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Experimental Study on Drying Characteristics of Alfalfa Hay Bales Using Hot Air Convection

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Abstract: Alfalfa hay bale drying technology can effectively reduce alfalfa leaf loss and improve forage quality. However, due to the large volume and high density of fresh-stored hay bales, deep-level drying is uneven, leading to nutrient loss in alfalfa. To address these issues, a hay bale drying test bench was constructed to systematically investigate the effects of initial moisture content, bale density, drying temperature, and air velocity on drying performance. The results showed that when the hot air temperature was 70 °C and the air velocity was 2 m/s, the average moisture content of hay bales with an initial moisture content of 25% (w.b.) could be reduced to 17% (w.b.) within 1.5 h, with a drying efficiency of 26.67 kg/h. However, increasing the bale density from 127.95 kg/m^3 to 144.15 kg/m^3 prolongs the drying time by 50% (w.b.). Batch drying of multiple bales further reduces drying efficiency due to increased airflow resistance. The problem of uneven drying is significant, especially when hot air is introduced in the horizontal direction. Therefore, the precise control of drying parameters such as temperature, airflow direction, and bale density is essential for achieving uniform moisture reduction. These findings provide important theoretical support for the efficient drying of alfalfa hay bales.

Keywords: drying efficiency; moisture content; uniformity; thermal efficiency

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1. Introduction

Alfalfa, as a nutritious and highly adaptable forage crop, plays a significant role in enhancing the efficiency of livestock production and promoting ecological protection [1]. With the rapid increase in demand for livestock and dairy products, the cultivation of alfalfa in China has been growing annually, and the quality of alfalfa hay has attracted widespread attention [2]. Currently, the primary method for harvesting and processing alfalfa hay is field drying. After mowing, alfalfa is left to dry in the field until its moisture content reaches the safe level of 14–17% (w.b.). It is then baled and stored mechanically. However, during the mechanical baling and collection process following field drying, a significant amount of the nutritious leaves and flowers of the alfalfa hay are lost, falling into the field. The proportion of loss ranges from one-quarter to one-third. In rainy weather, prolonged moisture exposure exacerbates nutrient degradation and microbial spoilage, leading to even greater losses in both yield and nutritional quality [3]. When the moisture content of freshly mowed alfalfa is around 40% (w.b.), the toughness of the connection between the leaves and stems is at its strongest. Baling operations at this stage can effectively preserve the most nutritious parts of the alfalfa—its flowers and leaves—within the bales. After baling, the density of alfalfa hay bales ranges from 110 to 180 kg/m^3. Alfalfa hay bales with a moisture content of 40% (w.b.) are still subject to respiration and oxidation. Artificial drying methods are required to quickly reduce the moisture content to below 20% (w.b.). Otherwise, the interior of the bales will turn yellow and rot, leading to a decline in the quality of the alfalfa hay [4]. Therefore, researching efficient and controllable drying methods is of great significance for reducing the loss of nutrients in alfalfa, improving the quality of dried hay, providing high-quality feed for the livestock industry, and promoting the large-scale and modern development of the alfalfa industry.

Research on alfalfa drying technology mainly focuses on the optimization of the initial state, improvement of drying methods, and precise control of drying parameters. In the current production process of alfalfa hay, the initial state of alfalfa is the first issue to be considered, for example, the initial moisture content, which is generally affected by harvesting methods [5,6] and harvesting time [7]. According to research by Luchini [8], a higher initial moisture content during ensiling can lead to increased contents of neutral detergent fiber (NDF) and acid detergent fiber (ADF) in alfalfa, thereby affecting its nutritional value. Additionally, the uniformity of the hay bales is also a key factor affecting drying efficiency. Roman et al. [9] found that a uniform bale structure helps hot air penetrate better, thus improving the drying effect through their research on round bale drying equipment. Gunhan [10] pointed out that the moisture content of thick-layer alfalfa can be reduced from 80% to 10% in just 40 min at an air temperature of 200 °C, but as the thickness of the alfalfa increases, the drying efficiency decreases significantly. Qian [11] studied the impact of alfalfa hay bales on solar drying characteristics and found that the lower the bale density, the better the drying effect. In terms of drying methods, common drying technologies currently include natural drying [12], hot air drying [13], infrared hot air drying [14], microwave drying [15], and solar drying [16]. Natural drying, although low-cost, generally has a drying rate that is positively correlated with solar radiation and is highly restricted by weather conditions, resulting in long drying times and severe nutrient loss [17]. In comparison, hot air drying and infrared hot air drying have attracted more attention due to their high efficiency and controllability. Although they have higher energy consumption compared to microwave drying and other technologies, they are more favorable for preserving nutrients such as proteins [18]. By optimizing drying parameters, drying efficiency can be further improved, and the quality of alfalfa can be better retained [19]. Neres [20] pointed out that different drying management methods have a significant impact on alfalfa hay production. Alfalfa hay dried in the sun and turned over has poorer quality, mainly due to leaf shedding, which reduces the proportion of nutrient-rich leaves in the final hay, thereby lowering its overall nutritional content. Wang [21] studied the drying process of high-moisture whole alfalfa bales and found that time has the greatest impact on bale moisture content, followed by temperature and then air velocity. The interaction between air velocity and drying time is the most significant. Sokhansanj [22] evaluated color differences and protein solubility and concluded that the optimal temperature for hot air drying is 175 °C, at which the quality and nutritional content of alfalfa are better preserved. Patil R T [23] conducted hot air drying experiments on alfalfa at temperatures of 40 °C and 120 °C and found that when the medium temperature increases by 10 °C, the drying speed can be increased by 10–15%. Sokhansanj [24] found through computer simulation and field experiments that when the inlet air temperature is between 500 °C and 800 °C, the temperature of the drying grass segments can reach 90 °C or even higher, indicating that high-temperature drying media can significantly improve drying efficiency. The relative humidity of hot air also has a certain impact on the quality of alfalfa and drying efficiency. Xu et al. [25] found that when the relative humidity of hot air is 20% (w.b.), the drying time of the samples is the shortest, while at a relative humidity of 40% (w.b.), the color difference ΔE is the smallest when compared to the fresh sample. Babu [26] found that the moisture concentration at different depths of the leaves during the drying process has a significant impact on the drying mechanism, with more moisture removed near the surface than in the middle layer, indicating a high initial moisture removal rate that gradually decreases as the drying process continues.

Despite numerous studies discussing optimization methods for the uniformity of alfalfa hay bales, involving the initial moisture content, drying temperature, and other processes and parameters, there is still a lack of systematic research on how to precisely control drying parameters to achieve the best drying effect for alfalfa with different initial states. This study uses hay bale drying and test equipment to systematically investigate the effects of the initial moisture content (25–30%), bale density (110–180 kg/m^3), drying temperature (50–90 °C), and air velocity (1–3 m/s) on the drying performance of alfalfa hay bales, including drying rate and uniformity, analyzes energy consumption patterns under different drying conditions, and discusses the relationship between bale density and airflow resistance. This work aims to provide valuable references for the production of high-quality alfalfa hay in livestock production.

2. Materials and Methods

2.1. Experimental Materials

This study was conducted in the Experimental Building of the Inner Mongolia University of Technology (see Figure 1), Hohhot, Inner Mongolia Autonomous Region, China (111°40′ E, 40°50′ N). The alfalfa used in the experiment was harvested in the first flowering stage, leaving a stubble height of ~5 cm after cutting. Then, it is immediately subjected to pretreatment: manual sorting (removal of 5% damaged samples), shade drying (25 °C, 50% RH, 2 h), and hydraulic baling (10 kN pressure). The initial moisture content of fresh alfalfa was 40.2 ± 1.8% (w.b.), which was reduced to 25–30% (w.b.) after pretreatment.

Figure 1. Field diagram of the hay bale drying test.

2.2. Experimental Setup

The alfalfa hay bales used in the experiment were rectangular prisms with maximum dimensions of 0.85 m (length) × 0.45 m (width) × 0.36 m (height). The hay bale is placed on the load-bearing plate. The air outlet channel is installed above the hay bale, and the upper and lower air outlets are tightly pressed against the upper and lower ends of the hay bale to carry out the drying of the hay bale.

The design of the hay bale drying test bench is shown in Figure 2. In accordance with the experimental requirements, the inside of the test bench is equipped with temperature sensors (Huagong Tech., Wuhan, China), air velocity sensors (Hengxin AZ, Shenzhen, China), flow sensors (Elettrotec, Wenzhou, China), load sensors (Keli Sensing, Ningbo, China), and other devices. The locations of the sensors are shown in Figure 2. During the hay bale drying process, a fan is used to dry the bales through air convection. In the drying characteristics test of the bales, the fan speed is controlled by a frequency converter and a programmable logic controller (PLC, Siemens, Suzhou, China), with an upper-level computer. The temperature controller (PID, Siemens, Suzhou, China) can be used to control the electric air heater through the computer to regulate the temperature of the drying air. Sensors for air temperature, air pressure, air velocity, and flow rate are installed in the air inlet chamber and the air duct to monitor the state parameters of the drying work medium. At the same time, temperature and humidity sensors are inserted into the interior of the alfalfa hay bales to measure the temperature and humidity in various regions inside the bales. The load sensor under the bales monitors the weight of the bales in real time. All measurement data are stored and analyzed through the upper-level computer. The specific technical parameters of the test bench are shown in Table 1.

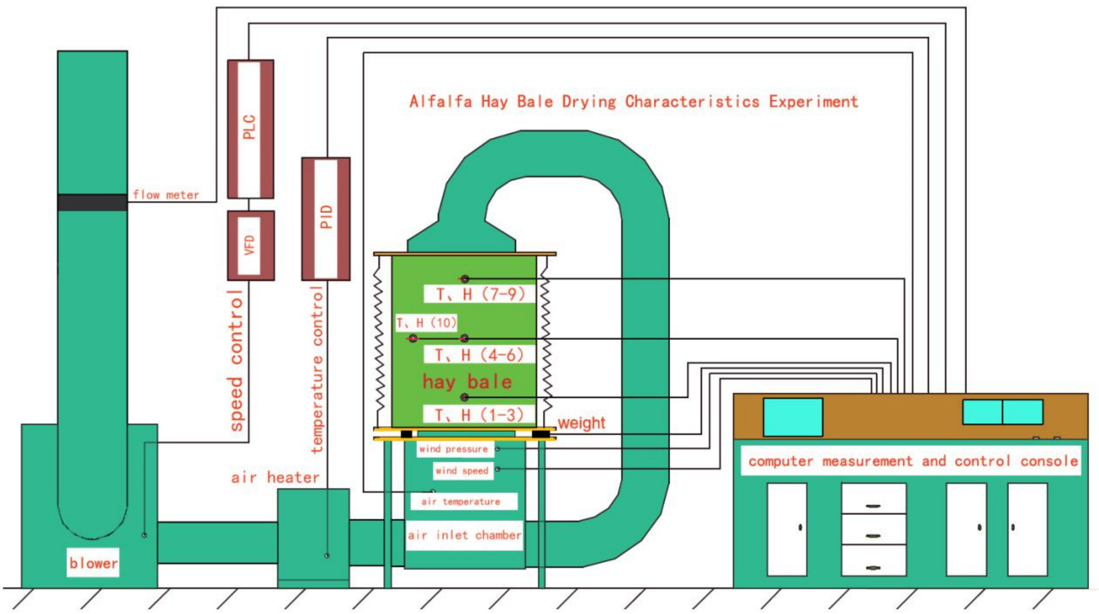

Figure 2. Diagram of the measurement and control system for the baled forage drying test bench.

Table 1. Technical parameters of the hay bale drying and test equipment.

Items	Technical Parameters
Bale size (L × W × H)	0.85 × 0.45 × 0.36 (m)
Quantity of dry bales in a batch	2
Fan flow rate	4600 m^3/h
Fan power	3 kW
Air outlet size	500 × 160 (mm)
Full pressure	1460 Pa
Drying air temperature	70 °C

2.3. Experimental Procedure

The experiment started on 14 July 2024 and ended on 3 August 2024, lasting a total of 20 days. The bales awaiting the drying process were stored in a well-ventilated, shaded area with an average ambient temperature of 20 °C and relative humidity of 60% (w.b.). The bales were placed on pallets to ensure proper air circulation and prevent moisture absorption from the ground. These storage conditions were selected to simulate typical pre-drying storage practices and maintain the initial moisture content of the bales before the drying experiments.

At the beginning of the experiment, the initial state of the hay bales was measured, including their weight, density, and initial moisture content. The fan and electric heater were then activated to begin the drying process, and the experiment time and drying conditions were recorded. Every hour, the fan was stopped to measure the real-time moisture content of the hay bales, and the weight of the bales was monitored and recorded. After the measurements, the fan was restarted to continue the drying process. The drying conditions, including drying air temperature and drying air velocity, were measured and recorded, along with the drying time. After a certain period, the drying state of the hay bales was assessed again. The drying process continued, and the above experimental operations were repeated until the drying of the hay bales was completed.

After completion of the drying, each hay bale was unbundled and sliced into 7–8 uniform sections (thickness = 5 cm) along the longitudinal axis using a hydraulic cutting machine (Jianke, Ningbo, China) with a precision of 0.2 cm. The slicing process aims to analyze cross-sectional moisture distribution (Figure 3).

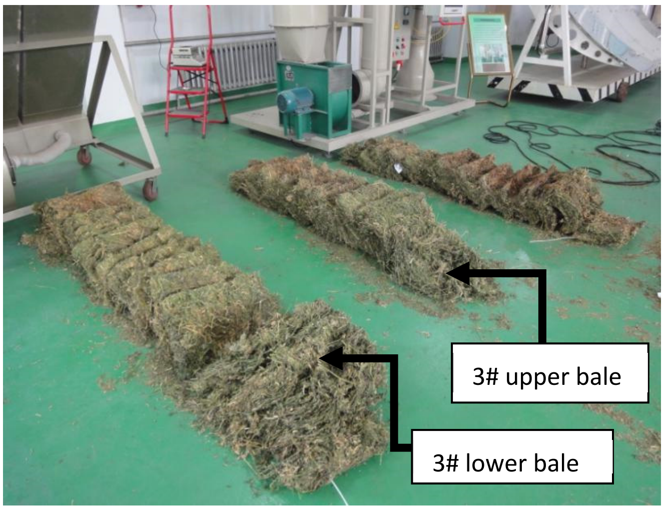

Figure 3. Dried samples after unbundling and slicing post-drying.

2.4. Calculation Methods for Key Parameters

Initial moisture content of hay bales: samples were collected from five positions across the three cross-sections shown in Figure 2. These samples were chopped and mixed thoroughly, and a total of 50 g was taken as the weighing sample for moisture content determination. This was dries continuously at a temperature of 105 °C for 4 h. The calculation formula is as follows:

$$\mathrm{H} = \frac{w_0 - w_1}{w_0} \times 100\% \quad (1)$$

where H is the initial moisture content (wet basis) of the hay bale, w_0 is the adjusted bale weight after sample removal before drying (g), and w_1 is the adjusted bale weight after sample removal after drying (g).

Real-time moisture content of hay bales: under the same experimental conditions, multiple samples are taken and the average value is calculated. The formula is as follows:

$$H_t = H_0 - \frac{w_t - w_0}{w_0} \times 100\% \quad (2)$$

where H_t is the real-time moisture content of the hay bale at t minutes, H_0 is the initial moisture content of the hay bale, and w_t is the adjusted bale weight after sample removal at t.

3. Results and Discussion

3.1. Overall Trend of the Decline in the Moisture Content of Hay Bales

A total of eight drying experiments (numbered 1# to 8#) were conducted on alfalfa hay bales to examine the changes in the moisture content of different bales under various drying methods, drying temperatures, and drying durations, as shown in Tables 2 and 3. And all the data were calculated and plotted using Excel (Ver. 2019, Microsoft, Redmond, WA, USA).

The experiment adopted 70 °C as the drying temperature. The study by Ihediwa [17] pointed out that the drying rate of oven drying at 70 °C is significantly higher than that at low temperatures (such as 40 °C), while higher temperatures may lead to nutrient loss (such as protein degradation). Under the same drying temperature, significant differences in drying efficiency occurred among different forms of hay bale drying, which has a significant effect on the drying intensity and ultimately affects the drying efficiency. As is shown in Figures 4 and 5, when the drying intensity is sufficient to allow hot air to penetrate the bales and remove moisture, the initial density of the bales is related to the drying rate, but the impact is relatively small. When the hot air temperature is around 70 °C and the air velocity is around 2 m/s, with an initial moisture content of about 30%, the average moisture content of two bales weighing 19 kg and 20 kg, as well as one bale weighing 40 kg, can be reduced to 20% within 2 h. The drying efficiency is 20 kg/h of the original grass. For two bales weighing 25 kg each, the average moisture content can be reduced to 17% (w.b.) within 2 h, with a drying efficiency of 25 kg/h of the original grass. For two bales weighing 27 kg each, the average moisture content can be reduced to 17% (w.b.) within 3 h, with a drying efficiency of 18 kg/h of the original grass. However, when the drying intensity is insufficient and hot air cannot penetrate the bales to remove moisture, the initial density of the bales has a significant impact on the drying rate. For two bales weighing 40 kg each, the average moisture content of the upper bale can be reduced to 17% (w.b.) in about 5 h, while the lower bale's moisture content drops to 25% (w.b.) and then changes very slowly. On July 17, during a drying experiment with three bales, the upper and lower bales had a moisture content of about 30% (w.b.) and weighed 33 kg each, while the middle bale was an old, already-dried bale. After 2 h, the moisture content remained at 27% (w.b.), indicating that it could not be dried further. Therefore, it is evident that when the drying intensity is sufficient, as the bale density and the amount of grass increase, the drying efficiency of the forage decreases. When the drying intensity is insufficient and the bale density is high, such as in the case of drying two 40 kg bales, the drying intensity at the upper outlet is greater than that at the lower outlet. The hot air tends to accumulate at the upper bale outlet, where the density is relatively lower, leading to particularly slow drying of the other bale. In the case of drying three bales weighing 33 kg each, with the middle bale being an already-dried bale, the upper and lower bales dried very slowly, almost at a standstill. These findings underscore the importance of optimizing drying conditions to ensure sufficient drying intensity, as when the drying intensity is insufficient, the initial density of the bales becomes a significant factor, leading to uneven and inefficient drying.

This highlights the need for careful control of drying parameters such as temperature, air velocity, and bale density to achieve uniform and efficient drying.

Recent studies [18] have indicated that the effect of the initial moisture content on the drying rate is highly dependent on the material's structure and is not universally applicable. The higher the initial moisture content, the longer the required drying time. There is no significant relationship between the initial moisture content and the drying rate.

Table 2. Effect of drying process on moisture content.

Treatment	Drying Form of Hay Bales	Drying Duration (h)	Hay Bales	Initial Weight (kg)	Initial Moisture Content (%(w.b.))	Final Weight (kg)	Final Moisture Content (%(w.b.))
1	Two bales heated from top and bottom	2	Upper bale	34.96	27.058	34.78	26.94
			Lower bale	32.92	29.522	31.54	26.71
2	Two bales heated from top and bottom	3.5	Upper bale	24.23	33.97	18.45	14.00
			Lower bale	25.06	31.65	22.7	24.91
3	Two bales heated from top and bottom	2	Upper bale	29.09	27.86	26.3	20.58
			Lower bale	29.53	26.34	24.9	13.41
4	Two bales heated from top and bottom	3	Upper bale	27.78	27.02	24.01	16.40
			Lower bale	27.98	26.34	24.43	16.01
5	Two bales heated from top and bottom	4	Upper bale	17.62	32.02	13.61	16.90
			Lower bale	19.85	29.27	16.00	14.00
6	Two bales heated from top and bottom	5	Upper bale	40.03	26.46	34.98	18.28
			Lower bale	42.55	30.16	39.50	25.71
7	One bale heated from top and bottom	4	Bale	39.3	26.07	33.52	13.96
8	One bale heated from left and right	4	Bale	40.18	26.46	33.78	13.08

Table 3. Data of the drying process of the 5# treatment.

Drying Time	Drying Hay Bales	Weight (kg)	Density (kg/m^3)	Moisture Content (%(w.b.))	Drying Temperature (°C)	Flow Velocity (m/s)
Initial	Upper Bale	17.62	127.95	32.02	68.10	2.70
	Lower Bale	19.85	144.15	29.27		
1 h	Upper Bale	16.07	116.70	25.82	73.50	2.90
	Lower Bale	17.90	157.33	22.00		
2 h	Upper Bale	15.23	110.60	21.16	73.10	3.10
	Lower Bale	16.96	123.16	17.94		
3 h	Upper Bale	14.48	105.15	18.46	72.70	3.20
	Lower Bale	16.33	118.59	15.11		
4 h	Upper Bale	13.61	98.83	16.90	72.50	3.30
	Lower Bale	16.00	116.19	14.00		

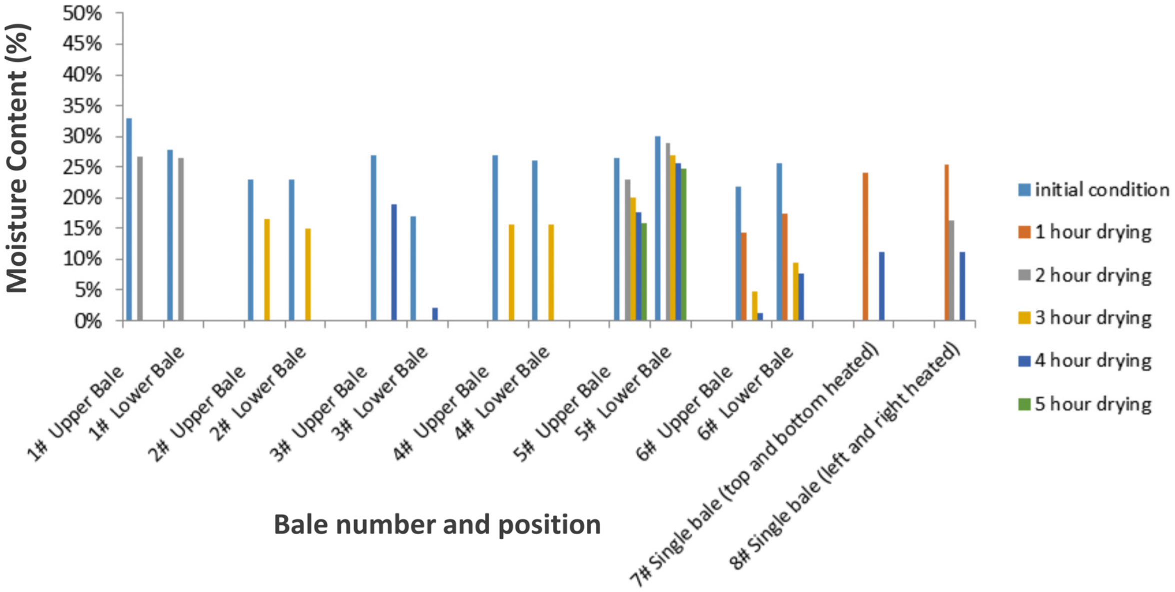

Figure 4. Trend of decreasing overall moisture contents of dried hay bales.

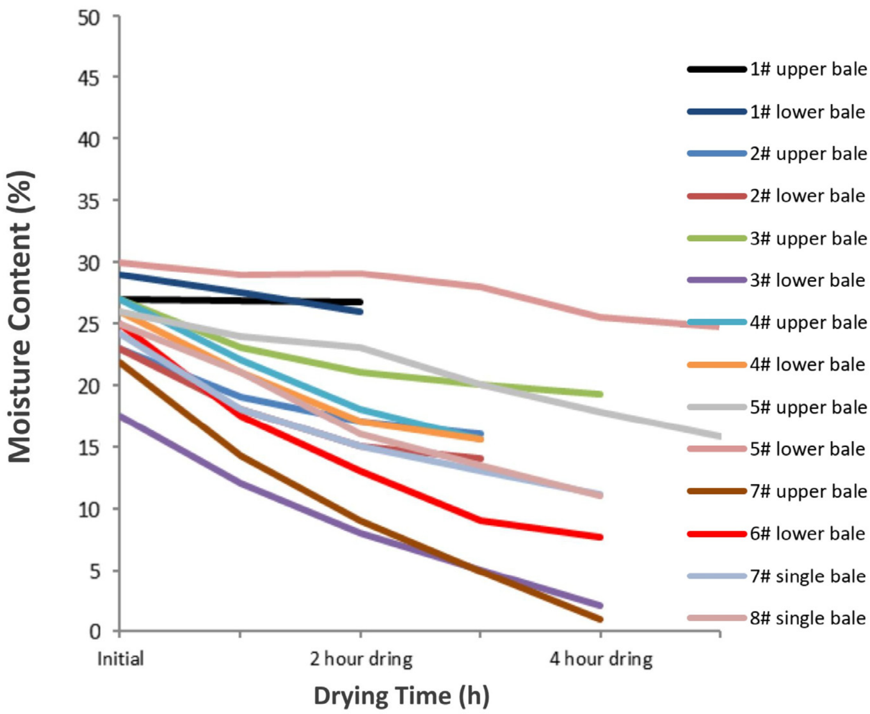

Figure 5. Trend of moisture content reductions in hay bales.

3.2. Moisture Distribution of Different Hay Bale Cross-Sections

Based on the sliced bale samples prepared in Section 2.3, the cross-sectional moisture distribution was analyzed after the drying process was completed. The hay bales were opened and divided into 7–8 uniform slices along the length of the bale. To observe the uniformity of drying, the moisture content of alfalfa within each slice's cross-sectional area was measured. The 450 mm direction was used as the x-coordinate, and the 360 mm direction as the y-coordinate. Since a moisture content below 20% (w.b.) meets the safe storage requirements for alfalfa hay, critical moisture coordinate points at 20% (w.b.) were plotted to create a cross-sectional moisture distribution diagram, as is shown in Figures 6–8.

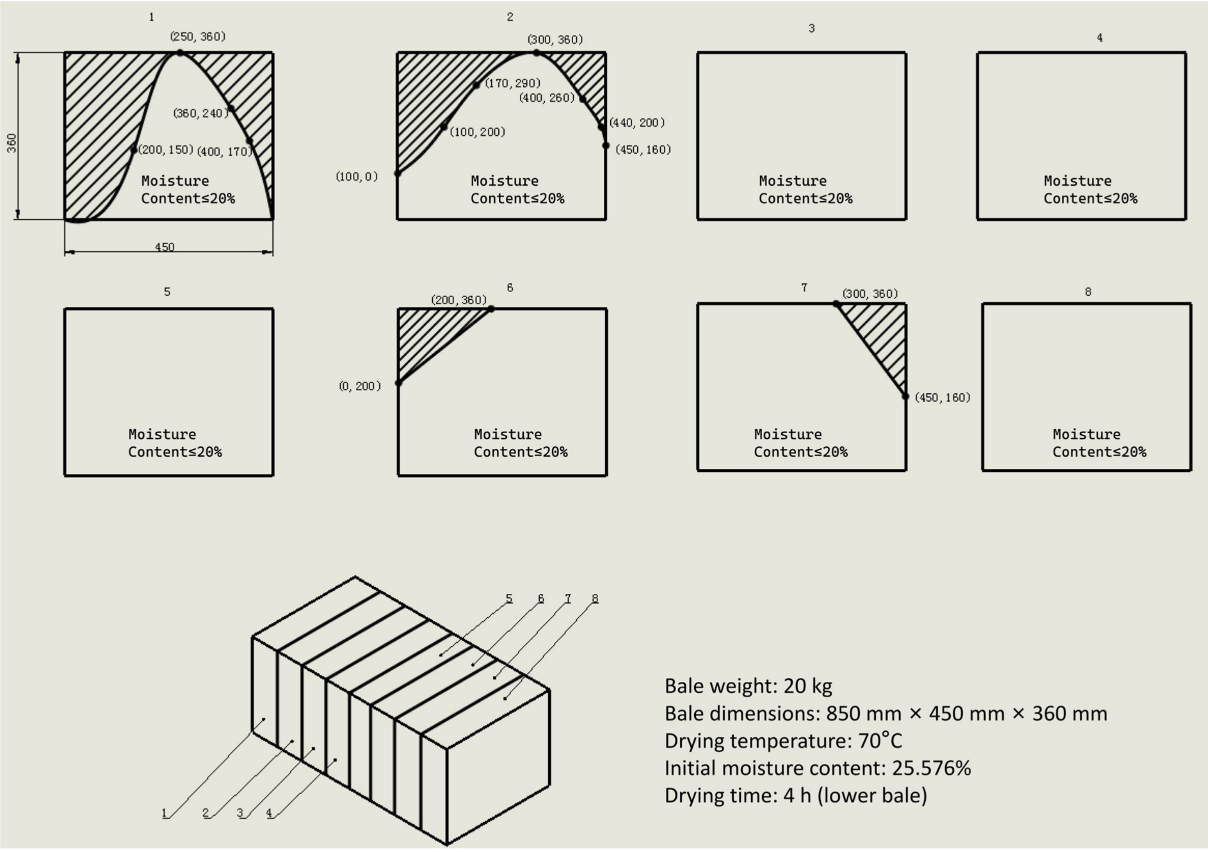

Figure 6. Cross-sectional moisture distribution diagram of the #5 bale (lower bale).

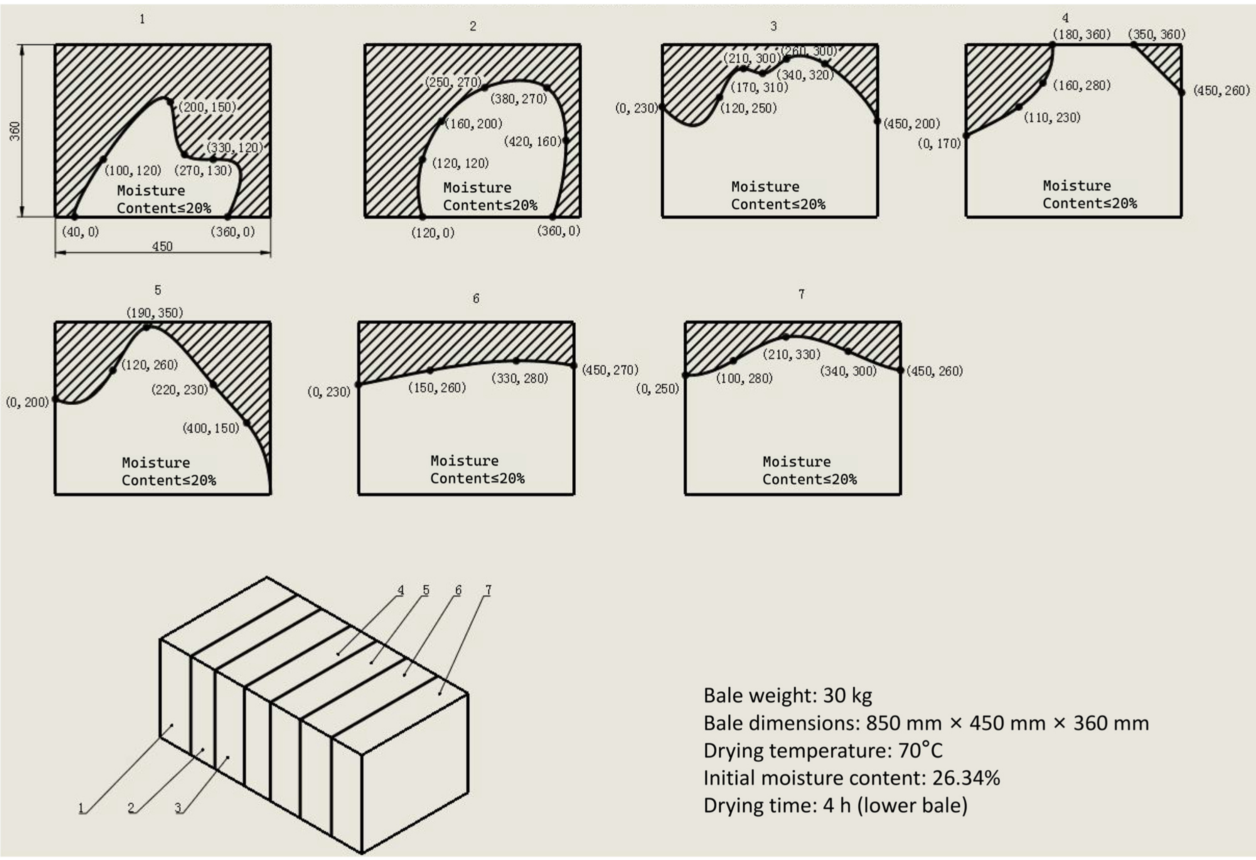

Figure 7. Cross-sectional moisture distribution diagram of the #3 bale (lower bale).

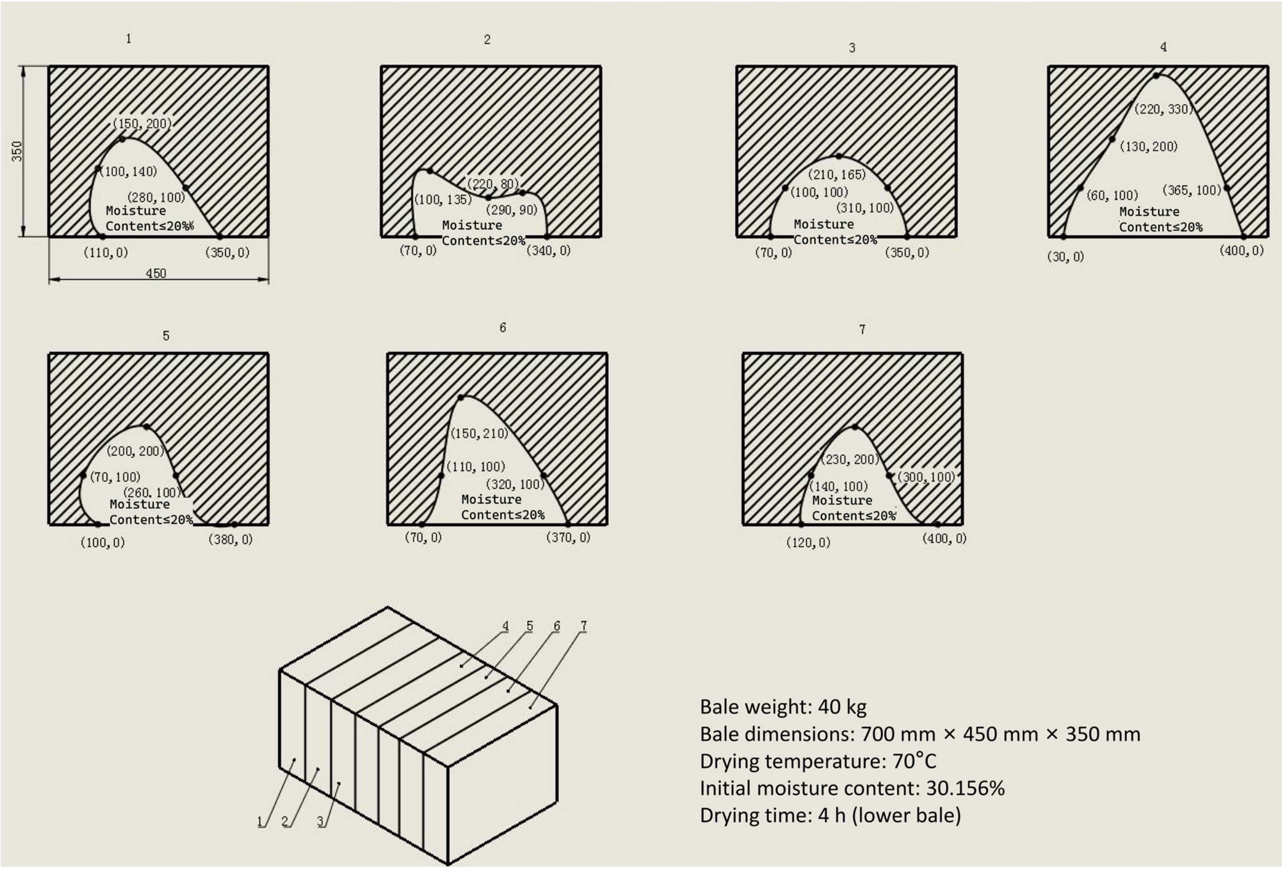

Figure 8. Cross-sectional moisture distribution diagram of the #6 bale (lower bale).

The most significant issue encountered in hay bale drying is the unevenness of the drying process. The previously mentioned moisture content refers to the average value. In reality, after drying is completed, the moisture content varies across different parts of the bale. Even though the average moisture content of the bale has dropped below 17% (w.b.), some areas still have a moisture content above 20% (w.b.), while others are below 10% (w.b.). Analysis of the cross-sectional diagram of uneven drying shows that drying begins at the upper and lower air outlets and gradually expands outward. The central part of the bale dries progressively. Under the driving force of hot air, moisture gradually moves towards the ends of the bale. During this movement, the density of the initially dried areas decreases, leading to reduced wind resistance and short-circuiting phenomena. This results in a diminished driving force for moisture movement. Consequently, the cross-sectional diagram reveals that the ends of the bale always have areas with moisture contents above 20% (w.b.). When the driving force of hot air is insufficient, the speed of moisture movement becomes extremely slow and eventually stagnates. For example, in the cross-sectional diagram of two 40 kg hay bales, after 5 h of drying, only two small, unconnected areas are formed around the air outlets. Similar to the mechanism of the formation of high-moisture regions at both ends during the later stage of drying in this experiment, Dana's [27] computational fluid dynamics (CFD) simulation also indicated that low stem porosity can hinder moisture migration and that local density can lead to issues such as short-circuiting.

The drying effects of different end faces of hay bales vary. Data charts show that blowing hot air into the cross-sectional end face of the hay is more effective than blowing it into the horizontal plane. The effectiveness of blowing hot air on the end face of the cross-section compared to the horizontal plane is attributed to the following factors: the end face of the cross-section provides a more direct pathway for hot air to penetrate the fiber bundles of the hay. This allows for more efficient moisture removal compared to blowing air horizontally, where the waxy surface of the hay can impede air flow. The compressed texture of the hay bale facilitates the movement of hot air along the fibers, enhancing the drying process. This is particularly effective when the air is introduced at the end face, as it aligns with the natural orientation of the fibers.

3.3. Analysis of Drying Characteristics for Different Bales and Optimization Proposal

Based on the experimental results, when the hot air temperature is around 70 °C and the air velocity is around 2 m/s, with an initial moisture content of about 25% (w.b.), the average moisture content of two bales weighing 19 kg and 20 kg, as well as one bale weighing 40 kg, can be reduced to 17% (w.b.) within 1.5 h. The drying efficiency is 26.67 kg/h of the original grass. For two bales weighing 25 kg each, the average moisture content can be reduced to 17% (w.b.) within 2 h, with a drying efficiency of 25 kg/h of the original grass. For two bales weighing 27 kg each, the average moisture content can be reduced to 17% (w.b.) within 4 h, with a drying efficiency of 13.5 kg/h of the original grass. Under the aforementioned drying conditions, two bales weighing 40 kg each cannot be dried effectively. When drying three bales weighing 33 kg each, with the middle bale being an already-dried bale, the upper and lower bales dry very slowly, almost at a standstill.

From the experimental data, it can be seen that the drying process of forage is essentially a process of moisture movement, transfer, and evaporation. In this process, only two factors affect drying: the first is the driving force that generates moisture movement, transfer, and evaporation; the second is the resistance encountered by moisture during its movement, transfer, and evaporation. The interaction of these two factors affects the drying process. Therefore, it is necessary to consider increasing the driving force by raising the air pressure and temperature, as well as reducing resistance by adjusting the amount of forage dried per batch, bale density, and the position of the end face, where hot air is blown into the forage. It is also important to reduce the unevenness of the driving force and resistance to avoid short-circuiting in mass transfer. Previous studies have made attempts with regard both aspects. For example, the oven-drying study by Ihediwa [17], which increased the driving force (temperature above 70 °C), significantly shortened the drying time. Tuğrul's [6] research used a disc mower to crush stems and reduce density, thereby lowering the resistance to accelerate drying. Meanwhile, Babu [26] controlled the relative humidity and recirculating airflow to reduce the retention of humid air, enhance the moisture gradient, and improve drying efficiency and uniformity.

Based on the principles derived from the existing experimental data above, as well as the literature review, potential solutions for the following two schemes can be proposed:

Scheme 1 (see Figure 9a): Increase the driving force for moisture movement, transfer, and evaporation by raising the fan's air pressure to ensure that the drying air penetrates through the bales. Enhance the moisture gradient between the forage and the external environment; as the gradient increases, the driving force becomes stronger. Corresponding measures include raising the temperature of the drying air, reducing the humidity of the drying air, or adding a suction device. The structure can be designed to enclose the bales on all sides, with the upper and lower end faces serving as the air inlet and outlet, respectively. One side is the air inlet, where a blower introduces hot air, preferably after passing through a chemical desiccant to dehumidify the air before blowing it into the bales. The other side is the air outlet, where another set of exhaust fans quickly removes the moist air blown out.

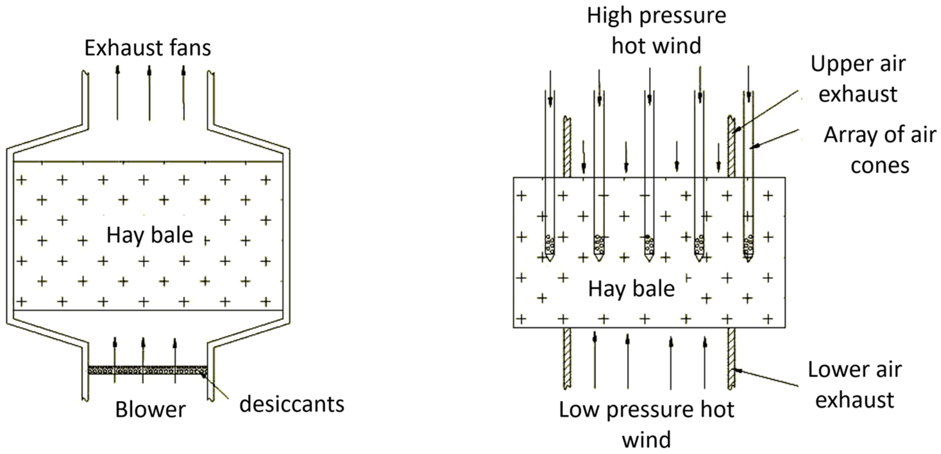

Figure 9. Optimization of the alfalfa hot air drying scheme: (**a**) increase the driving force; (**b**) reduce the resistance.

Scheme 2 (see Figure 9b): Reduce the resistance encountered by moisture during its movement, transfer, and evaporation by decreasing the density of the bales. The advantage of this method is that the drying efficiency will increase, meaning that more forage can be dried in the same amount of time. However, the disadvantage is that the deformation of the bales will be more significant, increasing the space required for transportation and storage after drying. Additionally, the frequency of loading and unloading will increase, leading to a rise in the non-drying time (time spent on loading and unloading operations) and higher labor intensity and costs.

The fundamental reason for the uneven drying of bales is the varying resistance encountered by moisture during its movement, transfer, and evaporation within the bales. To address the issue of unevenness, it is necessary to artificially control the resistance in different parts of the bales, thereby regulating the drying speed of each part to achieve uniform drying. The corresponding structure can be designed with two separate air supply systems: one high-pressure system and one low-pressure system. The low-pressure system functions as before, blowing hot air into the upper and lower end faces of the bales through the air outlets. The high-pressure system, which is newly designed, includes an array of air cones installed on the lifting device. Each air cone has a sharp tip that can easily be inserted into the middle of the bale, with small holes on the side walls. The interior of the air cones is supplied with high-pressure hot air from the high-pressure system. During operation, after the bales are loaded, the hydraulic lifting system lowers, and the array of air cones is inserted into the bales until the air outlets clamp the two end faces of the bales. During drying, while the low-pressure system blows air onto the two end faces of the bales, the high-pressure system uses the array of air cones to intensify drying in the central area of the bales, where resistance is higher, thereby ensuring uniform drying and improving drying efficiency. This is also similar to the scheme proposed by Wang [21]. Their thermodynamic simulations showed that inserting needles of hot air into hay bales can enhance the drying efficiency. These proposed schemes will be implemented and evaluated in future work.

4. Conclusions

This study systematically clarifies the drying behavior of alfalfa bales under hot air convection, indicating that drying efficiency and uniformity are significantly influenced by multiple factors, including the hot air temperature, air velocity, and initial moisture content of the hay bales. Specifically, we found that:

(1) Temperature–efficiency tradeoff: At 70 °C and an air velocity of 2 m/s, bales with 25% initial moisture (w.b.) reached the target moisture (17% w.b.) within 1.5 h, achieving a drying efficiency of 26.67 kg/h. While higher temperatures (>70 °C) may further accelerate drying, they risk nutrient degradation.

(2) Density-dependent airflow limitation: Increasing the bale density from 127.95 to 144.15 kg/m^3 extended drying time by 50%, indicating the relationship between density and airflow resistance. This necessitates density control (<130 kg/m^3) during baling to match dryer capacity.

(3) Directional drying heterogeneity: Horizontal air supply caused severe moisture gradients, with central regions exceeding 20% (w.b.) despite surface dryness. Vertical airflow (top–bottom) partially mitigated this, suggesting directional optimization as a priority for industrial dryers.

These results demonstrate that efficient drying of dense alfalfa bales requires balancing thermal input (70 °C), airflow penetration (2 m/s), and preprocessing control (moisture $\leq$ 25%, density $\leq$ 130 kg/m^3). Future work should focus on the optimization of the drying process by increasing the driving force and reducing bale density to lower resistance for drying combined with the precise control of the key parameters, thereby improving the quality and storability of alfalfa hay bales.

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