( M_t \) is the mass at time t, \( M_e \) is the mass at equilibrium and \( M_0 \) is the initial mass. For mathematical modeling, there are several thin-ayer drying equations; we tested them and select the best model to describe the drying curve equation for the sunflower stem using hot air.

The correlation coefficient \( R^2 \), the reduced chi-square \( \chi^2 \), and the root mean square error \( \text{RMSE} \) were used as criteria for adequacy of the fit. The lower the values of the reduced \( \chi^2 \), the better is the goodness of the fit. The \( \text{RMSE} \) gives the deviation between the predicted and experimental values, and it is required to approach zero. These statistical analysis values can be calculated as follow,

\[
R^2 = \frac{\sum_{i=1}^{N}(MR_{\text{exp},i} - \bar{MR}_{\text{exp}})^2}{\sum_{i=1}^{N}(MR_{\text{exp},i} - \bar{MR}_{\text{exp}})^2} \sum_{i=1}^{N}(MR_{\text{exp},i} - \bar{MR}_{\text{exp}})^2
\]

\[
\chi^2 = \frac{\sum_{i=1}^{N}(MR_{\text{exp},i} - MR_{\text{pre},i})^2}{N - n}
\]

\[
\text{RMSE} = \frac{\sum_{i=1}^{N}(MR_{\text{exp},i} - MR_{\text{pre},i})^2}{N}
\]

where \( MR_{\text{exp},i} \) for the experimental moisture ratio found in any measurement, \( MR_{\text{pre},i} \) is the predicted moisture ratio for this measurement and n are the number of observations and the number of constants, respectively [20].

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 an EA25-model EXTECH digital hygro-thermometer, with 0.1 % resolution. A 451112-model EXTECH anemometer (0.1 m/s resolution) was used to measure the velocity of air. Mass was quantified using a BL1505-model SARTORIUS scale, with a 0.001 g span. Data acquisition was programmed using LABVIEW software.

4. Experimental procedure.
Sunflower seeds were sown on soil contaminated with heavy metals, which was previously characterized [21]. When the plants grew to a height of approximately 1.60 m, they were cut and the stem was divided into pieces of 0.10 m length; diameter was 0.018 m on average, with an approximate weight of 0.028 kg, initial moisture content was of 65%. The temperature of air was 60 °C at a velocity of 3.0 m/s. Tests were done in a continuous drying process, to guarantee that no perturbation could hinder the course of the experiment [22]. The electrical resistances were operated to raise the surface temperature of the probes up to 60 °C. Mass, air temperature, probe-surface temperature and relative humidity were automatically monitored and registered in a computer. The measurements were done every 10 minutes.
5. Experimental apparatus
   The scheme of the drying tunnel used in this study is presented in figure 1. Air is conducted by means of a radial-flow fan, controlled by a variable-velocity motor (a). The velocity of air can be varied between 1.0 and 10.0 m/s; in this study the velocity applied was 3.0 m/s. There is a panel of electrical resistances (b); it is formed by two resistances of 2 kW each, two resistances of 1 kW and two more of 500 W, which together provide a maximum power of 7.0 kW. All of them are managed independently, which allows the selection of the energy to be provided. This section is covered with mineral wool as insulator (c); the length of the test chamber is 30 cm, the width, 30 cm, and the height, 40 cm (d); electronic scale (e); the computer for registration all the values (f), and finally the control system (h).

Figure 1. Vertical drying tunnel.

6. Results
   The initial average mass of the sunflower stem pieces was 28 g and the final value was 5 g, resulting in the aimed product. The temperature of the air at the entrance of the drying chamber was about 62 °C, and the temperature measured on the surface of the sample was 60 °C. At the beginning of the experiment the sample presented a moisture content of 4.82 kg water/kg dm and after 8 hours it was 0.1 kg water/kg dm. This was the minimum value that could be obtained, since the experiment continued for 30 minutes more but humidity remained unchanged. The variation of moisture against time is shown in figure 2. This experiment was carried out on a continuous basis and was repeated five times, the results were consistent.

Figure 2. Moisture contents vs time for sunflower stem, the air temperature was of 60 °C on its surface, and the velocity of air was 3.0 m/s.

Modeling the drying behavior of different agricultural products often requires statistical methods of regression and correlation analysis. Linear and non-linear regression models are important tools to find the relationship between different variables, especially, for those for
which no established empirical relationships exist. In this study, we determined relationships for constants of the best suitable model for the drying air temperature by multiple regression techniques, using Arrhenius, exponential and power regression models [19]. Regression analysis was performed using the Origin computer program. The mathematical model that best described the drying process under study was the logarithmic one, with \( R^2 \) close to one, \( \chi^2 \) close to zero and RMSE close to zero too (figure 3). For the sunflower stem the equation is:

\[
\text{MR} = 0.118 + 0.5071 \exp(-0.00016 \ t)
\]

\( R^2 = 0.996 \)

\( \chi^2 = 0.000012 \)

RMSE = 0.00053

![Figure 3. Logarithmic model of sunflower stem.](image)

A fast variation in the velocity of drying of the specimens at the beginning of the process was observed, reaching values of 0.348 kg water/kg dm min on average during the first 40 minutes. Afterwards it remained practically constant at a value of 0.13 kg water/kg dm min, until the last 20 minutes, in which it increased slightly. These results are summarized in figure 4.

![Figure 4. Drying rate of sunflower stem.](image)

The equation of the drying of the sunflower stem was obtained by the dimensionless plot of the data in figure 5, through the Marquardt-Levenberg’s non-linear optimization, and it is as follows:

\[
Y = 0.0211 + 1.3088 \times X - 1.7594 \times X^2 + 1.3243 \times X^3
\]

with \( R^2 = 0.979 \) and \( \text{SD} = 0.0127 \), values that reflect good precision in the modeling of the physical phenomena.

This curve is known as “characteristic curve of drying” of the product [23]. Thus, the characteristic curve of drying of the sunflower stem, according to the last equation, is:

\[
f = 0.0211 + 1.3088 \times \text{MR} - 1.7594 \times \text{MR}^2 + 1.3243 \times \text{MR}^3
\]

where \( f \) is the dimensionless drying relationship.
Finally, from the environmental point of view, since the stems contained concerning amounts of heavy metals [21], the resulting reduction of 82.12% of the total mass implied that the aimed final product, an easy- to- handle waste which could be economically sent to further treatment, confinement or metals recycling, was obtained.

7. Conclusions
In this investigation the sunflower stem could be dried within 8 hours with air at a temperature of 60 °C and a velocity of 3 m/s. The initial and final moisture contents were 4.82 kg water/kg dm and 0.1 kg water/kg dm, respectively. The numerical model that best represented the kinetics of drying of the product was the exponential one, according to the imposed conditions. The model was $MR = 0.118 + 0.5071 \exp(-0.00016 \ t)$. The characteristic drying curve turned out to be a third degree equation, namely $f = 0.0211 + 1.3088MR - 1.7594MR^2 + 1.3243MR^3$.

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