STUDY ON THE DETERMINATION OF PHYSICAL AND MECHANICAL PROPERTIES OF LAVENDER
/
薰衣草物理力学特性的测定研究

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ABSTRACT
The mechanical properties of lavender are the basis for design and study of mechanized equipment for planting and harvesting of lavender. This paper determines and studies the natural width and height of plant and spike length of three kinds of lavender widely planted in the Yili region and obtains the distribution rules of parameters of the basic physical properties of lavender. Meanwhile, the test of the mechanical properties of lavender was done at the moisture content in the harvest period and different moisture contents. The results indicated that the maximum separation force of the flower of three kinds of lavender (111.3N) was much smaller than the minimum breaking force of the stem (201.5N); and the moisture content significantly affected the mechanical properties of lavender, which could provide corresponding design parameters and important theoretical basis for the design of a new lavender harvester based on separation technology.

摘要
薰衣草的机械力学特性是设计研究薰衣草种植、收获机械化装备的基础。本文对伊犁地区广泛种植的三种薰衣草的植株自然宽度、自然高度以及花序长度进行了测定研究，获得了薰衣草基本物理特性参数的分布规律。同时，在收获期含水率和不同含水率条件下，进行了薰衣草的力学特性试验。结果表明，三种薰衣草花脱离力的最大值（111.3N）远小于茎拉断力的最小值（201.5N）;含水率对薰衣草的力学特性有显著影响，可为设计基于脱离技术的新型薰衣草收获机提供相应的设计参数和重要的理论基础。

INTRODUCTION
Lavender is a perennial plant with branched stems, growing to a height of 20-60 cm, with lance-shaped, linear or sessile leaves and flowers that are found at the tops of stems (*Katarzyna et al., 2014*). The branches at the bottom of the plant are tall and ramified, bearing multiple shoots. The flowers have a spiral shape, and the blue-violet corolla has the shape of two lips with a length of approximately 1 cm (*Fakhriddinova et al., 2020*). Lavender flowers play an important role because they contain 2-4.5% essential oils (*Katarzyna et al., 2014; Fakhriddinova et al., 2020; Prusinowska et al., 2014*). The essential oil extracted from its spike is widely used in articles of everyday use, including shampoo, soap, and detergent (*Li et al., 2016*), but they can also be used as pest and insect repellents (*Costea et al., 2019*). It is one of the most important natural essential oils in the perfume industry.

Thanks to its favorable geographical and climatic environments, Xinjiang's Yili region, which shares the same latitude as Provence, France, stands as the world's third-largest planting base of lavender (*Li et al., 2016*). Currently, the planting area of lavender in the Yili region of Xinjiang is up to 4,900 hm^2, accounting for 98% of that in the whole country. It has become the biggest lavender planting base in China (*Kan et al., 2017*). The weather of lavender harvest in Yili region is hot, but the harvest of lavender is mainly artificial, and the harvest efficiency is low, which seriously restricts the large-scale production and development of lavender. Therefore, it is urgently necessary to develop a new efficient lavender harvesting machinery.

The mechanical properties of lavender are the basis for the design and study of mechanized equipment for its planting and harvesting (*Dimitriadis et al., 2014*). Deniz Yilmaz et al. found that with the extension of harvest time, the shear stress of each stem segment of lavender decreased, and the mechanical property

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parameters such as biological yield force, shear force and bending stress of the bottom stem segment of lavender were much greater than those of the top stem segment, so it was recommended to harvest near the top (*Deniz et al., 2016*). The study of Deniz Yilmaz et al. also showed that water content had significant effects on the physical and mechanical properties of lavender, such as flower stem size, flower stem ratio, picking power and essential oil content (*Deniz et al., 2014*). Hassiotis et al. studied lavender in two regions of Greece and found that harvesting at 60% flowering time was the best harvest stage for lavender (*Hassiotis et al., 2014*). Dimitriadis' research has shown that the most cost effective operation was not achieved at maximum yield but at a set up in which the machine was capable of harvesting the maximum flower head with the minimum stem percentage (*Dimitriadis et al., 2016*). Ana Clara Aprotosoaie and Elvira Gille et al. found that lavender essential oil extraction can also use other parts except inflorescence, but the essential oil content is very low, and the content of linalool, camphor and other components are also low (*Aprotosoaie et al., 2017*). Cigdem Sonmez et al. found that the average value of fresh grass yield, hay yield, floating grass yield, essential oil content and essential oil yield of lavender was the highest at 8 am during the lavender harvesting period, while the average value of essential oil content and essential oil yield was the lowest at 14 PM (*Cigdem et al., 2019*). China primarily concentrates on lavender essential oil extraction and industrial development, with limited reports on the physical and mechanical characteristics of lavender.

This paper takes three kinds of lavender widely planted in the Yili region as an example, determines and studies their basic physical properties, and explores the mechanical properties of different kinds of lavender and the effect of moisture content on the mechanical properties of lavender. It can provide corresponding design parameters and an important theoretical basis for the mechanized harvesting and processing equipment of lavender.

MATERIALS AND METHODS

In this test, Princess Jieyou No. 1, French Blue, and High Yield Blue widely planted in the Yili region were considered as the test objects. The test samples were taken from the Wucai River Valley Lavender Base in Huocheng County, Yili Prefecture, Xinjiang Uygur Autonomous Region on July 13th, 2023. The lavender in this base is planted in a single row with a row spacing of 80 cm and a line spacing of 120 cm. All three kinds of lavender are in their growth period of the fourth year and full-blossom period (*50%～70% of them bloom*).

Test devices

Tape measure, steel ruler, electronic universal tensile testing machine (*Xiamen Jinheyuan Technology Co., Ltd., JHY-5000 single-column digital display, with a maximum range of 500 N and test force resolution of 1/300,000*), digital display vernier caliper (*Qinghai Measuring & Cutting Tools Co., Ltd., with an accuracy of 0.02mm*), and halogen moisture meter (*Xiamen Jinheyuan Technology Co., Ltd., JH-150F, with readability of ±0.01%*).

Determination of the basic physical properties of lavender plants

The lavender plant samples were selected with a reference to the provisions of NY/T1133-2006, an agricultural industry standard in China (*The Agricultural Mechanization Sub Technical Committee of the National Agricultural Machinery Standardization Technical Committee, 2016*). The field measurement method was as follows. The test field was a rectangular planting area. Two diagonal lines of the rectangular area were connected. The plot was divided into 4 parts. The central part of the plot was the fifth part. Each part was a sampling area. 20 healthy lavender plants with similar growth were randomly selected from 5 sampling areas and there was a total of 100 samples.

With reference to the Agricultural Machinery Design Manual (*China Academy of Agricultural Mechanization Science, 2017*), combined with the design requirements of the lavender harvesting device, the natural width and height and spike length of the lavender plant in the harvest period were selected as evaluation indicators of the basic physical properties of lavender. After the determination of the parameters of the basic physical properties of lavender, 50 lavender branches were selected from each plot randomly, cut 100 mm below the spike, and immediately put into a sealed and dry plastic box. After the samples were collected, they were sent to the Engineering Training Center of Yili Normal University for subsequent test of the mechanical properties of lavender.

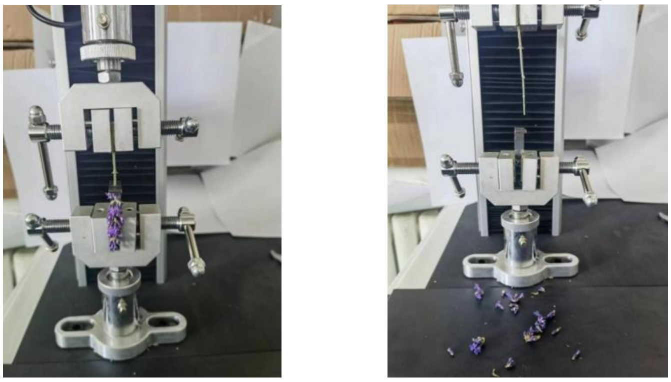
Determination of separation force of lavender flower *at the moisture content in the harvest period*

Researches show that 97.5% of the essential oil of lavender is from flowers when the essential oil is extracted and lavender stems only contain a little essential oil with poor quality (*Petras et al., 1997; Rabotyacov et al., 1980*). Therefore, to get essential oil with good quality, flowers and stems of lavender should be separated. Currently, in the manual harvesting of lavender in the Yili region, stems and flowers are cut off. And then, essential oil is extracted, which not only increases transportation and distillation costs but also hinders the production of essential oil with good quality. Therefore, an experimental study on the mechanical properties of lavender is necessary to provide corresponding theoretical data for the design of a new lavender harvester.

The separation force of lavender flowers was measured in the Engineering Training Center of Yili Normal University with an indoor temperature of 34°C and a relative humidity of 39% on that day. After sampling, the average moisture content of the lavender samples measured with a moisture meter was 12.1%, which was consistent with the most suitable moisture content for harvesting of medicinal plants and aromatic plants (*Deniz et al., 2014*).

To determine the force required to separate the flower from the stem, a metal plate with a hole was fixed and installed at the lower end of the electronic universal tensile testing machine. The diameter of the hole was 3 mm. Part of the end of the lavender stem without a spike was cut off with scissors. Only the part with a length of 30 mm was kept and fixed in the fixture at the upper end of the testing machine after passing through the small hole. The lavender spike is on the lower side of the hole, as shown in Figure 1a.

The loading speed of the electronic universal tensile testing machine can be adjusted in the range of 0.1～500 mm/min. However, considering that the operating speed of an agricultural harvester is usually 3～8 km/h, if the loading speed is too high, it can also affect the test results (*Ma et al., 2004; Wang et al., 2011*). Therefore, a constant loading speed of 60 mm/min was selected for the separation force test of lavender flowers (*Wang et al., 2015*). When the stem was completely separated from the metal plate, as shown in Figure 1b, the rising stopped and the data was recorded. After an experiment was completed, the remaining spikes in the small hole on the metal plate were removed. And then, the next experiment was done. The experiment was repeated for 15 times for each kind of lavender and the results were averaged.



a. Before separation of lavender flower *b. After separation of lavender flower*

Fig. 1 - Measurement of separation force of lavender flower with an electronic universal tensile testing machine

Determination of breaking force and ultimate tensile strength (UTS) of the stem of lavender at the moisture content in the harvest period

With reference to GB/T 1040 Determination Method of the Tensile Strength, Tensile Modulus, and Tensile Stress-Strain Relationship of Plastics and Composite Materials (*GB/T1040.1-2018, 2018*), the breaking force of the stems of lavender was determined. Before the test, the part of the spike of lavender was cut off, both ends of the remaining stem were cut off, and the part with a length of 80 mm in the middle was kept. The cross-section of the stem of lavender is rectangular and the middle part is slightly empty. If the stem is directly clamped on the fixture for a test, it may break or slide. In the test, to ensure that the clamps on both ends could grip the stem without damaging it, the binding wire with a length of 20 mm and diameter of 0.3 mm was inserted into both ends of the stem. Its outside was bonded firmly with medical tape to avoid sliding in the process of the test with a bonding length of 20 mm (*Guo et al., 2019*). The breaking force test of the stem was done with a constant loading speed of 60 mm/min. The test process is as shown in Figure 2.

Fig. 2 - Measure the breaking force of the stem with the universal tensile testing machine

The single-factor and single-level repeated test method was used, the experiment was repeated 15 times, and the results were averaged. As the load increased, the test was considered successful when the breaking part was not on both ends of the stem (*Wang et al., 2016*). When the stem was completely broken, the rising stopped and the data was recorded.

The ultimate tensile strength of the stem of lavender can be obtained from the results of the test of the breaking force of the stem. With the method specified in GB/T24887-2010 Guidelines for Test of the Specificity, Consistency, and Stability of New Varieties of Plants, the vertical and horizontal dimensions of the cross section of the stem of lavender were selected, the ultimate tensile strength in the directions of the maximum and minimum dimensions was measured, and the mean was considered as the final result. The cross-sectional area of the stem was calculated according to its vertical and horizontal dimensions. The ultimate tensile strength (UTS) of the stem could be obtained with Equation (1).

$$R_m = \frac{F}{A} \tag{1}$$

where:

R_m is the ultimate tensile strength, [MPa];

F is the breaking force of the stem of lavender, [N];

A is the cross-sectional area of the stem of lavender, [mm^2].

Test of mechanical properties of lavender at different moisture contents

To verify the effects of moisture content on the separation force of the flower, breaking force of the stem, and ultimate tensile strength of the stem of lavender, 30 plants of lavender samples of each kind at the moisture content in the harvest period were divided into 3 groups with 10 plants in each group and they were numbered. The samples were naturally dried at room temperature for 24, 48, and 72 hours. And then, some samples were taken and placed in the balance of the halogen moisture meter. The temperature was set as 100℃. The moisture content of the sample could be automatically measured. The average moisture content of each group of samples is shown in Table 1.

Table 1

Statistical table of moisture contents of samples

Lavender	Princess Jieyou No. 1/%	French Blue/%	High Yield Blue/%	Mean/%
Group 1 (24 hours)	10.81	11.12	10.63	10.85
Group 2 (48 hours)	8.23	8.42	8.13	8.26
Group 3 (72 hours)	5.94	6.05	5.82	5.94

After drying, the separation force of the lavender flower, the breaking force of the stem, and the ultimate tensile strength of the stem of samples were determined according to the above test steps.

RESULTS

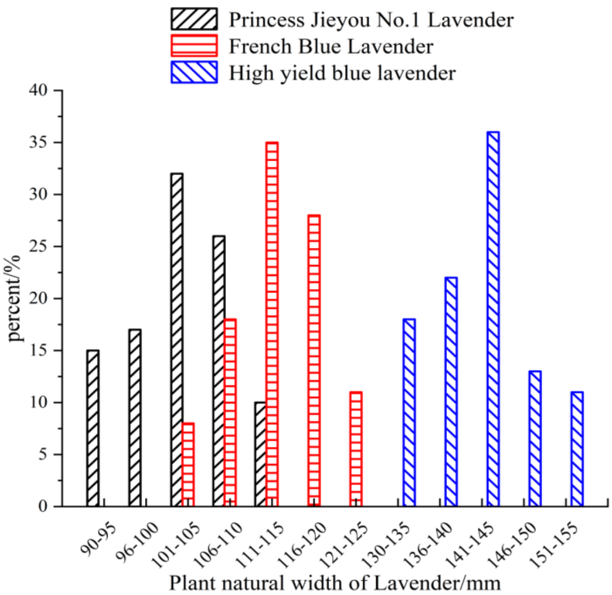
The statistical results of the parameters of the basic physical properties of three kinds of lavender plants are shown in Table 2. The probability distribution of plant samples is shown in Figure 3.

Table 2

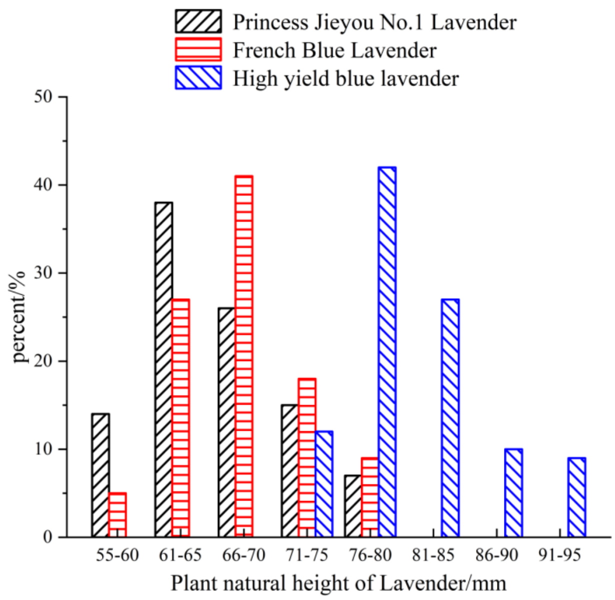
Parameters of the basic physical properties of three kinds of lavender

Lavender	Natural width of plant (mean/cm)	Natural width of plant (max/cm)	Natural width of plant (min/cm)	Natural height of plant (mean/cm)	Natural height of plant (max/cm)	Natural height of plant (min/cm)	Spike length (mean/cm)	Spike length (max/cm)	Spike length (min/cm)
Princess Jieyou No.1	102.8	115	91	65.6	80	55	11.2	16.8	7.2
French Blue	113.6	124	101	68.0	80	56	11.9	18.6	7.2
High Yield Blue	141.7	155	131	81.1	95	71	16.9	22.2	11.5

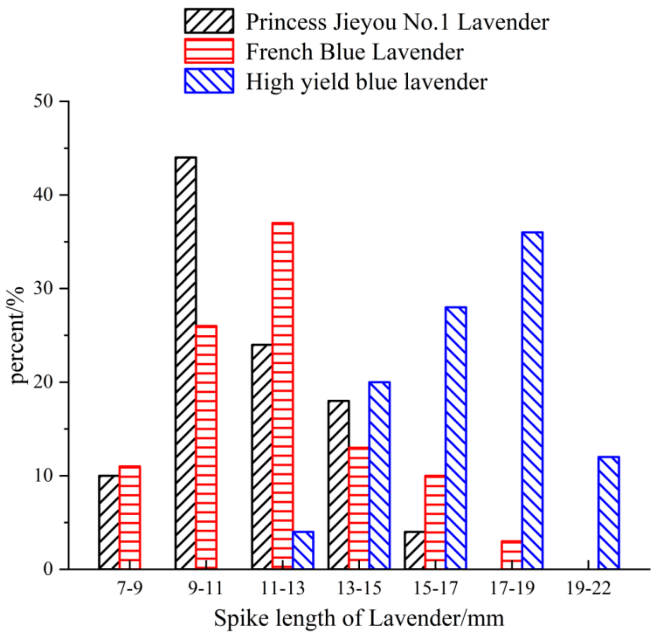
Table 2 shows that the average natural width, height, and spike length of plants of High Yield Blue lavender are the biggest among the three kinds of lavender, while the average natural width, height, and spike length of plants of Princess Jieyou No. 1 are the smallest among three kinds of lavender.



a. Distribution map of natural width of plants of lavender



b. Distribution map of natural height of plants of lavender



c. Distribution map of spike length of lavender

Fig. 3 - Histogram of the distribution of the basic physical properties of lavender

Figure 3a shows that the natural width of plants of Princess Jieyou No. 1 lavender is mainly in the range of 96～110 cm, accounting for 75% of the total sample size; that of French Blue lavender is mainly in the range of 106～120 cm, accounting for 81% of the total sample size; and that of High Yield Blue lavender is mainly in the range of 130～145 cm, accounting for 76% of the total sample size.

Figure 3b shows that the natural height of plants of Princess Jieyou No. 1 lavender is mainly in the range of 61～75 cm, accounting for 79% of the total sample size; that of French Blue lavender is mainly in the range of 61～75 cm, accounting for 86% of the total sample size; and that of High Yield Blue lavender is mainly in the range of 71～85 cm, accounting for 81% of the total sample size.

Figure 3c shows that the spike length of Princess Jieyou No. 1 lavender is mainly in the range of 9～15 cm, accounting for 86% of the total sample size; that of French Blue lavender is mainly in the range of 9～15 cm, accounting for 76% of the total sample size; and that of High Yield Blue lavender is mainly in the range of 13～19 cm, accounting for 84% of the total sample size.

By combining Table 1 and Figure 3, it can be known that the parameters of the basic physical properties of Princess Jieyou No.1 lavender and French Blue lavender are not quite different. The parameters of the basic physical properties of High Yield Blue lavender are much bigger than those of the other two kinds of lavender, which makes the design of a lavender harvesting device more difficult.

In the process of the test, the TESTER system in the electronic universal tensile testing machine automatically drew a load-time curve and recorded the maximum separation force, as shown in Figure 4.

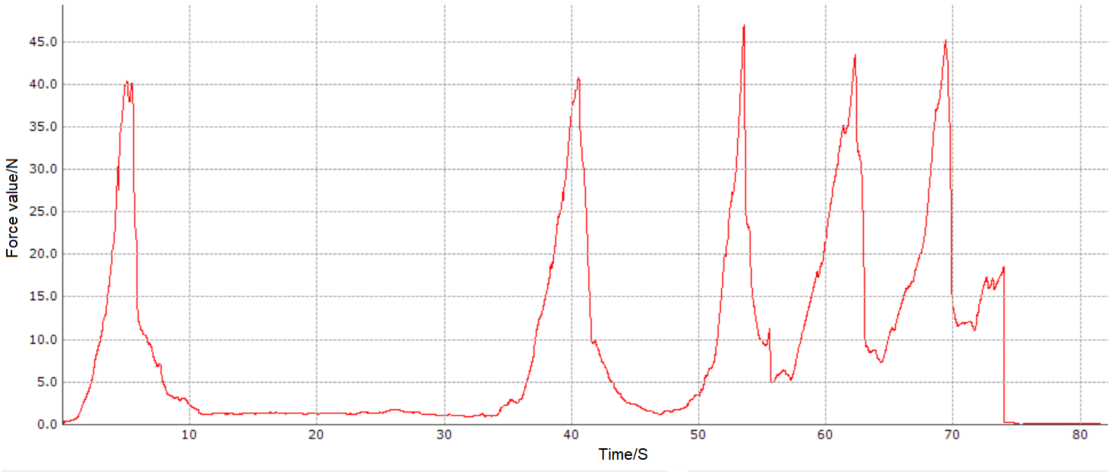


Fig. 4 - Separation force-time curve of lavender flower

Figure 4 shows that the separation force increased fast and the flower was peeled off with the increase of load after the test started. And then, the force decreased fast. At this time, the first spike was separated. After a long time, the separation force increased fast, and then decreased fast. The separation of the second spike started. The number of times of fast increase and decrease of the separation force represents the number of spikes of lavender. In most cases, the first and second spikes are farther than other spikes, so the interval is the biggest.

The statistical results of the separation force of the lavender flower, the breaking force of the stem, and the ultimate tensile strength (UTS) of the stem at the moisture content in the harvest period are shown in Table 3.

Table 3

Statistical table of parameters of mechanical properties of lavender at the moisture content in the harvest period

Lavender	Separation force of the flower (mean/ N)	Separation force of the flower (max/N)	Separation force of the flower (min/N)	Breaking force of the stem (mean/N)	Breaking force of the stem (max/N)	Breaking force of the stem (min/N)	Ultimate tensile strength (mean/MPa)	Ultimate tensile strength (max / MPa)	Ultimate tensile strength (min / MPa)
Princess Jieyou No.1	52.8	62.4	45.7	229.3	280.5	201.5	52.5	55.2	50.7
French Blue	59.3	70.3	49.8	231.1	285.7	205.4	52.8	56.7	50.6
High Yield Blue	88.3	111.3	69.8	247.6	287.6	210.6	59.8	63.9	55.4

The data in Table 3 shows that the average separation force of the flower, the breaking force of the stem, and the ultimate tensile strength of the stem of the lavender sample of Princess Jieyou No. 1 at the moisture content in the harvest period are the smallest; the average separation force of the flower, the breaking force of the stem, and ultimate tensile strength of the stem of the lavender sample of High Yield Blue are the biggest; and the parameters of mechanical properties of the lavender sample of French Blue are slightly higher than those of the Princess Jieyou No. 1 lavender and there is no significant difference between the two lavender samples. The separation force of the flower of samples of three kinds of lavender is 45.7～111.3 N, the breaking force of the stem is 201.5～287.6 N, and the ultimate tensile strength of the stem is 50.7～63.9 MPa.

The determination results of the mechanical properties of three kinds of lavender at different moisture contents are shown in Figure 5-7.

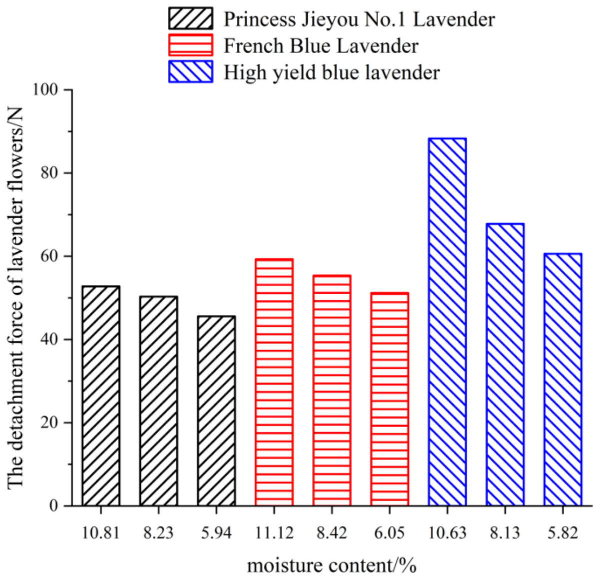


Fig. 5 - Separation force of lavender flower at different moisture contents

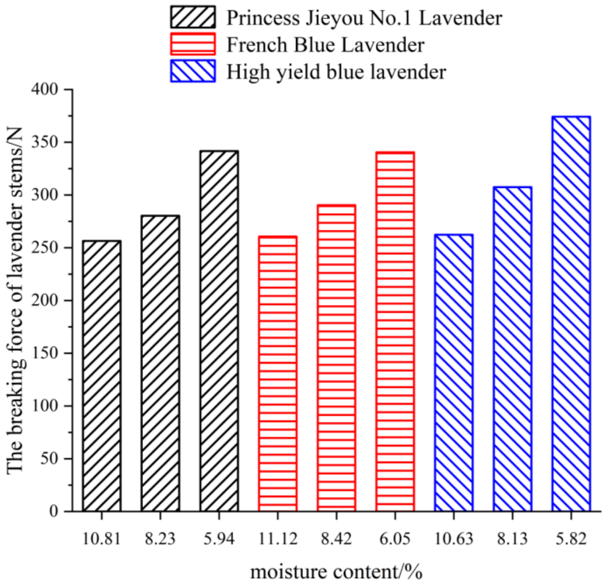


Fig. 6 - Breaking force of lavender stem at different moisture contents

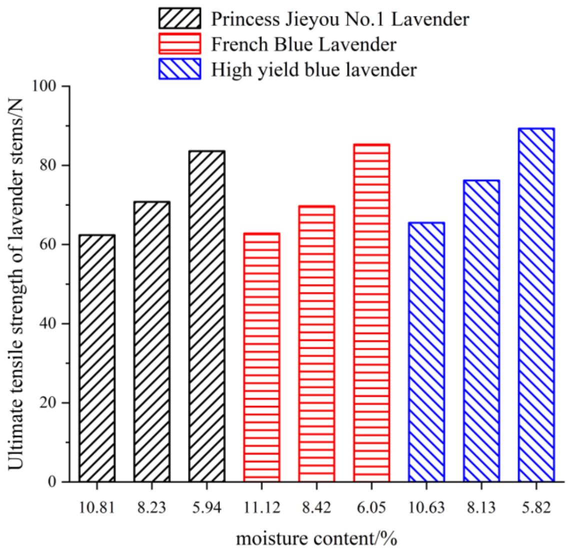


Fig. 7 - Ultimate tensile strength of lavender stem at different moisture contents

As the moisture content decreases, the separation force of the three kinds of lavender flowers also decreases, but the breaking force and ultimate tensile strength of the stems of the three kinds of lavender increase with the decrease of moisture content, because the decrease of moisture content causes the increase of cellulose intensity, thus improving the tensile resistance and tensile strength of the stem of lavender. It can be seen that moisture content has a significant effect on the mechanical properties of lavender.

CONCLUSIONS

1) According to the determination, the natural width of plants of three kinds of lavender is 91～155 cm, the natural height is 55～95 cm, and the spike length is 11.2～22.2 cm.

2) At the moisture content in the harvest period, the average separation force of the flower of three kinds of lavender is much smaller than the average breaking force of the stem. The average breaking force of the stem of Jieyou Princess No.1 lavender and French Blue lavender is 4 times the average separation force of the flower, and the average breaking force of the stem of High Yield Blue lavender is 2.8 times the average separation force of the flower. The maximum separation force of the flowers of three kinds of lavender (111.3 N) is much smaller than the minimum breaking force of the stem (201.5 N). This indicates that the flower can be peeled off from the stem without breaking it when lavender is harvested.

3) The moisture content has a significant effect on the mechanical properties of lavender. As the moisture content decreases, the separation force of the flowers of lavender also decreases. However, the breaking force and ultimate tensile strength of the stem of lavender increase.

4) At the moisture content in the harvest period and different moisture contents, the average separation force of the flower of High Yield Blue lavender is much greater than that of the other two kinds of lavender mainly because the peduncle of High Yield Blue lavender is relatively long. The average breaking force and ultimate tensile strength of the stem of High Yield Blue lavender are not significantly different from those of the other two kinds of lavender and have little effect on the design of a new lavender harvester based on the peeling technology.

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