A PRIMARY INVESTIGATION OF SEPARATING ALFALFA STEMS AND LEAVES BY CHOPPING AND BLOWING METHOD
/
苜蓿切断-气吹茎叶分离方法初步研究

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ABSTRACT

The protein content of alfalfa leaves surpasses that of stems significantly, rendering harvested alfalfa following stems-leaves separation a valuable resource for livestock feed, thus ensuring the provision of high-quality raw materials for production. This study introduces a novel process for stems-leaves separation, alongside the establishment of a suspension velocity experiment rig aimed at investigating and determining the suspension velocity of alfalfa leaves, stems, and plants across various moisture levels. The relationship among various factors including different alfalfa components, the length of lateral branches, stem lengths, Moisture Content (MC), and suspension velocity was empirically derived through experimentation. In this study, the chopping and blowing method was proposed, where the alfalfa was cut into pieces according to a certain length, and then the alfalfa was blown apart by generating airflow through a fan. To comprehensively analyze the impact of airflow velocity and cutting length on the Separation Evaluation Index, a response surface mathematical model was developed. The empirical findings indicate optimal stems and leaves separation of alfalfa when the airflow velocity reaches 4.29556 m/s, paired with a cutting length of 33.7956 mm. Conclusively, this experiment validates the efficacy of the chopping and blowing separation method for alfalfa stems and leaves segregation, thereby offering valuable insights into alfalfa stems and leaves separation practices. The outcomes of this study hold significant reference value for the broader alfalfa agricultural domain.

摘要

苜蓿的叶片蛋白质含量远远高于茎秆，进行茎叶分离收获后的苜蓿可以作为畜牧饲料提供优质的生产原料。本文采用了一种全新的工艺进行茎叶分离，搭建了悬浮速度试验台，分别研究测定了苜蓿的叶片、茎秆、植株在不同含水率情况下的悬浮速度。通过试验得出了苜蓿的不同组分、侧枝长度、茎秆长度、含水率(MC)与悬浮速度的关系。本研究提出了切断-气吹分离方法，将苜蓿按照一定的长度将其切分，再通过风机产生气流将苜蓿吹分。建立了响应面数学模型，分析了气流速度和切断长度对分离评估指数 (SEI)的影响。实验结果表明，在气流速度为4.29556m/s，切断长度为33.7956mm时，苜蓿的茎叶分离效果最好。本试验得出了切断-气吹分离法是苜蓿茎叶分离的一种可行方法，研究结果可以为苜蓿茎叶分离提供参考价值。

INTRODUCTION

Alfalfa is known as the " King of Forages "*(Liu et al., 2023)*, due to its significant role in the forage production systems. While it is renowned for its protein richness, there's a notable disparity in the nutritive value between its stems and leaves. The protein content in the leaves often surpasses that of the stems by 2-2.5 times *(Motsinger et al., 2021)*. However, traditional methods of utilizing alfalfa as feed, where the whole plant is used, have led to suboptimal nutrient utilization. Harvesting alfalfa with the separation of stems and leaves has emerged as a crucial technique for acquiring leaves protein *(Lange et al., 2023)*. By focusing on separating the valuable leaves from the stems, this method enhances the potential for utilizing alfalfa's high-protein content more efficiently.

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Presently, two primary modalities for separating alfalfa stems and leaves prevail: "post-harvest separation" and "direct separation in the field" *(Zhang et al., 2017)*. The former encompasses sieving, wind separation, and drying separation. The sieving technique employs vibrating screens to segregate dry, chopped forage stems and leaves. For instance, *Pfister (1980)* devised a technical solution involving striking, chopping, and sieving alfalfa post-harvest, subsequently segregating the fine leaves fraction from the coarse stem fraction. Wind separation exploits the differential aerodynamic properties of dry leaves and stems, with typical equipment categorized as vertical or horizontal. *Gan-Mor, et al. (1986),* demonstrated that horizontal wind separation yielded superior results, achieving a separation rate exceeding 90%. *Bilanski, et al., (1989)*, investigated the impact of material moisture content, feeding speed, wind speed, and other factors on the separation rate using horizontal wind separation equipment, offering an estimation formula for the separation rate of coarse proteins. Moreover, *Bilanski, et al., (1989)*, explored the drying separation method, achieving stems and leaves separation concomitant with artificial drying. *Adapa, et al., (2005)*, scrutinized the hot air separation method for cutting alfalfa, capable of simultaneously affecting the drying and stems and leaves separation of alfalfa. Beyond these conventional methods, some scholars have delved into stems and leaves separation techniques and equipment for post-harvest fresh forage *(Siles et al.,2015)*, aiming to transition from whole plant drying to leaf drying exclusively, thereby advancing energy conservation and efficiency goals. The "direct field separation" mode offers distinct advantages over the "post-harvest separation" approach, primarily in terms of operational simplicity and reduced nutrient loss of forage. This mode comprises two main methods: the stratified harvesting method and the segmented harvesting method. The layered harvesting method capitalizes on the natural distribution of alfalfa branches and leaves, which are predominantly concentrated in the upper part of the plant. This method involves harvesting alfalfa in staggered layers, both above and below. *Yang Zhao (2015)*, delved into determining the optimal mowing height for stratified harvesting of alfalfa, optimizing the process for maximum efficiency. In 1964, some academics pioneered the concept of segmented harvesting of alfalfa stems and leaves *(Currence, 1964 ; Currence and Buchele, 1967)*. Currence designed a double-drum alfalfa stems and leaves separation equipment, validating the feasibility of directly harvesting alfalfa leaves through field trials. These trials demonstrated that the collected leaves material had a higher nutritional value compared to whole alfalfa. Additionally, the alfalfa stems could be recovered after leaf harvesting, or left in the field to facilitate regrowth. In recent years, there has been a surge in research on alfalfa-segmented stems and leaves separation harvesting technology and equipment. Innovative solutions and joint harvesting equipment for forage stems and leaves separation have been continuously emerging *(Pratt and Jackson, 2021; Liebhardt, et al., 2022; Arinze, et al.,2007)*, indicating a growing interest and investment in this field. This trend underscores the ongoing efforts to optimize harvesting techniques for alfalfa, aiming to enhance efficiency and preserve the nutritional quality of the forage. Research into the storage treatment of leaf material after segmental harvesting has been progressively undertaken. *Digman, et al., (2013)*, proposed a methodology involving pressing and dehydrating the leaf material before storage, aimed at addressing the challenge of post-harvest leaf material preservation. Some academics *(Sikora, et al., 2019; Muck, et al., 2010; Bao, et al., 2023)*,explored the technique of mixed silage comprising alfalfa leaves, stems, and corn. *Andrzejewska, et al., (2017)*, conducted a study on the silage production of alfalfa, incorporating the separation technology and equipment for oriental goat bean stems and leaves.

Currently, the development trend of the alfalfa harvesting method is “direct separation in the field”. *Shinners et al. (2004, 2007)*, utilized a multi-tined rotor to strip the leaves directly in the field and obtained high leaf purity. This is a reliable way to separate alfalfa stems and leaves in the field. Additional mechanisms are needed on the machine to chop the stalks. In this study, by considering the combination of the chopping method in silage harvesting and the blowing method in alfalfa drying and separation, the chopping and blowing method was considered a potentially viable method of field alfalfa separation and harvesting. Before putting the methodology into practice, exploring the distinct suspension characteristics of each component of alfalfa is an important work. In this regard, *Li, et al., (2006),* studied the effect of alfalfa moisture content on suspension velocity, and *Wu, et al., (2014)*, measured the suspension velocity of alfalfa at different growth periods. However, there are no reference data on the suspension velocity of different fractions of fresh alfalfa with different cutting lengths.

In this study, the feasibility and optimal process parameters of the chopping and blowing separation method under laboratory conditions have been initially investigated. A suspension velocity experiment bench was constructed, to determine the suspension velocity parameters of various fractions of alfalfa, varying lengths of lateral branches, and different lengths of stems across different moisture content gradients during the harvesting period.

Through experimentation, relationships between different fractions of alfalfa, lengths of lateral branches, stem lengths, MC, and suspension velocity were established. On this basis, an investigation focused on the separation of alfalfa stems and leaves using the chopping and blowing separation method was conducted aiming to discern the relationship between cutting length, airflow velocity, and the Separation Evaluation Index. The experimental findings can offer valuable insights for alfalfa stems and leaves separation research.

MATERIALS AND METHODS

Experiment equipment

The suspension speed of alfalfa was assessed using a custom-made suspension speed experiment bench, illustrated in Figure 1. During experimenting, the feeding gate and material net facilitate the placement of alfalfa materials, while the material blocking bag, designed as a net, prevents material displacement due to excessive airflow without impeding airflow discharge. The airflow velocity is measured by TES-1341 Thermal Anemometer with a range of 0-30 m/s and a resolution of 0.01 m/s.

Fig. 1 - Suspension speed experiment device

1- Material-blocking bag; 2 - Observation tube; 3 - Frame; 4- Rectification grille; 5 -Transition hose; 6- Damper; 7- Centrifugal fan; 8- Down regulator; 9- Material net; 10- Feeding door 11- Up regulator

The harvesting occurred during a period characterized by high temperatures and dry conditions, resulting in the alfalfa plants exhibiting weakened growth and smaller dimensions, with both leaves and stems being relatively diminutive. At the time of cutting, the average height of the harvested alfalfa was measured at 534.57 millimeters, with stem diameters falling within the range of 1.5 to 2.5 millimeters. Notably, the initial moisture content（MC) of the alfalfa material was recorded at 70.34%.

Theoretical analysis of suspended velocity

By Newtonian principles, suspension velocity denotes the fluid velocity at which particles of a solid or liquid are held in suspension within the fluid medium *(Shehryar et al., 2019)*. Newton's law elucidates that the force exerted by the airflow upon the material was calculated as follows:

$$F = \frac{1}{2} k \gamma s v^2 \tag{1}$$

where: F is airflow force, [N]; γ is air density, [kg/m³]; v is relative velocity of the material to the airflow, [m/s]; s is material in the direction of airflow velocity cross sectional area, [m²]; k is resistance coefficient.

When the airflow force (F) on the material is equal to gravity, the material will be suspended in the airflow *(Meibohm et al., 2017; Dana and Moghaddam, 2022)*. At this time, the absolute speed of the material is zero, and the magnitude of the airflow velocity is the suspension velocity of the material, so the suspension velocity of the material was calculated as follows:

$$v_f = \sqrt{\frac{mg}{k \gamma s}} \tag{2}$$

v_f is material suspension speed, [m/s]; m is the mass of material, [kg]; g is gravitational acceleration, [N/kg].

During the suspension of alfalfa material at a specified elevation within the observation tube, the assessment entails the extension of an experiment rod housing a thermal sensing element from the anemometer into the observation tube through the designated measurement orifice. Sequentially, the wind velocity at several measurement points is determined, and subsequently averaged for each assessment. The determination of measurement point placement is conducted employing the equal-area circle method.

As illustrated in Figure 2, the cross-section of the pipe is stratified into three segments based on area, with measurement points situated along the equidistant lines within each segment.

$$R_i = R_0 \times \sqrt{\frac{2i-1}{2n}} \tag{3}$$

where: R_i is equidistant radius, [m]; R_0 is radius of cross-sectional area of down regulator, [m]; n is equivalent fraction of cross-section of Down regulator.

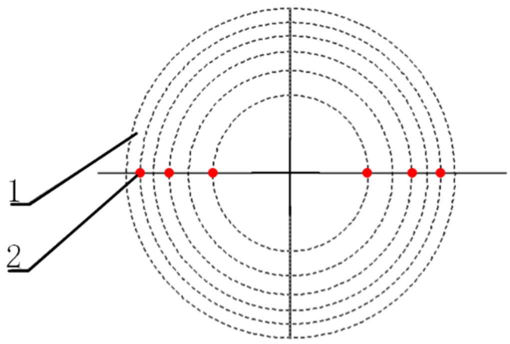


Fig. 2 - Position of measuring points
1- Pipe cross section; 2- Measuring points

Suspension velocity experiment of different components of alfalfa

Before commencing the experiment, alfalfa samples from the same batch were meticulously arranged on an elevated drying rack to ensure uniform distribution. For each experiment iteration, alfalfa was randomly selected, while the remaining samples underwent natural drying until reaching the requisite MC range. Throughout the experiment, the randomly chosen alfalfa samples were methodically sorted into three distinct components: leaves, stems (measuring 100 mm in length and 1.5 mm-2.5 mm in diameter), and whole plants (measuring 300 mm in length from tip to root). Each component comprised a minimum of 15 specimens, as depicted in Figure 3-a. These specimens were then positioned on the mesh material, with the feeding door subsequently closed. Initiating the experiment procedure entailed activating the fan and gradually adjusting the dampers to incrementally increase airflow until achieving a stable suspension of the material at a predetermined height within the observation tube. After airflow velocity measurement *(We et al., 2021)*, the fan was deactivated, and the material was removed. The MC of the leaf, stem, and plant specimens were independently measured thrice per group to ascertain the mean value. Suspension velocity assessments were repetitively conducted for 15 samples of alfalfa leaves, stems, and plants across varying MC gradients, with the resultant average value deemed the definitive outcome.

Suspension velocity experiment of alfalfa with different lengths of lateral branches

Before experimenting, the alfalfa experiment materials from the same batch were uniformly spread onto the suspension drying rack. A selection of alfalfa was then chosen for experimenting at a given interval, while the remaining materials were naturally air-dried to achieve the desired MC range. Throughout the experiment, a random assortment of alfalfa materials was manually segmented into six groups based on length categories: <60 mm, 80-120 mm, 120-160 mm, 160-200 mm, 200-240 mm, and >240 mm. It was ensured that each group contained a minimum of 15 specimens, as illustrated in Figure 3-b.

These six groups of sidestep samples were then positioned on the material net. Subsequently, the feeding door was sealed, the fan was activated, and the airflow was meticulously adjusted until the material could be suspended at a consistent height within the observation tube. The airflow rate was quantified, following which the fan was deactivated, and the material was withdrawn for MC analysis. This process was repeated thrice for each of the six sidestep sample groups to derive an average MC value.

Each of the six sample groups underwent three repetitions to calculate the average MC. Furthermore, within each MC gradient, the experiment was replicated with the six groups of alfalfa systems to measure the suspension speed of 15 samples. The resultant average value was deemed as the measurement outcome.

Suspension velocity experiment of alfalfa with different lengths of stems

Before conducting the test, the alfalfa test materials from the same batch were first evenly spread on an overhanging drying rack. A portion of the alfalfa was then selected for testing, while the remaining materials were allowed to naturally air-dry until they reached the desired MC range. During the test, the selected alfalfa materials were manually divided into eight groups based on stem lengths: 25 mm, 50 mm, 75 mm, 100 mm, 125 mm, 150 mm, 175 mm, and 200 mm. It was ensured that each group contained at least 15 specimens, as shown in Figure 3-c. These eight groups of stem samples were separately placed on the material net. The feeding door was closed, the fan was started, and the air valve was adjusted to gradually increase the airflow until the material could be stably suspended at a certain height in the observation tube. The airflow velocity was then measured, the fan was shut down, and the material was removed. For each of the eight groups of stem specimens, the MC was measured three times to obtain an average value. This process was repeated under each gradient of MC. Additionally, under each MC gradient, the experiment was repeated with the eight groups of stems to measure the suspension speed of 15 specimens per group. The final average value was then taken as the measurement result for each group.

Chopping separation experiment

Before the start of the experiment, the fresh alfalfa was randomly divided into nine groups manually. Each group of alfalfa will be cut according to different cutting lengths, and the lengths of the nine groups of cuttings are 10 mm, 15 mm, 20 mm, 25 mm, 30 mm, 35 mm, 40 mm, 45 mm, and 50 mm, ensuring that there are 15 specimens in each group. After the alfalfa is processed, it is chopped into alfalfa fractions of the same length, which consist of three fractions: leaves-stems connection fractions, pure leaves fractions, and pure stems fractions. The alfalfa fractions were then manually selected and separated strictly according to the three different fractions, and the contents of stems and leaves still adherent, pure leaves, and pure stems were counted in each set of trials. Each set of trials was repeated three times and the results were averaged.

(a) Different components (b) Different lateral branches lengths (c) Different stem lengths

Fig. 3 - Different forms of alfalfa

Chopping and blowing separation experiment

In order to explore the optimal process parameters for chopping and blowing separation, the central composite design (CCD) of the response surface method was used to construct the experiment proposal. Response surface design is a statistically comprehensive experimental technique for dealing with the action of multiple variables on response, which can construct the regression fit with a limited number of trials. Previous experimental research identified airflow velocity and cutting length as influential factors affecting the separation of alfalfa stems and leaves. Accordingly, airflow velocity (X_1) and cutting length (X_2) were chosen as the test factors, with the Separation Efficiency Index (*SEI*) serving as the evaluation index.

According to the CCD method, five levels were selected for each test factor and experimental factor coding was employed, as outlined in Table 1. Design-Expert 12.0 software is used for Central Composite Design, there are 13 different groups of the experiment proposal as shown in Table 5. The different experimental groups contained both replicates (Test No. 6, 9, 8, 12, and 13) and different combinations of levels of each factor.

Table 1

Factors and levels

Level	Airflow velocity X_1[m/s]	Cutting length X_2 [mm]
-1.41421	1.17	1.72
-1	2	10
0	4	30
1	6	50
1.41421	6.83	58.28

Before the experiment begins, fresh alfalfa is manually divided into 13 groups according to the experimental plan shown in Table 1. An equal amount of alfalfa is selected for each trial. The alfalfa is first cut into small sections according to the length requirements specified in Table 1, and then thoroughly mixed. The segments of alfalfa are tested using a suspended velocity tester. During the experiment, the alfalfa is blown into two parts: one part is blown by the airflow into the material-blocking bag, while the other part remains on the material net without being blown away by the airflow. The pure leaves, pure stems, and leaves-stems connection of the two parts of alfalfa were sieved separately, and the leaves-stems connection fraction was further divided into pure leaves and pure stems. The masses of stems and leaves in both the retained and blown-away parts are recorded separately. Each of the 13 experimental groups is repeated twice, and the average values are taken as the results.

This paper introduces an index, Separation Evaluation Index (*SEI*), where 0 < *SEI* < 2. A higher *SEI* indicates signifying a more effective stems and leaves separation. Conversely, a lower *SEI* indicates implying a less efficient stems and leaves separation.

$$SEI = \frac{m_{2L}}{m_{1L} + m_{2L}} + \frac{m_{2S}}{m_{1S} + m_{2S}} \tag{4}$$

where: m_{1L} is the total mass of leaves in the left-behind portion, [g]; m_{1S} is the total mass of stems in the left-behind portion, [g]; m_{2L} is the total mass of leaves in the blown-away portion, [g]; m_{2S} is the total mass of stems in the blown-away portion, [g].

RESULTS

Suspension velocity of different components of alfalfa

The experimental findings regarding the suspension velocities of distinct fractions of alfalfa across varying MC are presented in Figure 4-a. As the MC of alfalfa leaves decreased from 70% to 13%, the suspension velocity decreased from 2.21 m/s to 1.34 m/s. Similarly, a reduction in MC from 71% to 17% for alfalfa stems corresponded to a decrease in suspension velocity from 6.85 m/s to 4.01 m/s. Likewise, as the MC of whole alfalfa plants decreased from 67.75% to 13.33%, the suspension velocity diminished from 6.96 m/s to 3.0 m/s. Notably, the results reveal a significant disparity in suspension velocity among alfalfa leaves, stems, and whole plants. Specifically, alfalfa leaves exhibited a notably lower suspension velocity compared to both stems and whole plants. Conversely, the difference in suspension velocities between alfalfa stems and whole plants was negligible. Moreover, a consistent decrease in suspension velocities across all alfalfa components was observed with declining MC, indicating a linear relationship between suspension velocities and moisture levels.

Analysis of variance (ANOVA) was conducted on the experimental data about the suspension speed of various components of alfalfa under differing MC conditions, with the analysis outcomes presented in Table 2. Examination of the analysis results reveals that the P-values associated with the two factors, MC, and alfalfa components, are both less than 0.05. This observation underscores the highly significant impact that both factors exert on the suspension speed of alfalfa.

Table 2

ANOVA of alfalfa suspended velocity experiments with different alfalfa components at different MC.

Source	SS	DF	MS	F	P-value
MC	16.14186	7	2.30598	8.40834	0.0004**
components	50.63991	2	25.31995	92.32465	< 0.0001**
Pure Error	3.839488	14	0.274249		
Cor Total	70.62126	23			

Suspension velocity of alfalfa with different lengths of lateral branches

The results depicted in Figure 4-b illustrate the findings from suspension velocity tests conducted on alfalfa with varying stem lengths under different MC conditions. When the length of alfalfa lateral branches decreased from over 240 mm to less than 60 mm, the suspension velocity of lateral branches with over 70% MC decreased from 5.33 m/s to 2.72 m/s. Similarly, for lateral branches with MC ranging between 50% and 60%, the suspension velocity decreased from 5.17 m/s to 2.65 m/s. Additionally, for lateral branches with MC between 20% and 30%, the suspension velocity decreased from 4.70 m/s to 2.19 m/s. A similar decreasing trend in suspension velocity was observed for lateral branches with moisture content below 20%, where the velocity decreased from 3.31 m/s to 2.02 m/s. It was observed that the suspension velocity of alfalfa lateral branches exhibited an increase corresponding to the increase in lateral branch length. Conversely, a decrease in suspension velocity was noted with a reduction in MC, while maintaining a consistent length of alfalfa lateral branches.

The experimental data about the suspension speed of alfalfa, considering varied lengths of lateral branches across different MC levels, underwent thorough analysis via ANOVA. Table 3 delineates the outcomes of this analysis. Upon scrutiny of the analysis results, it becomes apparent that the P-values associated with both factors, namely MC and lateral branch length, fell below the threshold of 0.05. This observation signifies the presence of statistically significant effects exerted by both factors on the suspension speed of alfalfa.

Table 3

ANOVA of alfalfa suspended velocity experiments with different lateral branch lengths at different MC

Source	SS	DF	MS	F	P-value
lateral branch lengths	14.39204	5	2.878408	21.28784	< 0.0001**
MC	10.89201	3	3.63067	26.85135	< 0.0001**
Pure Error	2.028205	15	0.135214		
Cor Total	27.31225	23			

Suspension velocity of alfalfa with different stem lengths

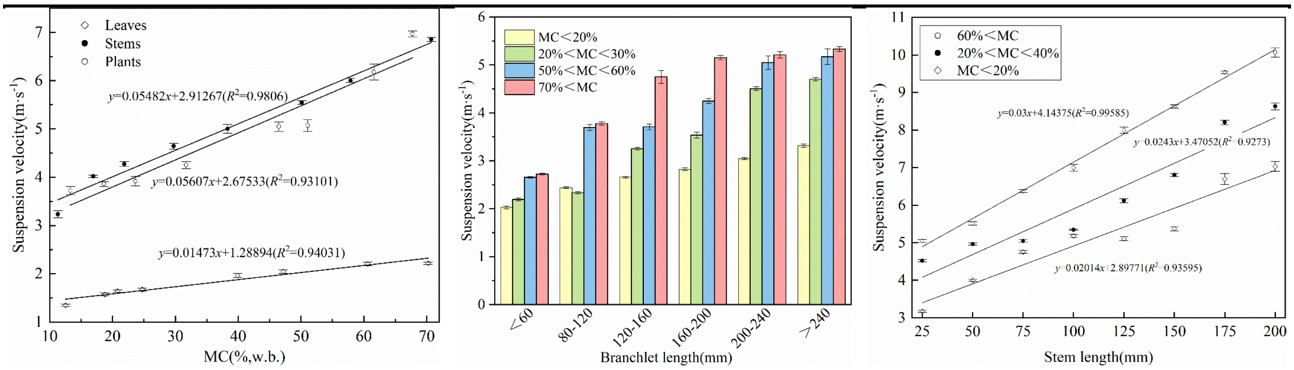
The levitation velocities of alfalfa stalks of various lengths under differing water contents are depicted in Figure 4-c. As the length of alfalfa stalks reduces from 200 mm to 25 mm, the suspension velocity decreases accordingly. Specifically, for stalks with a moisture content exceeding 60%, velocities decline from 10.06 m/s to 5.04 m/s, while for those with a moisture content below 20%, velocities decrease from 8.63 m/s to 4.51 m/s and 7.032 m/s to 3.17 m/s, respectively. A consistent trend emerges that the suspension velocity of alfalfa stalks decreases proportionally with diminishing water content. Notably, a linear correlation is observed between suspension velocity and stalk length, indicating that longer stalks exhibit greater suspension velocities.

ANOVA analysis was conducted to examine the suspension speeds of alfalfa stalks of different lengths and water contents, as presented in Table 4. Notably, both water content and stalk length yielded P-values below 0.05, indicating their significant impact on alfalfa suspension speed.

Table 4

ANOVA of alfalfa suspended velocity experiments with different stem lengths at different MC

Source	SS	DF	MS	F	P-value
stem lengths	49.30891	7	7.04413	39.06163	< 0.0001**
MC	22.30518	2	11.15259	61.84416	< 0.0001**
Pure Error	2.524673	14	0.180334		
Cor Total	74.13876	23			



(a) (b) (c)

Fig. 4 - Results of the two-factor test

Chopping separation results

The results illustrated in Figure 5 elucidate the percentage composition of each component of alfalfa following separation at distinct cutting lengths. At a cutting length of 10 mm, the proportion of leaves-stems connection stood at 7.5%, whereas it escalated to 42.2% at a cutting length of 50 mm. Conversely, the proportion of pure stem was declining from 60.5% to 45.5%, and the proportion of pure leaf was diminishing from 31.9% to 12.3%. Analysis of the experimental data reveals discernible trends in the proportions of the leaves-stems connection, pure stems, and pure leaves in response to varying cutting lengths. As the cutting length increased, there was a notable augmentation in the proportion of the stem and leaf connection parts. Conversely, a contrasting trend was observed in the content of the pure stems and pure leaves, which exhibited a decrement with increasing cutting length. These results collectively indicate a significant influence of cutting length on the separation of stems and leaves in alfalfa. Notably, a smaller cutting length yielded more effective stem and leaf separation, as evidenced by the observed trends in component proportions.

Chopping and blowing separation results

As delineated in Table 5, the experimental design incorporated airflow velocity and cutting length as pivotal factors, with *SEI* serving as the response metric. Employing Design Expert 12.0 software, the experiment's outcomes were fitting via multiple regression and subsequent analysis via ANOVA, as detailed in Table 6. Notably, the analysis revealed a significant influence of both X_1 and X_2 on *SEI*, with the interaction term X_1 X_2 also exhibiting a noteworthy effect. The model's P-value <0.05 underscores its statistical significance, further reinforced by the non-significant misfit term (P = 0.4426 > 0.05), indicating a favorable model fit. Moreover, the Coefficient of Variation (CV) stood at 4.21%, signifying a commendable degree of precision, as corroborated by a noteworthy Adequacy Precision value of 15.4129, affirming the model's reliability. The determination coefficients R^2 and R^2adj were calculated at 0.8245 and 0.9264, respectively. Similarly, the Predicted R^2 and R^2adj were established at 0.8245 and 0.9264, demonstrating a minimal discrepancy between them, indicative of a robust fitting correlation. This congruence implies the model's utility for predictive purposes, as it accurately reflects the observed data trends.

The results of the regression analysis experiments are shown in Table 5, which were analyzed by Design Expert software for multiple regression and fitting. The multiple regression equations for airflow velocity, cutting length, and *SEI* were established.

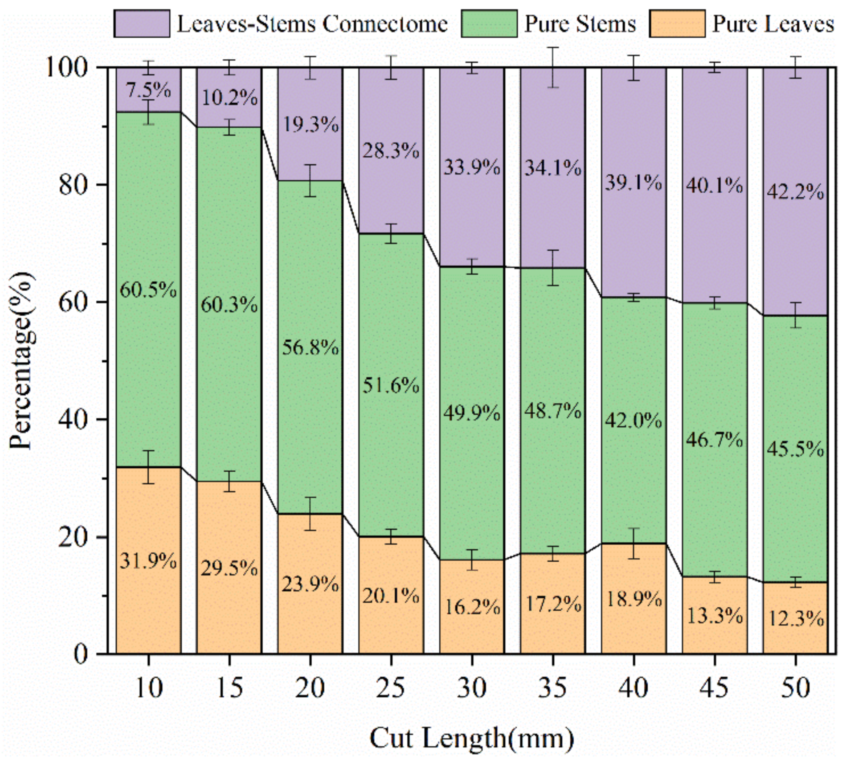


Fig. 5 - Content of alfalfa components under different cutting lengths

Table 5

Experimental results and range analysis

Test No.	Airflow velocity X_1 [m/s]	Cutting length X_2[mm]	*SEI*
1	1.17	30	1.0000
2	6.83	30	1.1048
3	4	1.72	1.4766
4	6	10	1.2565
5	2	10	1.2216
6	4	30	1.4995
7	2	50	1.1482
8	4	58.28	1.4408
9	4	30	1.5733
10	4	30	1.6582
11	6	50	1.4718
12	4	30	1.5980
13	4	30	1.5937

Table 6

Variance analysis of test result of the separation evaluation index

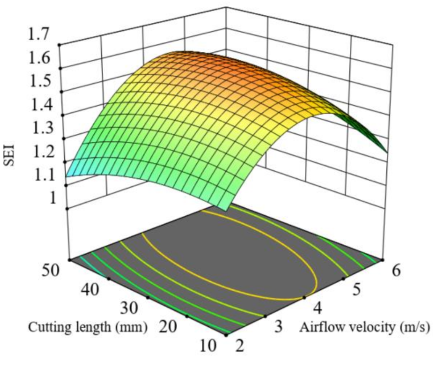
Source of variation	Sum of squares	Degree of freedom	Mean square	F- Value	P-Value
Model	0.5332	5	0.1066	31.19	0.0001**
X_1	0.0321	1	0.0321	9.39	0.0182*
X_2	0.001	1	0.001	0.3046	0.5982
$X_1 X_2$	0.0208	1	0.0208	6.1	0.0429*
X_1^2	0.4751	1	0.4751	138.97	< 0.0001**
X_2^2	0.0235	1	0.0235	6.89	0.0342*
Residual	0.0239	7	0.0034		
Lack of Fit	0.0109	3	0.0036	1.11	0.4426
Pure Error	0.013	4	0.0033		
Cor Total	0.5571	12			

$$SEI = 1.58 + 0.0633X_1 + 0.0114X_2 + 0.0722X_1X_2 - 0.2613X_1^2 - 0.0582X_2^2 \quad (5)$$

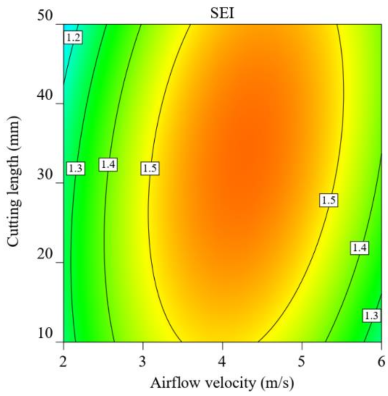
where: X_1 is airflow velocity, [m/s]; X_2 is cutting length, [mm].

The influence of airflow velocity X_1 and cutting length X_2 on *SEI* is shown in Fig. 6.

When the airflow velocity X_1 = 4.29556, and cutting length X_2 = 33.7956, the SEI achieved a maximum value of 1.59029, indicating the best separation of alfalfa stem and leaves by chopping and blowing method under this condition. Conversely, the orthogonal rotation center combination of the control group in the experimental results indicates X_1=4 and X_2=30, and *SEI* =1.60579. The discrepancy in *SEI* values between these two data sets is merely 0.98%, affirming the model's predictive accuracy against experimental outcomes. This validation confirms that an airflow velocity of X_1=4.3 m/s and a cutting length of X_2=34 mm represent the optimal parameter combination for the alfalfa chopping and blowing separation method.



(a)



(b)

Fig. 6 - Response surface of the airflow velocity and cutting length to the separation evaluation index

Discussion

A chopping and blowing method was proposed in this study by considering the combination of the chopping method in silage harvesting and the blowing method in alfalfa drying separation, which was considered a potentially viable method of field alfalfa separation and harvesting. In order to explore the feasibility and optimal process parameters of the chopping and blowing separation method, this paper investigated the suspension velocity characteristics of alfalfa, and analyzed the effects of airflow velocities and cutting lengths on the separation of alfalfa stems and leaves by response surface experiment.

The suspension velocity of all alfalfa components decreased with the decrease of MC, and there was a linear relationship between the suspension velocity and MC. Under the same MC gradient, the suspension velocity of the whole plant was the largest, followed by the suspension velocity of stems, and the suspension velocity of leaves being the smallest. The greater the length of alfalfa lateral branches and stems, the greater their suspension velocity. The results of chopping separation experiment showed that a smaller cutting length yielded more effective stem and leaf separation.

Response surface test results confirmed the feasibility of the chopping and blowing separation method and obtained optimum airflow velocity and optimum cutting length. Currently, a reliable way to separate fresh alfalfa stems and leaves is stripping method that was proposed by *Shinners et al. (2004, 2007),* which utilized a multi-tined rotor to strip the leaves directly in the field. However, the use of different evaluation metrics makes it difficult to compare the separation efficiencies directly. An indirect comparison can still be made. When using the Stripping method, test indicators were measured after drying, and the purity of dry leaves in the stripped component typically ranges from 50.2% to 89.5%, with a stem-leaf separation efficiency between 65.7% and 97.1%. In contrast, The Separation Evaluation Index (*SEI*) in this study was measured for wet samples. By further calculating the *SEI* results, the purity of fresh separated leaves ranged from 51.65% to 79.14%, with a stem-leaf separation efficiency between 58.05% and 79.47%. Considering that the water content of the stems in the samples should greatly exceed that of the leaves, the data of the separation results of these two separating method should be at essentially the same level.

It should be noted that there are still some limitations of this study. Although the feasibility of the chopping and blowing separation method under laboratory conditions has been demonstrated, there are still many issues to address before it is realized in the field. When harvesting in the field, the flow rate of alfalfa material will inevitably be much larger than that of the sample in the laboratory, and the length of alfalfa cutting can only fluctuate in a range, which does not guarantee the uniformity of the length of cut alfalfa. What's more, field conditions also have a great influence on machine operations. How to realize the chopping and blowing separation method by means of mechanical engineering, and promote the reliability as much as possible, is what needs to be further investigated.

CONCLUSIONS

(1) The suspension characteristics of different fractions of alfalfa, and different lengths of lateral branches and stems at different MC gradients were determined by setting up a test bench. The suspension velocity of alfalfa components decreased with the decrease of MC, and there was a linear relationship between suspension velocity and MC. At the same MC gradient, the suspension velocity of the plants was the largest, the stems were the second, and the leaves were the smallest. The greater the length of alfalfa lateral branches and stems, the greater the suspension velocity.

(2) Cutting length has a significant effect on the stems-leaves separation of alfalfa. Longer cutting lengths resulted in more content of adherent stems and leaves and less pure stems and pure leaves content in the chopped material. Instead, a smaller cutting length improves the separation of alfalfa stems and leaves.

(3) The central composite design (CCD) of the response surface method was used to study the effect of airflow velocity and cutting length on *SEI*. The optimum process parameters of the chopping and blowing method are as follows: the airflow velocity of 4.29556 m/s and cutting length of 33.7956 mm. The *SEI* is 1.59029 under this condition. These results can provide a reference basis for the determination of engineering solutions for alfalfa field separation and harvesting, such as the structure of the chopping device and the blowing device and the setting of operating parameters.

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