HOT AIR DRYING, IMPACT OF INFRARED DRYING, AND COMBINED HOT AIR-INFRARED DRYING ON ALFALFA DRYING QUALITY AND PERFORMANCE
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热风干燥、红外干燥以及热风-红外联合干燥对苜蓿干燥质量和干燥性能的影响

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ABSTRACT
This study analyzes the drying of alfalfa using hot air, infrared and combined drying techniques at different temperatures, irradiation heights and radiant powers. Different temperatures, radiation heights, radiation power and wind speed are used as control factors, and drying time, color, crude protein and specific energy consumption are used as evaluation indicators. After assigning weights to each indicator, the comprehensive evaluation index is calculated. Test results and data analysis show that the drying performance is optimal when the hot air flow velocity is 1.5 m/s, the hot air temperature is 62.1°C, the radiation distance is 10 cm, the radiation power is 1200 w, and the material thickness is 20 mm, it has the best drying performance; its coefficient of determination R^2 is 0.9995. The comprehensive evaluation index of alfalfa drying after combined drying is between 1.00 and 1.30, which is overall higher than hot air drying and infrared drying. Combined drying technology can effectively improve the efficiency and quality of the alfalfa drying process.

摘要
本研究分析了在不同温度、辐照高度和辐射功率下使用热风、红外和组合干燥技术对苜蓿进行干燥的情况。以不同温度、辐射高度、辐射功率和风速为控制因素，以干燥时间、色泽度、粗蛋白和比能耗为评价指标。对各指标赋予权重后，计算综合评价指数。测试结果及数据分析表明，当热风流速为 1.5m/s、热风温度为 62.1℃、辐射距离为 10cm、辐射功率为 1200w、物料厚度为 20mm 时，具有最佳干燥性能；其决定系数 R^2 为 0.9995。联合干燥后苜蓿干燥的综合评价指数在 1.00～1.30 之间，总体高于热风干燥和红外干燥，组合干燥技术可以有效提高苜蓿干燥过程的效率和质量.

INTRODUCTION
Alfalfa (*Medicago sativa L*.) is a highly nutritious leguminous plant with low leaf fiber content and high content of nutrients such as protein and carotenoids. Nitrogen fertilization is rarely required during planting, but the dry matter at maturity can have an average protein content of 17%, 60% digestible nutrients, and 23% fiber. The water content of freshly harvested alfalfa grass is more than 75% and is easy to rot and deteriorate after harvest, leading to a severe decrease in actual yield and loss of nutrients. Therefore, the treatment of harvested alfalfa is essential to prolong its storage time and reduce quality loss during storage. There are many ways to achieve material dehydration, hot air drying (*Vega-Gálvez et al., 2012*), infrared drying (*Huang, Li, Wang & Wan, 2021*), and a combination of various drying methods *(Bai-Ngew, Therdthai, Dhamvithee & Zhou, 2015; Wang, Li, Han, Ni, Zhao & Hao, 2019*) have been within the field of agricultural and sideline products such as research and application for many years. But, the mechanism research and application of new drying technology and combined drying are less.

Due to the robust adaptability of infrared drying, it is easy to combine with hot air to exert a synergistic effect (*Onwude, Hashim & Chen, 2016*). Mesery et al. studied the performance of infrared-hot air combined drying of apples and concluded that combined drying can produce lower specific energy consumption and higher thermal efficiency (*Hany S. El-Mesery & Gikuru Mwithiga, 2016*). Wang et al. attributed the reduction in infrared-hot air combined drying time of shiitake mushrooms to the rapid heating of infrared radiant energy that increases the moisture migration rate (*Hongcai Wang et al, 2014*).

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Zhang et al. studied the infrared convection drying of luffa and found that the drying time decreases with the increase of infrared intensity and the decrease of radiation distance, but too high infrared intensity and too low radiation distance will cause the material to be scorched (*Zhang et al., 2020)*. Different drying methods and conditions will affect dried products' nutritional value and sensory characteristics, and a large amount of energy consumption in drying will also lead to high costs. Therefore, it is necessary to determine the optimal drying method and process parameters for alfalfa.

MATERIALS AND METHODS

Materials

The material was fresh alfalfa, which was collected from Shangzhuang Experimental Station of China Agricultural University. The samples with good appearance and no damage were selected. After cleaning, the samples were evenly cut into 5 cm segments, put into sealed bags, and refrigerated at 4°C for the experiment. The moisture content of alfalfa was measured with ASAE Standard and the initial moisture content was 77.55±0.50% (wb).

Drying equipment

A schematic diagram of the drying test bench is shown in Fig. 1. Drying apparatus is mainly composed of a heating system and a control system. The experimental parameters were set via the control system. During hot air drying experiments, the air heater is the primary heating source and the temperature reaches the predetermined value. The infrared heating plate is mainly used for radiation heating samples and also is the heating source to heat the air during infrared drying as well. A thermocouple was plugged in the drying chamber to monitor the inside temperature. The air temperature was controlled in a stable range since the temperature data were transferred to the control system. The material tray is connected with an electronic balance to measure the mass change of the material in real-time during drying.

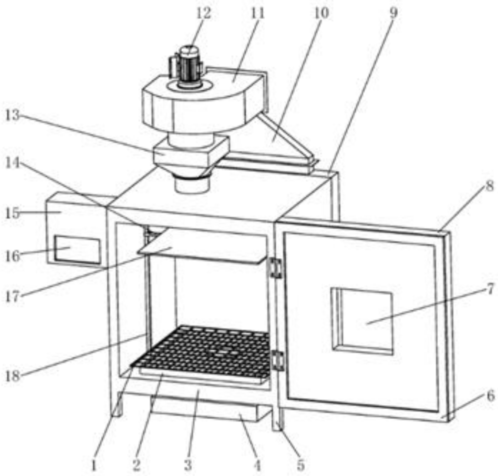


Fig. 1 - Structure diagram of infrared-hot air combined drying test bench

1. Mesh tray; 2. Uniform outflow plate; 3. Air distribution room; 4. Electronic balance; 5. Support frame; 6. Sealing gasket; 7. Observation window; 8. Door; 9. The back hollow wall; 10. Air channel; 11. Centrifugal fan; 12. Motor; 13. Air heater; 14. Slider bracket; 15. Control cabinet; 16. Touch screen; 17. Infrared heating plate; 18. Slide table

Experimental methods

In order to compare the effects of different drying conditions on the drying effect of alfalfa, a thin layer drying test was carried out. The experimental design was shown in Table 1. Since each drying test was repeated three times, the design did not express the repeated tests. The equipment adopts a hot air circulation design. When combined drying, the air was heated by the infrared plate, which kept the temperature constant. Therefore, the hot air temperature changed with different infrared parameters.

Table 1

The experimental design

Drying method	Experiment No.	Air velocity (m/s)	Air temperature (℃)	Material layer thickness (mm)	Radiant power (W)	Radiation heights (cm)
	1	1.0	55	15	---	---
Hot air drying	2	1.5	55	15	---	---
	3	2.0	55	15	---	---

Drying method	Experiment No.	Air velocity (m/s)	Air temperature (℃)	Material layer thickness (mm)	Radiant power (W)	Radiation heights (cm)
	4	1.5	45	15	---	---
	5	1.5	65	15	---	---
	6	1.5	55	10	---	---
	7	1.5	55	20	---	---
Infrared drying	8	1	---	15	1200	20
	9	1.5	---	15	1200	20
	10	2	---	15	1200	20
	11	1.5	---	10	1200	20
	12	1.5	---	20	1200	20
	13	1.5	---	15	600	20
	14	1.5	---	15	1800	20
	15	1.5	---	15	1200	10
	16	1.5	---	15	1200	30
Combined drying	17	1	70.5	15	1200	20
	18	1.5	61.8	15	1200	20
	19	2	55.4	15	1200	20
	20	1.5	62.1	10	1200	20
	21	1.5	61.5	20	1200	20
	22	1.5	51.2	15	600	20
	23	1.5	72.3	15	1800	20
	24	1.5	61.8	15	1200	10
	25	1.5	61.8	15	1200	30

Drying parameters

Moisture content

$$M_t = \frac{m_t - m_0}{m_0} \tag{1}$$

where:

M_t is the dry base moisture content of alfalfa at time t, (g water/g dry matter);

m_t is the mass of alfalfa at time t, g; and m_0 is the dry matter mass of alfalfa, g.

Moisture rate

$$MR = \frac{M_t}{M_0} \tag{2}$$

where MR is the moisture rate of alfalfa at time t, and M_0 is the initial dry base moisture content of alfalfa, (g water/g dry matter).

Drying rate

$$DR = \frac{M_t - M_{t+\Delta t}}{\Delta t} \tag{3}$$

where DR is the dry rate of alfalfa at time t, (g water/g dry matter·min); $M_{t+\Delta t}$ is the dry base moisture content of alfalfa at time $t+\Delta t$, (g water/g dry matter) and Δt is the interval time, min.

Water diffusion coefficient

$$MR = \frac{8}{\pi^2} exp\left(-\frac{\pi^2 D_{eff}}{4L_m^2} t_{dry}\right) \tag{4}$$

where D_{eff} is the effective water diffusion coefficient of alfalfa, m^2/s; L_m is the half of alfalfa layer thickness, m; t_{dry} is the drying time, s.

$$D_{cal} = \frac{L_m^2}{60\alpha} = D_{eff} \cdot R_g \tag{5}$$

where D_{cal} is the estimated water diffusion coefficient, m^2/s; R_g is a parameter related to geometric size.

Drying curve fitting based on the Weibull function

$$MR = \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] \tag{6}$$

where α is the scale parameter, min; β is the shape parameter, and t is the drying time, min.

Color measurement

The fresh alfalfa served as a control. The dried alfalfa samples were crushed and passed through a 40-meshes sieve. The color was measured by using a LabScan XE type colorimeter (HunterLab, USA). The results were presented as averages of three determinations (*Xiao, Law, Sun & Gao, 2014*).

Crude protein

Crude protein content was determined by the Kjeldahl method. The KT8000 type Kjellott nitrogen analyzer was used for detection, and the final nitrogen content was multiplied by 6.25 to obtain the crude protein content (*Wang, Jiang & Shen, 2020*). The results are expressed as an average of the three measurements.

Energy Consumption

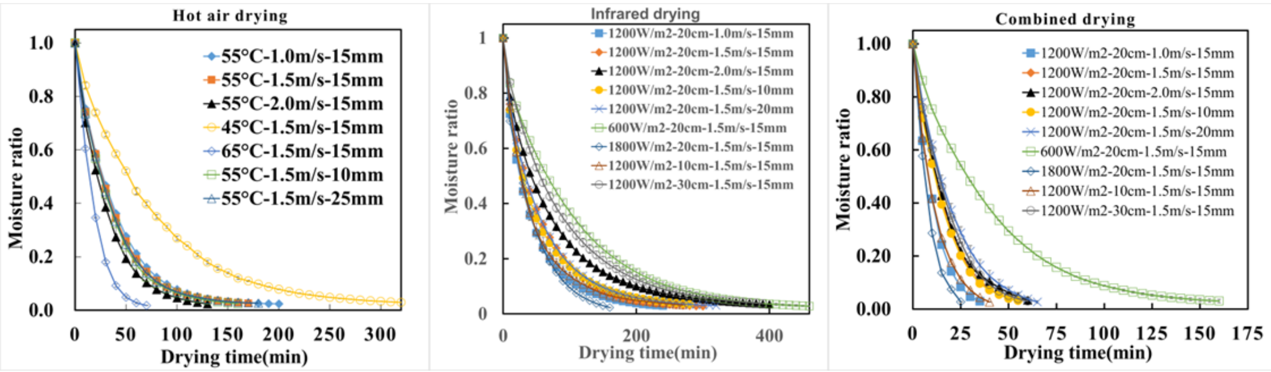
Since the total energy consumption of the equipment is the energy consumed by the entire pallet area (the drying bench is fully loaded), the specific energy consumption of drying materials in the test is calculated as follow *(Chauhan, Singh, Dhar & Powar, 2021*):

$$SEC = \frac{3.6E}{m_{\text{loss}}} \times \frac{A_s}{A_t} \quad (7)$$

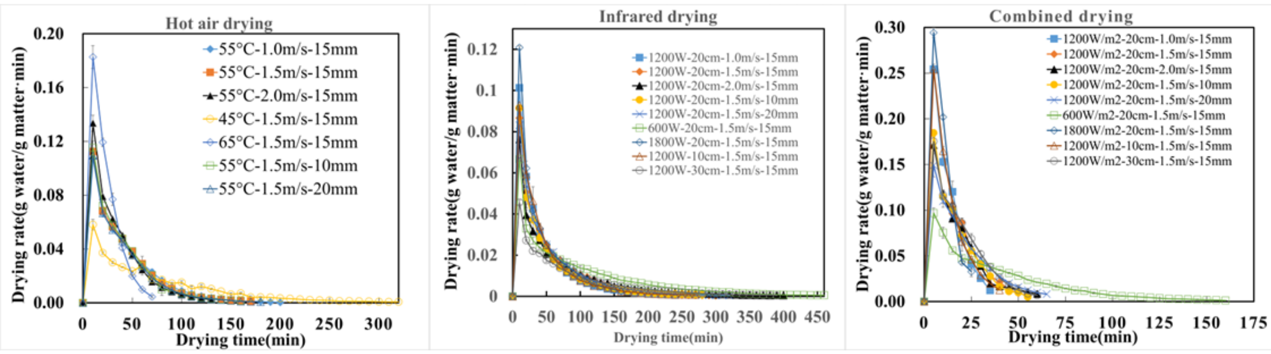
where SEC is the specific energy consumption of alfalfa drying, MJ/kg; E is the total energy consumption of the drying test bench, kW·h; m_{loss} is the mass of evaporated water in drying, kg; A_s is the contact surface area between material layer and tray, m^2; A_t is the surface area of the tray, m^2.

RESULTS AND DISCUSSION

Effects of different drying conditions on drying dynamic



(a) Moisture ratio



(b) Drying rate

Fig. 2 - Drying curves of alfalfa under different drying conditions

The effects of three different drying conditions on the moisture content and drying rate of alfalfa are shown in Fig. 2. The effects of different drying conditions on the alfalfa's moisture ratio and drying rate during hot-air drying were shown in Fig. 2. In the same environment, the increasing temperature can reduce the steam pressure of air, which is far less than the material surface's steam pressure and accelerates the outward migration of water from inside of the materials. In addition, the high drying temperature can accelerate the convective heat transfer rate, which makes the temperature of samples rise rapidly and improves the water migration rate. The drying rate of materials reached the maximum in the early stage and then decreased gradually. At the same drying temperature, increasing the airspeed can increase the heat flux of air per unit time and reduce the thickness of the material drying boundary layer (*Wang et al., 2017*), which can improve the heat transfer efficiency and speed up the evaporation rate of water on the material surface. Fig. 2 showed that when the air velocity was 2.0 m/s, the drying rate of alfalfa decreases rapidly in the middle and late periods. In addition to the decreased moisture ratio, another important reason is that the high temperature and high-speed air accelerates the drying rate and leads to tight fiber structure and hardened material surface (*Namkanisorn & Murathathunyaluk, 2020*), which impedes the migration of moisture inside the material to the surface.

The infrared drying time was longer than the hot air drying time, and the drying rate was low compared to hot air drying. The infrared radiation mode in the drying process was continuous radiation. To avoid the excessive temperature caused by the continuous accumulation of heating, the ambient air was inhausted into the drying chamber and took away the heat of the material, which decreased the drying rate and increased the drying time. At the same infrared power, the decrease of radiation intensity will weaken the infrared penetration, reduce the activity of water molecules, and lead to the extension of drying time. The moisture ratio slowed down with the increase of air velocity, and the drying time was prolonged, which was consistent with the research results of Adak et al. *(Adak, Heybeli & Ertekin, 2017*). The effect of hot air velocity on drying rate in combined drying was different from that in hot air drying. In the combined drying, infrared radiation is the primary heat source. While hot air brings in heat, it will also take away the heat generated by infrared radiation and reduce the drying temperature of materials. However, the hot air still heats the material. With the function of hot air, the heat loss of the material is much smaller than that of ambient temperature air. Therefore, the impact of changes in hot air speed in combined drying was greater than that of ambient air speed in infrared drying. It can be seen from Fig. 2 that the maximum drying rate variation between different material layer thicknesses is less than 3%. Under the same drying condition, the moisture ratio has no significant difference with the increase of the material layer thickness.

Drying characteristics based on the Weibull distribution function

Table 2

Calculation parameters of drying process under different drying conditions

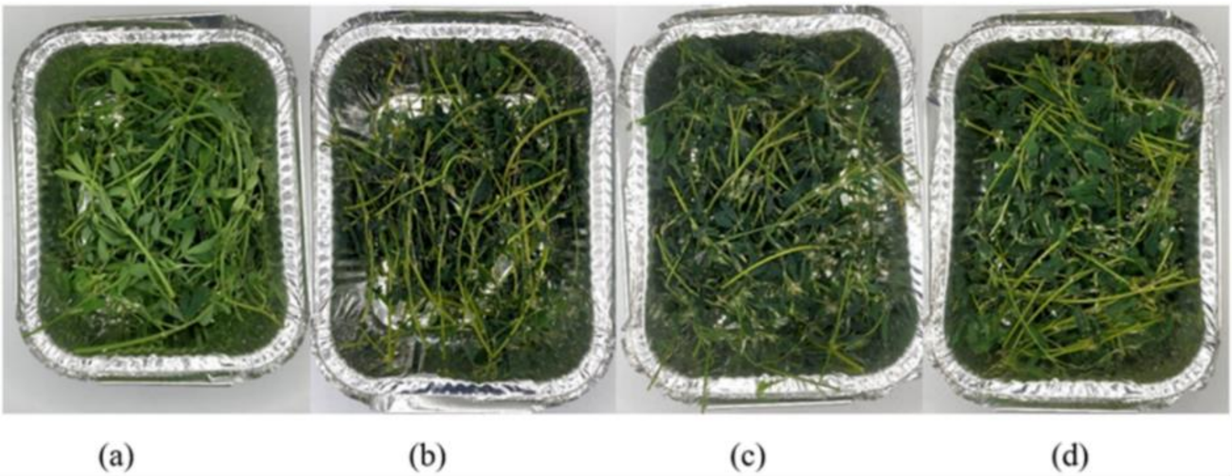
Drying method	Experiment NO.	D_{eff} (×10^{-9}m^2/s)	D_{cal} (×10^{-8}m^2/s)	R_g	α	β	R^2
Hot air drying	1	7.49	2.43	3.25	38.5709	0.9585	0.9985
	2	8.55	2.63	3.08	36.8514	0.9611	0.9990
	3	11.13	3.07	2.75	30.5799	0.9680	0.9993
	4	4.29	1.25	2.91	75.0529	0.9400	0.9990
	5	22.68	5.02	2.21	18.6696	0.9954	0.9989
	6	4.02	1.19	2.97	34.9082	0.9720	0.9987
	7	14.19	4.40	3.10	37.8952	0.9539	0.9988
Infrared drying	8	5.40	2.39	4.43	39.2568	0.7755	0.9990
	9	4.60	1.83	3.98	51.1746	0.7694	0.9993
	10	3.04	1.40	4.60	66.9974	0.7511	0.9989
	11	1.91	0.89	4.64	47.0266	0.7370	0.9993
	12	7.23	3.20	4.42	52.1263	0.7885	0.9990
	13	3.00	0.96	3.21	95.0237	0.8016	0.9982
	14	8.59	2.41	2.80	35.1246	0.7532	0.9977
	15	4.94	2.24	4.53	41.8499	0.7561	0.9965
	16	3.15	1.11	3.51	84.3887	0.8277	0.9995
Combined drying	17	3.91	8.65	2.21	10.8356	1.0703	0.9995
	18	2.44	5.72	2.35	16.3963	1.0418	0.9993
	19	2.12	5.49	2.58	17.0910	1.0098	0.9992
	20	1.09	2.63	2.42	15.8270	1.0273	0.9995
	21	3.72	8.33	2.24	20.0190	1.0485	0.9998
	22	0.85	2.32	2.72	40.3655	1.0060	0.9995
	23	5.40	11.25	2.09	8.3329	1.1509	0.9998
	24	3.42	8.19	2.40	11.4457	1.0065	1.0000
	25	2.29	5.09	2.23	18.4089	1.0784	0.9992

Table 2 shows the drying process parameters under different drying conditions. Alfalfa's porous nature allows hot air to penetrate the material layer, promoting external water evaporation and making the shape parameter β less sensitive to layer thickness. In hot air drying, β ranged from 0.9 to 1.0, indicating the significant impact of external water evaporation. Unlike solid materials, convective drying in alfalfa mainly occurs on the outer surface, influenced by thickness more than temperature. Infrared drying exhibited β values of 0.73 to 0.83, smaller than for solid materials. The main heat source in infrared drying is radiation, with internal moisture migration driven by infrared radiation. The β of infrared-hot air combined drying was greater than 1.0. It indicated that no matter how the radiation power and space changed in combined drying, the total drying process was determined by internal and external moisture diffusion, and was consistent with its drying principle (*Huang, Li, Wang & Wan, 2021*). The α in infrared drying was positively correlated with material layer thickness, air velocity, and radiation height and negatively correlated with radiation power.

For alfalfa, the effective water diffusion coefficient range under different drying methods was $(1.91\sim 54.0)\times10^{-9}m^2/s$, which was within the normal range of agricultural and sideline products ($10^{-12}\sim10^{-8}$ m^2/s)(*Çağlar, Toğrul & Toğrul, 2009*). The estimated moisture diffusivity was $(1.19\sim 11.3)\times10^{-8}m^2/s$. Overall, compared to hot air and infrared drying, the moisture diffusion coefficient is high in infrared-hot air combined drying, which is more favorable for drying. In addition, the geometric parameter Rg of alfalfa ranges from 2.09 to 4.64, with an average value of 3.37, which was different to the geometric parameter 13.1 proposed by *Marabi et al.* (*Marabi, Livings, Jacobson & Saguy*, *2003*). There are a lot of gaps between alfalfa material layers, through which the air can flow to carry out heat exchange with materials inside the material layer. And the mechanism of heat transfer and moisture transfer is quite different from that of material slicing. Therefore, for porous media layers of materials, their geometric parameters should not be simply reduced to flat materials.

Effects on the color and crude protein of dried alfalfa

Fig. 3 showed the images of alfalfa under different drying conditions. The stems of alfalfa after hot-air drying yellowed, and the leaves showed obvious shrinkage, dark color, and high fragmentation degree, which were unavoidable problems in hot-air drying (*Huang et al., 2021*). After infrared drying, the alfalfa stems were yellow, but the leaves were intact, and the overall effect was similar to that of hot air drying. The leaves of alfalfa were best preserved after combined drying.



(a) Fresh alfalfa (b) Hot-air dried alfalfa (c) Infrared dried alfalfa (d) Combined dried alfalfa

Fig. 3 - Photographic views of alfalfa under different drying conditions

Table 3

Color of alfalfa and crude protein content of alfalfa under different drying conditions

Drying method	Experiment No.	L^*	a^*	b^*	ΔE	Crude protein (%)
Fresh samples		32.14 ± 1.28^{n}	-7.73 ± 0.71^{n}	14.20 ± 1.19^{bcdef}	---	19.08 ± 0.35a
Hot air drying	1	42.15 ± 0.70^{cd}	-6.02 ± 0.10^{abc}	13.08 ± 0.42^{j}	10.22 ± 0.61^{cd}	16.29 ± 0.25^{jk}
	2	41.13 ± 0.40^{defg}	-6.09 ± 0.07^{bc}	13.76 ± 0.59^{defghij}	9.17 ± 0.34^{defg}	16.74 ± 0.01^{ghi}
	3	40.33 ± 1.27^{fghi}	-6.21 ± 0.03^{cde}	13.72 ± 0.82^{defghij}	8.38 ± 1.17^{fghi}	17.08 ± 0.09^{cdefg}
	4	42.29 ± 1.74^{bc}	-5.99 ± 0.13^{abc}	14.60 ± 0.70^{abc}	10.34 ± 1.72^{bc}	16.46 ± 0.02^{ij}
	5	40.00 ± 0.35^{hi}	-6.15 ± 0.04^{cd}	13.59 ± 0.28^{efghij}	8.05 ± 0.31^{hi}	17.26 ± 0.22^{bcde}
	6	40.87 ± 0.76^{efgh}	-6.36 ± 0.06^{def}	13.75 ± 0.77^{defhij}	8.88 ± 0.77^{efgh}	16.75 ± 0.02^{ghi}
	7	41.63 ± 0.64^{cde}	-5.79 ± 0.25^{a}	13.06 ± 0.27^{j}	9.77 ± 0.59^{cde}	16.80 ± 0.01^{fghi}

Drying method	Experiment No.	L^*	a^*	b^*	ΔE	Crude protein (%)
Infrared drying	8	40.58±1.25^{efghi}	-6.39±0.07^{defg}	14.06±0.33^{cdefghi}	8.55±1.20^{fghi}	16.89±0.12^{efghi}
	9	41.63±0.26^{cde}	-6.21±0.19^{cde}	14.62±0.19^{abc}	9.62±0.27^{cde}	16.54±0.08^{hij}
	10	43.29±0.23^{ab}	-6.09±0.10^{bc}	14.87±0.19^{ab}	11.29±0.23^{ab}	15.89±0.02^{kl}
	11	41.42±0.46^{cdef}	-6.40±0.11^{efg}	14.32±0.15^{bcde}	9.38±0.45^{cdef}	16.47±0.12^{ij}
	12	41.97±0.11^{cd}	-5.98±0.09^{abc}	14.60±0.35^{abc}	9.99±0.13^{cd}	16.53±0.08^{hij}
	13	43.73±1.47^{a}	-6.08±0.04^{bc}	13.03±0.27^{j}	11.78±1.41^{a}	15.77±0.08^{l}
	14	40.20±0.89^{ghi}	-6.49±0.09^{fg}	13.12±0.37^{j}	8.25±0.85^{ghi}	16.94±0.06^{efgh}
	15	40.77±0.56^{efgh}	-5.85±0.12^{ab}	13.36±0.42^{hij}	8.88±0.54^{efgh}	16.76±0.06^{fghi}
	16	43.35±1.10^{ab}	-6.53±0.11^{fgh}	15.19±0.25^{a}	11.33±1.11^{ab}	16.01±0.10^{kl}
Combined drying	17	37.99±0.76^{kl}	-6.92±0.09^{klm}	13.42±0.24^{ghij}	5.96±0.77^{kl}	17.02±0.01^{efg}
	18	38.62±0.52^{jk}	-6.83±0.15^{jkl}	13.61±0.34^{efghij}	6.58±0.56^{jk}	17.54±0.35^{b}
	19	39.57±0.71^{ij}	-6.77±0.12^{hijk}	14.10±0.95^{cdefgh}	7.56±0.73^{ij}	17.20±0.28^{bcdef}
	20	38.22±0.30^{k}	-6.61±0.07^{ghij}	13.52±0.44^{fghij}	6.23±0.25^{k}	17.50±0.07^{bc}
	21	38.82±0.81^{jk}	-6.96±0.30^{klm}	14.15±0.47^{bcdefg}	6.77±0.83^{jk}	17.47±0.05^{bcd}
	22	40.08±0.44^{ghi}	-6.78±0.30^{ijkl}	13.33±0.41^{ij}	8.05±0.41^{hi}	16.94±0.14^{efgh}
	23	36.26±0.43^{m}	-7.13±0.10^{m}	14.16±0.19^{bcdefg}	4.17±0.41^{m}	16.46±0.17^{ij}
	24	37.09±0.97^{lm}	-7.01±0.24^{lm}	13.49±0.41^{fghij}	5.07±0.91^{lm}	17.30±0.03^{bcde}
	25	40.55±0.55^{efghi}	-6.58±0.14^{fghi}	14.46±0.22^{abcd}	8.50±0.56^{fghi}	17.05±0.12^{defg}

Note: Different letters within the same column indicate significant differences in the results.

Table 3 shows the significant impact of three different drying methods on alfalfa color difference (ΔE). As hot air temperature increased from 45°C to 65°C, ΔE decreased by 22.15%, indicating that high temperature can reduce the color change of alfalfa during hot air drying, which is contrary to the results of Xiao et al.*(Xiao et al., 2014*). But it is consistent with other references *(Tello-Ireland, Lemus-Mondaca, Vega-Gálvez, López & Di Scala, 2011; Zia & Alibas, 2021*). The reduction in color difference at higher temperatures is attributed to the occurrence of Maillard and non-enzymatic browning reactions, favored in dehydration under high temperatures and low humidity conditions. In infrared drying, radiation power significantly affects ΔE.

In infrared drying, the radiation power had the most significant effect on the color difference ΔE of alfalfa due to shortening the drying time. Based on the study of Chua et al. (*Chua, Chou, Mujumdar, Ho & Hon, 2004*), the longer time of infrared radiation leads to more drastic changes in color. The relationship between the radiation height and air speed and the color difference of alfalfa is consistent with the radiation power. The reason is that the smaller radiation height and air speed can effectively improve the drying efficiency of materials and reduce the exposure time of materials under infrared radiation. Combined drying yields smaller color differences than infrared and hot air drying. It shortens alfalfa's exposure to high-temperature environments, mitigating pigment oxidation and browning reactions. Thermal convection compensates for drying rate decreases, resulting in limited color changes.

In hot air drying, crude protein loss in alfalfa decreases with higher hot air temperature and speed. However, excessive heat, particularly above 60°C (*Chen et al., 2017*), leads to protein denaturation and inactivation. Prolonged exposure to high temperatures or prolonged low-temperature drying can both result in protein loss. In infrared drying, radiation power has the most significant effect on crude protein loss due to its impact on drying rates. The increase in air speed and radiation height reduces the accumulation of heat in the alfalfa material layer, allowing it to remain within the suitable temperature range for microbial activity for a long time during drying, resulting in protein loss. In combined drying, the radiation power controlled the hot air temperature. Although the flowed air could limit the heat inside the material, the higher hot air temperature kept the drying at a high temperature. When the radiation power was 1800 W, the hot air temperature was 72.3°C. Obviously, the denaturation of protein was intensified under this drying condition, and the rapid inactivation in a short period of time resulted in a significant decrease in the retention of crude alfalfa protein after drying. The change of hot air velocity and radiation height can change the drying time and temperature and increase the protein inactivation or decomposition rate, consistent with the change of crude protein loss caused by radiation power.

Overall, all three drying methods (hot air drying, infrared drying, and combined drying) cause significant crude protein loss in alfalfa, with combined drying showing the highest protein retention, followed by hot air drying, and then infrared drying.

Effects of different drying methods on drying time and energy consumption

The changes in drying time and energy consumption of alfalfa under different drying conditions were shown in Table 4. The infrared drying had the longest drying time, while the combined drying had the shortest drying time. This is in contrast to the fact that infrared drying can greatly reduce drying time and energy consumption as mentioned by Yang et al. *(Huang, Yang, Tang, Luo & Sunden, 2021*) , which is caused by different drying parameters, and the continuous normal temperature air in infrared drying reduces the heat inside the material and reduces the drying temperature, thereby increasing drying time and energy consumption.

Table 4

Drying time and energy consumption of alfalfa under different drying conditions

Drying method	Experiment No.	Drying time (min)	Energy consumption (kW·h)	Specific energy consumption (MJ/kg)
Hot air drying	1	200	2.77±0.23^{hi}	42.31±3.38^{h}
	2	170	3.45±0.25^{fg}	51.49±2.19^{fg}
	3	130	3.18±0.11^{gh}	46.60±2.75^{gh}
	4	320	3.71±0.18^{f}	57.93±3.56^{f}
	5	70	2.05±0.15^{jk}	30.26±2.87^{i}
	6	160	3.20±0.18^{gi}	57.92±1.27^{f}
	7	180	3.56±0.25^{fg}	45.76±1.32^{gh}
Infrared drying	8	240	6.27±0.13^{e}	96.02±1.06^{e}
	9	300	8.25±0.16^{bc}	126.35±7.29^{c}
	10	400	11.20±0.20^{a}	185.62±4.58^{a}
	11	280	7.96±0.15^{c}	153.91±4.72^{b}
	12	320	8.63±0.14^{b}	111.35±1.24^{d}
	13	460	7.41±0.13^{d}	111.84±1.42^{d}
	14	160	6.58±0.13^{e}	101.06±1.00^{e}
	15	270	7.29±0.11^{d}	115.73±3.40^{d}
	16	390	10.82±0.15^{a}	184.76±1.55^{a}
Combined drying	17	35	1.02±0.06^{n}	16.03±1.09^{l}
	18	55	1.56±0.06^{lm}	25.49±1.19^{ij}
	19	60	1.60±0.05^{lm}	25.76±0.71^{ij}
	20	55	1.57±0.07^{lm}	29.94±1.76^{i}
	21	65	1.84±0.10^{kl}	24.40±1.74^{ijk}
	22	160	2.45±0.12^{ij}	38.84±2.02^{h}
	23	25	1.06±0.05^{n}	16.93±0.60^{kl}
	24	40	1.21±0.06^{mn}	19.61±0.78^{jkl}
	25	60	1.75±0.08^{kl}	27.21±1.47^{ij}

Note: Different letters within the same column indicate significant differences in the results.

Among the three drying methods, the energy consumption ranging from large to small was infrared drying, hot air drying, and combined drying, which kept consistent with the changing trend of drying time. The infrared heating plate was continuous heated, and its power consumption is proportional to the drying time. In the combined drying, the heat in the hot air came from the heat dissipated by infrared radiation when drying materials, which improved the energy utilization rate and shortened the drying time. But in hot air drying and infrared drying, the drying time increased first and then decreased with the increase of air velocity and radiation power, respectively. In hot air drying, increasing the hot air flow rate could reduce the heating time of air and the rate of convection heat transfer. Consequently, the overall energy consumption increased. In addition, the change of feeding layer thickness in the three drying modes has no significant effect on the dryer's energy consumption.

Although the tray area is normalized, the maximum load of the test bench has not been reached. Hence, the specific energy consumption of the test bench is still large, and the unit energy consumption has a significant correlation with the change in material thickness.

Analysis of optimal parameters based on SWARA-EM

Evaluate the optimal drying method through the hybrid weight method of SWARA-EM. The fuzzy weight of SWARA was corrected by the EM method, and the final correction weight was obtained and shown in Table 5.

Table 5 Indicator weights based on SWARA-EM

Evaluation indicators	Objective weight (ξ_j)	Fuzzy weight (ω_j)	Fixed weight (λ_j)
Specific energy consumption (MJ/kg) A_1	0.28	0.30	0.33
Crude protein (%) A_2	0.27	0.30	0.32
The color difference value A_3	0.19	0.21	0.15
Drying time (min) A_4	0.26	0.18	0.19

The final weight corresponding to specific energy consumption (A_1), crude protein (A_2), color difference value (A_3), and drying time (A_4) were 0.33, 0.32, 0.15, and 0.19, respectively. The normalized data were used for calculation. The comprehensive evaluation index of alfalfa under different drying conditions was obtained, as shown in Fig. 4.

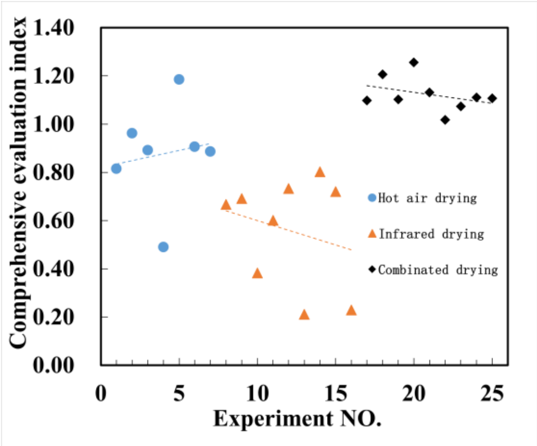


Fig. 4 - Comprehensive evaluation index based on SWARA-EM method

As can be seen from Fig. 4, the comprehensive evaluation index of alfalfa drying after combined drying is between 1.00 and 1.30, which is overall higher than hot air drying and infrared drying. The comprehensive evaluation index of hot air drying has a larger span, between 0.40 and 1.20. Under optimal drying conditions, the effect is even higher than some of the combined drying, but the overall effect is still lower than the combined drying; the comprehensive evaluation index of infrared drying is between 0.20 and 0.90, and the overall effect is lower than hot air drying and combined drying. Therefore, among the three drying methods compared, infrared-hot air combined drying has the potential to dry alfalfa with high efficiency and high quality.

The comprehensive evaluation index of Experiment NO.5 is better than that of the partial combined drying method. This is due to the higher hot air temperature shortening the drying time and reducing energy consumption. Compared with enzymatic browning and Maillard reaction caused by temperature changes, significantly reducing drying time has a more significant impact on color; it also reduces the time the material is exposed to high temperature environments, thereby improving the retention of crude protein. Therefore, the comprehensive evaluation index of test 5 is better than that of partial combined drying.

CONCLUSIONS

This study delved into the thin-layer drying characteristics of various methods applied to alfalfa. Remarkably, the combined drying method efficiently reduced the moisture content of alfalfa from 77.55% to less than 10% within a mere 25 minutes. Comparing these three drying methods, combined drying incurred minimal overall color loss in alfalfa, with the lowest color difference value recorded at 4.17, while infrared drying caused the most significant color loss, with a maximum color difference value of 11.78. Under varying drying parameters in the combined drying approach, the overall crude protein loss in alfalfa remained minimal, with a mere 1.54 percentage point reduction, surpassing the performance of hot air and infrared drying methods. In line with the Multi-Criteria Decision-Making analysis, it is evident that combined infrared-hot air drying technology holds promise in enhancing both the efficiency and quality of alfalfa drying processes.

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