DYNAMIC DRYING CHARACTERISTICS OF ALFALFA UNDER SOLAR ENERGY-HEAT PUMP COMBINED DRYING CONDITIONS
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太阳能-热泵联合干燥条件下紫花苜蓿动态干燥特性

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ABSTRACT

To promote the application of solar energy-heat pump combined drying technology in forage processing and enhance the drying efficiency of alfalfa, an experimental study was conducted. The research utilized a solar energy-heat pump drying system and a mesh belt dynamic drying device to investigate the drying characteristics of alfalfa. Drying characteristic curves were obtained, and the drying model and parameters were determined through model comparison. The study also analysed the impact of factors such as hot air velocity, temperature, alfalfa stacking thickness, turning angle of the spinner rack, and conveyor belt speed on the drying characteristic curves and parameters of alfalfa. A predictive model for alfalfa moisture content was developed, and the effective moisture diffusivity and activation energy were calculated. The findings revealed that alfalfa does not exhibit a constant speed drying stage, and its drying primarily occurs during the deceleration drying stage. The Logarithmic model was found to accurately describe the moisture change pattern during the dynamic drying process of alfalfa, with a model fitting coefficient R^2 exceeding 0.994, with an effective moisture diffusivity ranging from 2.776×10^{-10} m^2/s to 4.7324×10^{-9} m^2/s, and an activation energy of 37.02 kJ/mol. The study suggests that increasing the hot air velocity and temperature, reducing the conveyor belt speed, and adjusting the alfalfa stacking thickness can further enhance the drying rate and reduce the drying time.

摘要

为推动太阳能-热泵联合干燥技术在饲草加工领域的应用，改善苜蓿干燥效率和效果，借助太阳能-热泵干燥系统及其网带式动态干燥装置对苜蓿进行了干燥特性试验研究，获取了干燥特性曲线，并通过模型对比确定了干燥模型及参数。分析了热风风速、温度、苜蓿堆积厚度、转架偏转角度、输送带移动速度等因素对苜蓿干燥特性曲线与参数的影响，得到了苜蓿水分比预测模型，同时计算得到有效水分扩散率和活化能。结果表明苜蓿无恒速干燥阶段，其干燥主要发生在降速干燥阶段，Logarithmic 模型可以精准描述苜蓿动态干燥过程中的水分变化规律，模型拟合决定系数 R^2 大于 0.994。有效水分扩散率介于 2.776×10^{-10}m^2/s ~4.7324×10^{-9}m^2/s、活化能为 37.02 KJ/mol，可通过增加热风风速、温度、降低输送带移动速度、苜蓿堆积厚度，进一步增大干燥速率，缩短干燥时间。

INTRODUCTION

Alfalfa, a perennial leguminous forage grass, is prized for its adaptability, high nutritional value, and abundant yield. With a protein content surpassing that of corn and rich in essential amino acids and trace elements, it is extensively cultivated in China's Inner Mongolia region, boasting a national planting area of 6.355 million mu and an annual yield of 4.224 million tons in 2021. Due to its substantial yield and harvest timing during the rainy season, rapid moisture reduction after harvest is crucial to prepare alfalfa for feed processing and minimize the impact of weather conditions on the drying process *(Liu Z. H., 2022)*.

Drying is a critical step in preserving and storing alfalfa, directly influencing its quality. High-temperature dehydration can lead to the loss of aromatic amino acids and protein aging, resulting in reduced digestibility and palatability when used as feed. After experimenting with various drying methods, solar energy hot air drying has emerged as a suitable, energy-efficient, and cost-effective approach for alfalfa processing *(Sun Q. Y. et al., 2022)*.

However, the fluctuating temperatures of sunlight exposure, influenced by natural conditions such as day-night alternation and varying weather, pose challenges in meeting the demands for continuous drying of large quantities of alfalfa during the harvesting period. Therefore, a solar energy-heat pump combined drying method is adopted in this study. This method demonstrates high efficiency, low energy consumption, and strong continuity, and has been widely applied in the agricultural material processing field *(Wang Q. et al., 2012; Anfal A.H., 2022)*. Analysing the drying characteristics of alfalfa under these conditions and determining relevant drying processes can offer valuable insights for improving the efficiency of alfalfa drying processing. Singh and his team have designed a dynamic drying device, which can increase the hot air temperature and drying efficiency (*Singh P., 2010*). In a study by Li Y.Y, the moisture changes of alfalfa during the drying process using hot air drying technology were investigated. Experiments were conducted on alfalfa density, the distance between the heating plate and the material, and heating temperature to explore the moisture change patterns under different influencing factors (*Li.Y.Y., 2020*).

This study focuses on fresh alfalfa and conducts dynamic drying experiments under solar energy-heat pump combined drying conditions. It involves plotting drying characteristic curves, establishing drying models, analysing the effects of hot air temperature, air velocity, material pile thickness, turning angle of the spinner rack, and conveyor belt speed on the drying characteristics of alfalfa, and optimizing dynamic drying processes. The results obtained will promote the application of solar energy-heat pump combined drying technology in forage processing, thereby enhancing the drying processing capacity of alfalfa.

MATERIALS AND METHODS

Materials

The experimental materials used in the study were fresh purple alfalfa grown in the grasslands in Horinger County (figure 1), Hohhot City, Inner Mongolia Autonomous Region, with an initial moisture content of approximately 76% ± 2%. The alfalfa had 3 times mowing, and the second batch was used for the experiments, leaving a stubble height of 5~6 cm *(Luo S H et al., 2024)*, and the stubble was neatly cut to facilitate regrowth.

Fig. 1 - Fresh alfalfa

Instruments and equipment

The experimental setup utilized was the TGS-2 solar energy-heat pump combined drying system (figure 2a), comprising solar collectors, a drying chamber, a control system, a dehumidification system, and a dynamic drying device (figure 2b). During operation, air heated by the solar collectors is directed into the drying chamber from the bottom by fans, facilitating the drying of alfalfa on the dynamic mesh belt drying bed. To optimize drying efficiency, adjacent layers of the mesh belt move in opposite directions during drying. This allows the material to transition from one layer to the next, ensuring thorough contact with the hot air and achieving dynamic drying. When sunlight intensity decreases and the temperature inside the drying chamber drops below the set drying temperature, the control system will switch from solar drying to solar energy-heat pump combined drying mode, with the heat pump supplementing the drying heat to maintain a constant drying temperature.

(a) (b)

Fig. 2 - (a) Solar-heat pump combined drying system; (b) Dynamic drying device

1.Solar collector; 2. Dehumidification system; 3. Drying room; 4. Mesh belt drying bed; 5. Control system; 6. Drying frame; 7. Drive chain; 8. Swivel frame; 9. Drying bed; 10. Electric motor

Drying Process

To investigate the impact of temperature, air velocity, material pile thickness, turning angle of the spinner rack, and conveyor belt speed on drying characteristics, and minimize loss of alfalfa leaves and nutrients, specific parameters were selected. Hot air temperatures of 45, 50, 55, 60, and 65°C were chosen, along with hot air velocities of 1.5, 3.0, 4.5, 6.0, and 7.5 m/s. Material pile thicknesses of 4, 7, 10, 13, and 16 cm were considered, as well as turning angles of 0°, 5°, 10°, 15°, and 20°, and conveyor belt speeds of 0.01, 0.02, 0.04, 0.08, and 0.16 m/s. Prior to the experiment, the levels of each experimental factor were adjusted according to the experimental design, and the equipment was preheated for half an hour before commencing the experiment.

Test metrics

The dry-base moisture content

The definition of moisture content on a dry basis is the ratio of the mass of water in a material to the mass of dry matter in the material. The calculation formula is as follows:

$$M_t = \frac{m_t - m_d}{m_d} \tag{1}$$

where: M_t is the dry-base moisture content, (g/g); m_t is the quality of alfalfa at a certain moment (g), m_d is the weight of alfalfa dry matter (g).

Drying rate

The drying rate can reflect the drying characteristics, describing the weight of water removed from the material per unit of time. The formula for calculation is as follows:

$$D_R = \frac{M_{t1} - M_{t2}}{t_1 - t_2} \tag{2}$$

where:

M_{t1} and M_{t2} are the moisture of samples (g/g) at time t_1 and t_2 (minutes), respectively.

Moisture ratio

The moisture ratio represents the proportion of the moisture content at a certain point in the drying process to the initial moisture content. The smaller the ratio of the moisture content, the more water loss, thereby reflecting the speed of drying. The formula for calculating the moisture content is as follows:

$$MR = \frac{M_t}{M_0} \tag{3}$$

where: M_t, M_0 *are moisture content* (g/g) *at any time, initial moisture content (g/g).*

Mathematical modelling and Statistical Analysis

Drying of alfalfa is a complex non-steady-state heat and mass transfer process, thus mathematical models can be used to describe the trend of moisture change in alfalfa during drying *(Simal S, 1997)*. Negligible deformation and shrinkage of alfalfa during drying are ignored, and the proposed mathematical models were employed to analyse the drying process. The details are shown in Table 1.

Table 1

Name	Equation
Page	$MR=exp(kt^n)$
Logarithmic	$MR=aexp(-kt)+c$
Two-term model	$MR=aexp(-k_0t)+bexp(-k_1t)$
Approximation of diffusion	$MR=aexp(-kt)+(1-a)exp(-kat)$

The data obtained from the experiments are subjected to nonlinear regression analysis. The evaluation criteria for the goodness of fit of the models include the coefficient of determination R^2, chi-square χ^2, and root mean square error *RMSE (Chang Jiang D. et al., 2017)*. The model with the highest R^2 value and the lowest χ^2 and RMSE values is considered the best model to describe the drying characteristics. Drying characteristic curves are plotted for mathematical model data analysis. The above indicators are used to evaluate the mathematical models, and calculated as follows.

$$R^2 = \frac{\sum_{i=1}^{N}\left(MR_{pre,i} - \overline{MR}_{exp}\right)^2}{\sum_{i=1}^{N}\left(MR_{exp,i} - \overline{MR}_{exp}\right)^2} \tag{4}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N-P} \tag{5}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{N}} \tag{6}$$

where: $MR_{exp,i}$ is the experimental dimensionless moisture ratio, $MR_{pre,i}$ is the predicted dimensionless moisture ratio, N is the number of observations, and P is the number of constants in the mathematical model.

Effective Moisture Diffusivity

The effective moisture diffusivity can reflect the moisture migration mechanism during the material drying process, describing the evaporation of moisture within a certain period under specific conditions. It is of great significance for analysing internal moisture diffusion and process optimization. As alfalfa drying primarily occurs during the deceleration drying stage, the effective moisture diffusivity can be calculated using a simplified form of Fick's second law. Assuming negligible volume shrinkage of the drying material and a constant diffusion coefficient and temperature, the effective diffusivity can be expressed as:

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

The equation (7) can be expressed in logarithmic form as follows:

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

By plotting $ln(MR)$ against drying time as coordinates and obtaining the slope of the line, the effective moisture diffusivity can be then determined.

$$S = \frac{\ln\left(MR\right) - \ln\left(\frac{8}{\pi^2}\right)}{t} = \frac{\pi^2 D_{eff}}{4L^2} \tag{9}$$

where: D_{eff} is the effective moisture diffusivity (m^2/s), L is half of the alfalfa thickness (m), S is the slope, and t is the drying time (minutes).

Activation energy

The drying activation energy represents the energy required to remove the moisture from 1 mole of material, and its value directly reflects the difficulty of the drying process. A higher value indicates a more difficult drying process *(Onwude D.I. et al., 2016)*. Therefore, this study aims to measure the difficulty of alfalfa drying under dynamic conditions by calculating the activation energy. The activation energy is calculated using the Arrhenius equation to establish the relationship between the effective diffusivity and the activation energy, as follows:

$$D_{eff} = D_0 \exp\left[-\frac{E_a}{R\left(T + 273.15\right)}\right] \tag{10}$$

where: D_0 is the pre-exponential factor (m^2/s), E_a is the activation energy (kJ/mol), R is the ideal gas constant (8.314 kJ/mol), T is the absolute temperature (℃).

The equation (10) can be expressed in logarithmic form as follows:

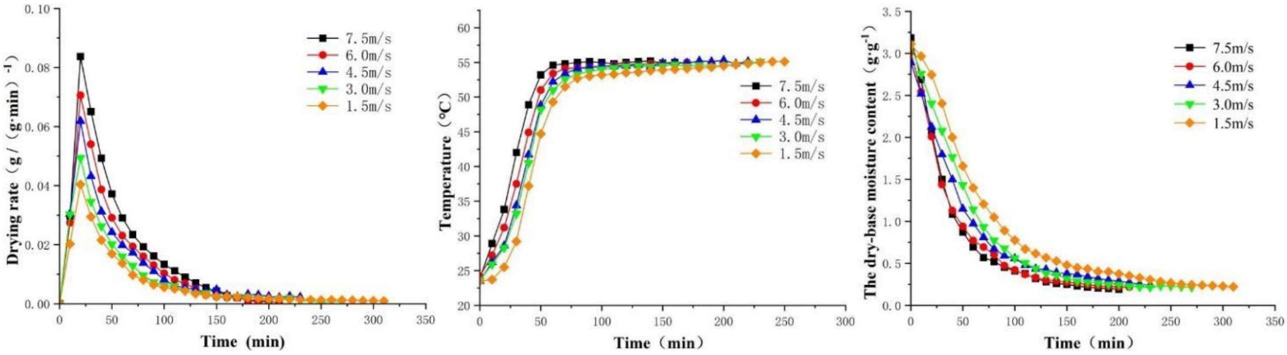
$$\ln D_{eff} = \ln D_0 - \frac{E_a}{R}\frac{1}{T + 273.15} \tag{11}$$

By plotting a line with $\ln(D_{eff})$ and $1/(T+273.15)$ as coordinates, the slope of the line can be determined, and thus the activation energy can be calculated.

RESULTS

Analysis of drying characteristics under different wind speeds

When the temperature was 55 °C, the alfalfa was stacked to a thickness of 7 cm, the turning angle of the spinner rack was 0°, and the conveyor belt moved at a speed of 0.01 m/s, the drying characteristic curves under different wind speeds were obtained, as shown in Figure 3. As the drying time increased, the drying rate showed a trend of initial increase followed by a decrease (figure 3a), without a constant speed drying stage. This is similar to the curves obtained for alfalfa drying under static conditions *(Shi Q et al., 2013)*. During the initial stage of drying, the alfalfa experienced a preheating phase *(Cowen A.A. et al., 2008)*, characterized by a rapid increase in temperature (figure 3b) and subsequent decrease in the dry-base moisture content (figure 3c), leading to a linear rise in the drying rate. When the solar energy-heat pump system provided heat exclusively for evaporating moisture, the alfalfa temperature stopped rising and entered a constant temperature phase (figure 3b), causing the drying rate to decrease to a lower level. By the drying time reached 170 minutes, the wet basis moisture content fell below 18% (the dry-base moisture content below 22%), reaching a safe moisture content level.



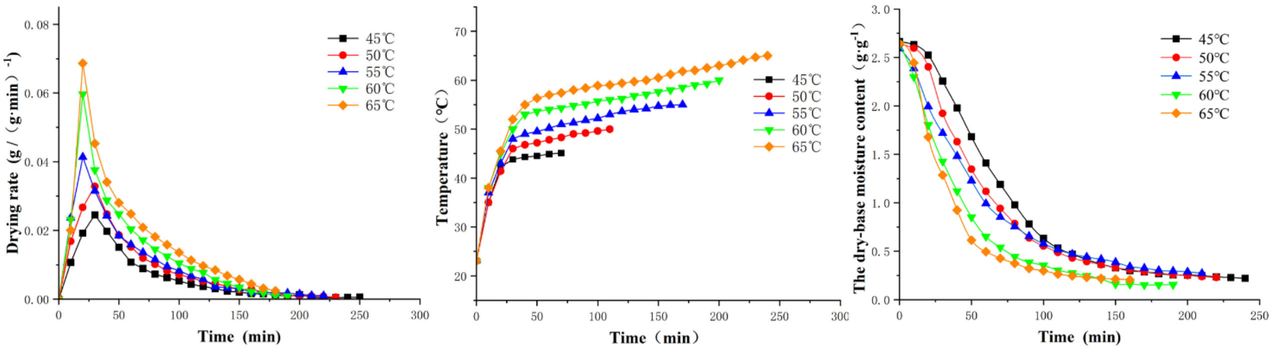
(a) (b) (c)

Fig. 3 - (a)Effect of wind speed on drying rate; (b)Effect of wind speed on alfalfa warming; (c)Effect of wind speed on the water content of alfalfa

The impact of varying wind speeds on the drying rate, moisture content, and temperature of alfalfa was interconnected. Higher wind speeds resulted in a faster drying rate during the preheating phase (figure 3b), an earlier transition to the constant temperature phase (figure 3b), an earlier transition to the constant temperature phase (figure 3b), and a shorter time to reach the target moisture content (figure 3c). This acceleration was attributed to the increased wind speed expediting the removal of moisture from the drying chamber, thereby requiring less time to achieve equilibrium and resulting in a more rapid increase in alfalfa temperature. Specifically, at wind speeds of 1.5, 3.0, 4.5, 6.0, and 7.5 m/s, the times required for alfalfa to reach the target moisture content were 310, 270, 230, 210, and 200 minutes, respectively. Higher wind speeds accelerated the evaporation rate of moisture, leading to reduced drying time *(YunHong Liu et al., 2016)*. Compared to static drying *(Qian W. et al., 2018)*, the moisture content decreases more rapidly and the time required for drying is shorter during mesh belt dynamic drying.

Characterization of drying at different temperatures

Drying characteristic curves for alfalfa at various temperatures were obtained under specific conditions, including a wind speed of 7.5m/s, an alfalfa stacking thickness of 10 cm, a spinner rack turning angle of 0°, and a conveyor belt speed of 0.01 m/s, as depicted in Figure 4. Over time, the drying rate curve displayed an initial increase followed by a decrease (figure 4a). Obviously, there were both acceleration and deceleration drying stages, with no constant speed drying stages. Moreover, the primary drying process occurred during the deceleration stage. The drying temperature significantly impacted the drying rate and heating effect of the alfalfa. Higher temperatures led to greater heat absorption by the alfalfa as well as a faster temperature increase (figure 4b). The higher the maximum drying rate (figure 4a), the faster the dry-base moisture content decreased (figure 4c). This was because in the initial stage of drying, the alfalfa surface contained a higher amount of free water, which rapidly evaporated with rising temperature, leading to an increase in the drying rate. As drying progressed, the internal moisture of the alfalfa, including bound water, began to migrate outward and evaporate. However, due to the influence of the internal tissue structure, the rate of moisture diffusion decreased, leading the alfalfa into the deceleration drying stage. At this point, the temperature tended to stabilize, and the drying rate continued to decline until the alfalfa reached the desired moisture content.



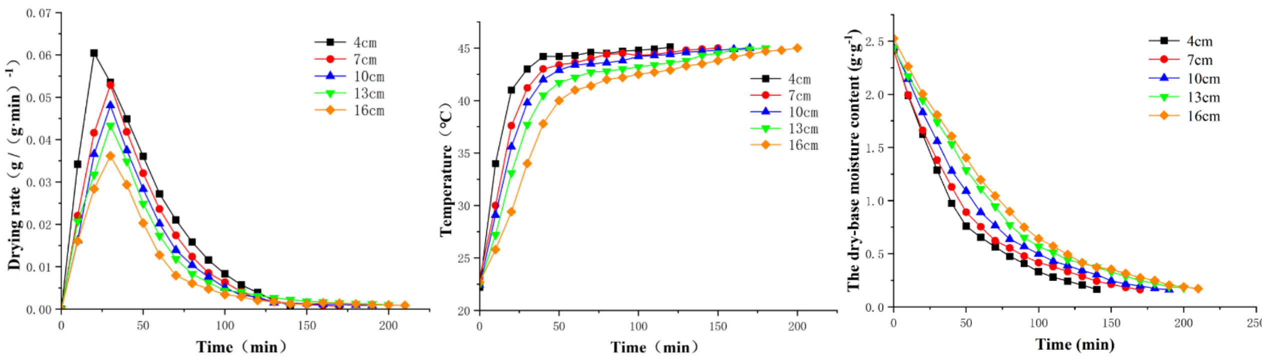
(a) (b) (c)

Fig. 4 - (a) Effect of temperature on drying rate; (b) Effect of temperature on alfalfa warming; (c) Effect of temperature on the water content of alfalfa

The trend of the drying characteristic curves of alfalfa remained consistent at different inlet air temperatures. It was evident that higher temperatures resulted in a faster drying rate (figure 4a) and a more pronounced decrease in the dry-base moisture content of the alfalfa (figure 4c). The alfalfa temperature increased more rapidly (figure 4b), the value tended to be larger when the temperature reached equilibrium, leading to a shorter time to reach the target moisture content. This aligns with results obtained under static drying conditions, as higher temperatures accelerated the diffusion of moisture within the alfalfa, increased the heat flow between the alfalfa and the hot air, enhanced the rate of heat transfer, and ultimately led to a rapid increase in alfalfa temperature (figure 4b), accelerating the outward transfer of moisture *(Xiao H.W. et al., 2010)*.

Characterization of drying under different stack thicknesses

When the temperature was 45°C, the wind speed was 7.5 m/s, the conveyor turning angle was 0°, and the conveyor belt speed was 0.01 m/s, dynamic drying characteristic curves for alfalfa at various stacking thicknesses were obtained, as depicted in Figure 5. Under dynamic drying conditions, stacking thickness significantly affected the dry-base moisture content of the alfalfa (figure 5c). Smaller stacking thickness led to a more pronounced decrease in moisture content and a faster temperature increase (figure 5b). This was due to the easy access of hot air into the spaces between alfalfa particles during dynamic drying, promoting efficient heat exchange and timely moisture removal, thus accelerating internal moisture migration and diffusion within the alfalfa. Moreover, higher stacking thickness (13 cm and 16 cm) increased alfalfa density per unit area, impacting the entry of hot air into interstitial spaces between the alfalfa particles for heat exchange.



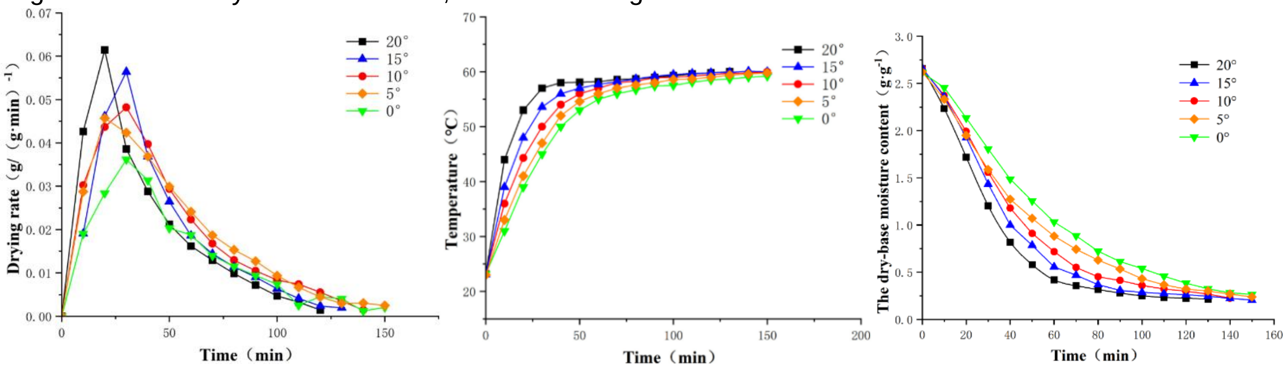
(a) (b) (c)

Fig. 5 - (a) Effect of stack thickness on drying rate; (b) Effect of stack thickness on the warming of alfalfa; (c) Effect of stack thickness on water content

Additionally, stacking thickness had a differential impact on alfalfa's drying rate (figure 5a). A smaller stacking thickness resulted in a higher maximum drying rate and shorter drying time. This reaffirms that even under dynamic drying conditions, thin-layer alfalfa drying offers the advantage of a faster drying rate, a similar conclusion to that obtained under static drying conditions *(Hu Y.Q. et al., 2022)*. As stacking thickness decreased, the alfalfa's absorption rate of thermal energy increased under continuous hot air action, leading to an accelerated drying rate. Conversely, as stacking thickness increased, the alfalfa's drying rate gradually declined. This was because as stacking thickness gradually reached the maximum inside the drying chamber, the removal of moisture content per unit time had already peaked *(Kamruzzaman M et al., 2010)*.

Analysis of drying characteristics under different deflection angles of rotary frame

Under the conditions of a temperature of 60°C, an alfalfa stacking thickness of 7 cm, a wind speed of 7.5 m/s, and a conveyor belt speed of 0.01 m/s, drying characteristic curves for alfalfa at different turning angles of the conveyor were obtained, as shown in Figure 6.



(a) (b) (c)

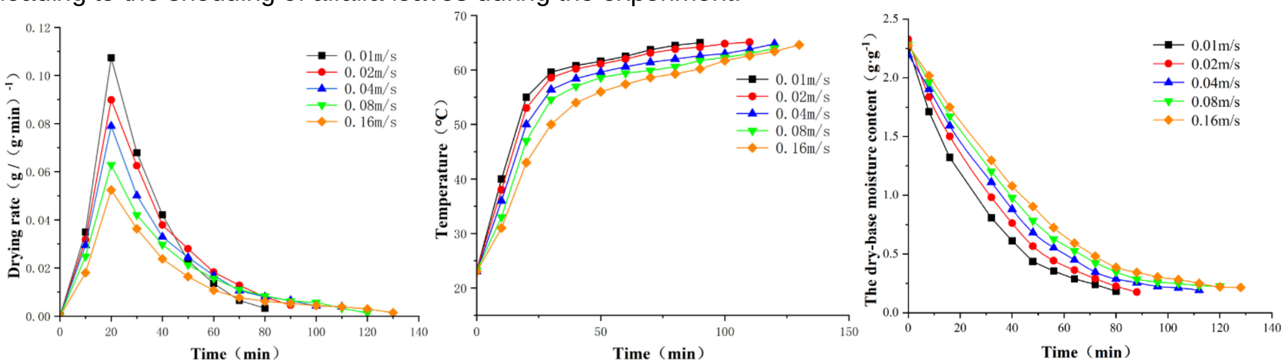
Fig. 6 - (a) Effect of deflection angle on drying rate; (b) Effect of deflection angle on alfalfa warming; (c) Effect of deflection angle on water content

In the initial stage of alfalfa drying, different turning angles had a significant impact on the drying rate, temperature increase, and moisture content change of the alfalfa. Furthermore, a larger turning angle of the spinner rack resulted in a greater tilt angle between the direction of alfalfa placement on the conveyor and the flow direction of the hot air. This led to a more pronounced drying effect of the hot air on the surface moisture of the alfalfa, causing rapid loss of free water from the alfalfa surface and a higher drying rate in the initial drying stage (figure 6a). As a result, the alfalfa temperature rose rapidly (figure 6b), and the dry-base moisture content decreased quickly (figure 6c). After entering the deceleration drying stage, the differences in drying characteristic parameters caused by different turning angles gradually diminished, and the drying rate, temperature, and dry basis moisture content of the alfalfa essentially reached consistency at the same drying time. It is therefore concluded that the different turning angles of the conveyor do not affect the time it takes for the alfalfa to dry to a safe moisture content.

Analysis of drying characteristics under different conveyor belt moving speeds

Compared to static drying, the movement of the conveyor belt can optimize airflow positioning during the drying process, thereby improving drying efficiency. However, a faster conveyor belt speed is not necessarily better. When the temperature was 65°C, the stacking thickness was 10 cm, the wind speed was 7.5 m/s, and the turning angle of the spinner rack was 0°, drying characteristic curves for alfalfa at different conveyor belt speeds were obtained (Figure 7).

It's evident that varying conveyor belt speeds resulted in significant differences in drying rate, temperature, and moisture content patterns over time. A slower conveyor belt speed led to a faster increase in the drying rate during the acceleration drying stage, with a higher maximum value. In the deceleration drying stage, the time required for alfalfa to reach a safe moisture content was shorter. This suggests that a slower conveyor belt speed allowed for more thorough contact between the hot air medium and the alfalfa, enhancing heat and mass transfer effects and thus improving drying efficiency and quality. For instance, at a conveyor belt speed of 0.16 m/s, the drying time required for alfalfa to reach a safe moisture content was 128 minutes (figure 7c), whereas at a speed of 0.01 m/s, the drying time was only 80 minutes (figure 7c), reducing the drying time by 37.5%. It's worth noting that at a conveyor belt speed of 0.16 m/s, the belt was prone to vibration, leading to the shedding of alfalfa leaves during the experiment.



(a) (b) (c)

Fig. 7 - (a) Effect of conveyor speed on drying rate; (b) Effect of conveyor speed on alfalfa warming; (c) Effect of conveyor speed on moisture content

Model fitting of drying curves

To further analyse the drying characteristics of alfalfa under dynamic drying conditions and predict the moisture change during the drying process, four drying models were non-linearly fitted. The R^2, χ^2, *RMSE* values of the four drying mathematical models obtained are shown in Table 2. It can be observed that the R^2 values of the fitted curves for all four models are greater than 0.97, and the χ^2 and *RMSE* values are less than 0.003 and 0.034, respectively. Among them, the Logarithmic model has the best fitting effect, with an R^2 value exceeding 0.994, and the lowest χ^2 and *RMSE* values among the four models. Therefore, the Logarithmic model can effectively describe the moisture change pattern of alfalfa during dynamic drying, well predict the moisture content of alfalfa at a certain moment, and analyse its moisture migration trend.

Table 2

Model parameters and Statistical analysis result of drying kinetic models

Models	R^2	χ^2	*RMSE*
Page	0.98368	0.00159	0.02738
Logarithmic	0.99454	0.00140	0.01479
Two-term model	0.98109	0.00297	0.03160
Approximation of diffusion	0.97988	0.00186	0.03334

Table 3

Logarithmic Model fitting results

Drying condition	Parameters		
	a	k	c
7.5 m/s	0.9987	0.02874	0.06091
6.0 m/s	0.9422	0.02656	0.07113
4.5 m/s	1.0138	0.01736	0.03301
3.0 m/s	0.9572	0.02085	0.07783
1.5 m/s	0.9807	0.01767	0.06281
45 ºC	0.9767	0.01684	0.08089
50 ºC	1.0772	0.01481	0.01169
55 ºC	1.0109	0.01879	0.04810
60 ºC	0.9658	0.02217	0.06770
65 ºC	1.0051	0.03098	0.05742
4 cm	0.9460	0.03384	0.07109
7 cm	0.9870	0.01901	0.05898
10 cm	0.9293	0.01918	0.10794
13 cm	0.9701	0.01721	0.11071
16 cm	0.9961	0.01302	0.08722
0°	1.0098	001883	0.05204
5°	0.9799	0.02215	0.06010
10°	1.0275	0.02858	0.04556
15°	1.1063	0.02299	-0.00872
20°	1.014	0.03175	0.04079
0.01m/s	1.0755	0.01843	-0.04009
0.02m/s	1.0574	0.01990	-0.01417
0.04m/s	1.0574	0.02269	-0.02646
0.08m/s	1.2723	0.01836	-0.22371
0.16m/s	1.0738	0.03294	-0.01281

The Logarithmic model fitting results obtained are shown in Table 3. To analyse the relationship between the model parameters (a, k, c) and the experimental factors, including drying air velocity, drying temperature, stacking thickness of alfalfa, turning angle of the spinner rack, and conveyor belt speed, the regression equations of Logarithmic model parameters are obtained using multivariate statistical analysis:

$$\mathrm{a} = 0.708 + 0.004T + 0.005V + 0.005M + 0.002N + 0.678V_m \tag{12}$$

$$\mathrm{k} = 0.022 + 0.000063T + 0.001042V - 0.001378M + 0.000205N + 0.061296V_m \tag{13}$$

$$c = 0.326 - 0.004431T - 0.004333V - 0.000091M + 0.000553N - 0.634629V_m \quad (14)$$

where: T is the drying temperature in ℃, V is the drying air velocity in m/s, M is the stacking thickness in cm, N is the turning angle of the spinner rack in °, and V_m is the moving speed of the conveyor belt in m/s.

From the above expression, it can be seen that the drying air velocity, drying temperature, stacking thickness of alfalfa, turning angle of the spinner rack, and conveyor belt speed all have an impact on the model parameters a, k, and c. By substituting the expressions 12-14 into the Logarithmic equation, the predicted model for the moisture content of alfalfa can be obtained, as shown in expression 15.

The prediction of alfalfa moisture content during dynamic drying can be carried out based on the experimental conditions.

$$MR=(0.708+0.004T+0.005V+0.005M+0.002N+0.678V_m)\exp[-(0.022+0.000063T+0.001042V-0.001378M+0.000205N+0.061296V_m)\cdot t]+(0.326-0.004431T-0.004333V-0.000091M+0.000553N-0.634629V_m) \quad (15)$$

Validation of Logarithmic model

To verify the accuracy of the model, experimental conditions were set as follows: hot air velocity of 7.5 m/s, hot air temperature of 55℃, stacking thickness of 7 cm, turning angle of the spinner rack at 0°, and conveyor belt speed at 0.01 m/s. A comparison of the experimental values and the model-predicted values was conducted, and the results are shown in Figure 8. The fitting accuracy between the experimental and predicted values is high ($R^2 > 0.998$), confirming that the Logarithmic model can effectively describe the moisture change pattern of alfalfa during the drying process.

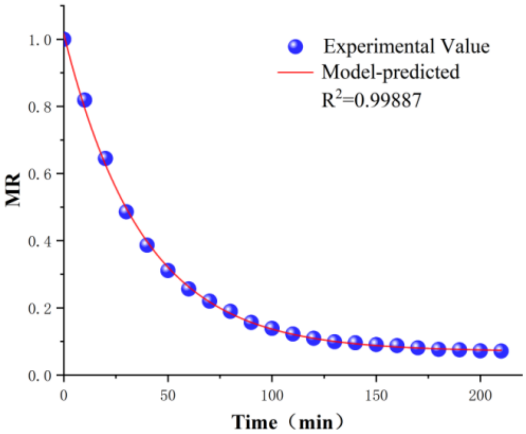


Fig. 8 - Validation of Logarithmic model

Moisture Diffusivity

From the drying rate curves under different conditions, it can be observed that alfalfa drying under solar energy-heat pump drying mainly occurred during the deceleration drying stage. During this stage, resistance controlled the mass transfer process, and moisture transfer during the drying process was influenced by diffusion. The effective moisture diffusivity during dynamic drying was calculated, as shown in Table 4.

Table 4

Effective diffusivity for alfalfa under different drying

Temperature [℃]	Air velocity [m/s]	Stack thickness [cm]	Angles [°]	Speed [m/s]	D_{eff} [$m^2 \cdot s^{-1}$]
45	7.5	10	0	0.01	1.9323×10^{-9}
50	7.5	10	0	0.01	2.1499×10^{-9}
55	7.5	10	0	0.01	2.2533×10^{-9}
60	7.5	10	0	0.01	2.4180×10^{-9}
65	7.5	10	0	0.01	3.1067×10^{-9}
55	1.5	7	0	0.01	1.0049×10^{-9}
55	3.0	7	0	0.01	1.2849×10^{-9}
55	4.5	7	0	0.01	1.5604×10^{-9}
55	6.0	7	0	0.01	1.6155×10^{-9}
55	7.5	7	0	0.01	1.7466×10^{-9}
45	7.5	4	0	0.01	4.7324×10^{-9}
45	7.5	7	0	0.01	4.4360×10^{-9}
45	7.5	10	0	0.01	2.8720×10^{-9}
45	7.5	13	0	0.01	1.0524×10^{-9}
45	7.5	16	0	0.01	2.7760×10^{-10}
60	7.5	7	0	0.01	1.0391×10^{-9}
60	7.5	7	5	0.01	1.2978×10^{-9}
60	7.5	7	10	0.01	1.3683×10^{-9}

Temperature [℃]	Air velocity [m/s]	Stack thickness [cm]	Angles [°]	Speed [m/s]	D_{eff} [$m^2 \cdot s^{-1}$]
60	7.5	7	15	0.01	1.3976×10^{-9}
60	7.5	7	20	0.01	1.4464×10^{-9}
65	7.5	10	0	0.01	2.3254×10^{-9}
65	7.5	10	0	0.02	2.3021×10^{-9}
65	7.5	10	0	0.04	2.2808×10^{-9}
65	7.5	10	0	0.08	2.2744×10^{-9}
65	7.5	10	0	0.16	2.1847×10^{-9}

The effective moisture diffusivity of alfalfa ranged from 2.776×10^{-10} to 4.7324×10^{-9} m^2/s. This result is similar to the range of effective moisture diffusivity reported by Madamba *(Madamba P.S. et al., 1996)*, which is 10^{-12}~10^{-8} m^2/s for drying materials. The results in Table 4 demonstrate that the effective moisture diffusivity increases with higher air velocity, as it accelerates the heat exchange between the moisture in alfalfa and the air, leading to an increase in effective moisture diffusivity. The effective moisture diffusivity increased with temperature. This was because the heightened temperature within the drying chamber increased the energy of water molecules, resulting in a faster transition frequency and accelerated moisture transfer to the material surface. This further enhanced the efficiency of heat and mass transfer, ultimately leading to an increase in effective moisture diffusivity. Moreover, an increase in stacking thickness lengthened the distance for bound water evaporation within the alfalfa, leading to greater resistance to moisture migration and a decrease in effective moisture diffusivity.

An increase in the turning angle of the spinner rack also led to an increase in effective moisture diffusivity. This was because with a larger turning angle, the alfalfa experienced greater impact from the hot air, making it easier for the hot air to pass through the alfalfa layer and carry away moisture, thereby accelerating the migration of moisture in the alfalfa. Additionally, a decrease in conveyor belt speed increased effective moisture diffusivity. This was because a slower speed allowed the hot air to more easily penetrate the internal gaps of the alfalfa layer, causing rapid evaporation of surface moisture. When the surface moisture concentration was lower than the internal moisture concentration, a concentration gradient was formed, thereby reducing the resistance to moisture diffusion and increasing effective moisture diffusivity. In summary, variations in the levels of the various experimental factors impacted the effective moisture diffusivity during alfalfa drying. Therefore, in practical processing, reasonable process parameters can be selected based on production needs and the above results to improve the efficiency and effectiveness of alfalfa drying.

Activation energy

The slope of the ln (D_{eff}) versus 1/(T+273.15) curve obtained from Figure 9 allows for the calculation of the activation energy E_a of alfalfa.

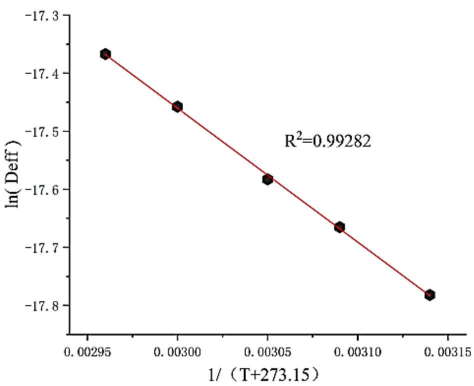


Fig. 9 - The relationship between change of ln(D_{eff}) and 1/(T+273.15)

The calculated activation energy is 37.02 kJ/mol when the air velocity is 7.5 m/s, the stacking thickness is 10 cm, the turning angle of the spinner rack is 0°, and the conveyor belt speed is 0.01 m/s. This indicates that at least 37.02 kJ of energy is required to remove 1 mole of water during the dynamic drying process. This value is lower than the activation energy of 38.34 kJ/mol obtained for lemongrass by Thi Van Linh Ngu-yen *(Nguyen T et al., 2019)*.

Additionally, based on the research results of Azeez *(Azeez L et al., 2017)*, the activation energy of agricultural materials generally falls within the range of 12.7~110 kJ/mol. Therefore, it can be concluded that under the conditions of solar-heat pump combined drying, the difficulty level of dynamically drying alfalfa is moderate, similar to that of drying other agricultural materials.

The activation energy of alfalfa falls within the normal range, indicating the feasibility of the drying method adopted for alfalfa in this study. In practical processing, adjustments can be made to the process parameters such as stacking thickness and particle size of alfalfa to further reduce the activation energy and enhance the effective moisture diffusivity.

CONCLUSIONS

In this study, a dynamic drying test platform is constructed under the conditions of solar-heat pump combined drying. The dynamic drying characteristics of alfalfa are studied by considering factors such as hot air velocity, temperature, alfalfa stacking thickness, turning angle of the spinner rack, and conveyor belt speed. The drying characteristic curves obtained show that the drying rate of alfalfa exhibits an increasing and then decreasing trend, without a constant speed drying stage. The drying process mainly occurs in the deceleration drying stage. During this stage, the moisture content of alfalfa continuously decreases, and the decreasing rate shows a pattern of initially fast and then slow decline. The temperature also corresponds to a pattern of rapid increase followed by a tendency to stabilize.

The analysis of the influence of various experimental factors on the drying characteristic curves reveals the following trends: Higher air velocity accelerates the temperature increase and drying rate of alfalfa, reducing the time to reach the safe moisture content level. Moreover, elevated drying temperatures enhance heat absorption by the alfalfa, leading to faster temperature rise and higher drying rates, resulting in a swifter decrease in moisture content. Furthermore, a smaller stacking thickness prompts a quicker temperature increase, faster drying rates, and a more rapid decrease in moisture content during dynamic drying. Additionally, a greater turning angle of the spinner rack initiates a faster initial decrease in moisture content, accelerated temperature rise, and quicker drying rates for alfalfa. However, the impact of the turning angle diminishes during the deceleration drying stage, exerting minimal influence on the total time for alfalfa to reach the safe moisture content level. A slower conveyor belt speed leads to a quicker increase in drying rate and a shorter time to reach the safe moisture content level.

Comparison and regression analysis of drying models show that the Logarithmic model is the optimal model for describing the moisture change during dynamic drying of alfalfa, with a fitting determination coefficient R^2 being greater than 0.994, and χ^2 and *RMSE* being both less than 0.003 and 0.034, respectively. Multivariate statistical regression analysis of the model parameters a, k, and c reveals that each experimental factor has an impact on the model parameters. A predictive model for moisture content during dynamic drying of alfalfa is developed and validated. Additionally, calculations indicate that the effective moisture diffusivity of alfalfa ranges from 2.776×10^{-10}m^2/s to 4.7324×10^{-9}m^2/s, with an activation energy of 37.02 kJ. These results suggest that under solar energy-heat pump combined drying conditions, the difficulty of dynamic drying of alfalfa is moderate. Furthermore, process parameters can be adjusted according to production requirements to further improve drying efficiency and effect.

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