EXPERIMENTAL INVESTIGATION ON THE SHEAR MECHANICAL PROPERTIES OF LICORICE ROOT
/
甘草根剪切力学特性的试验研究

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ABSTRACT
The process of slicing is a vital component in the preliminary treatment of licorice roots. The physical properties and shear mechanical attributes of licorice root are of considerable importance for the development and optimization of machinery intended for slicing licorice root. In this research, four-year-old mature licorice roots were selected as the experimental specimens, and shear strength evaluations were conducted on these roots by means of a universal testing machine (Instron 3344 series). The experimental design utilizes a blend of univariate and multivariate orthogonal testing techniques. Within this design, moisture content, shear speed, and shear speed are identified as the independent variables, while the maximum cutting force is defined as the primary assessment criterion. The experimental results reveal that the primary and secondary factors influencing the shear strength of licorice root follow the order: moisture content > shear speed > shear angle. The optimal conditions for the slicing pretreatment process are identified as a moisture content of 50 ± 2%, a shear speed of 0°, and a shear speed of 90 mm·min^{-1}.

摘要
切片是甘草根预处理流程中的关键环节之一。甘草根的物理参数和剪切力学特性对于甘草根切片设备的研发和工艺优化具有重要意义。本研究选取四年生的成熟期甘草根作为试验材料，利用万能试验机（Instron3344 系列）开展甘草根剪切性能试验。试验设计采用单因素和多因素正交试验，将含水率、剪切角度、剪切速度设定为试验因素，以最大剪切力作为评价指标。结果表明，影响甘草根剪切力的主次因素为：含水率>剪切速度>剪切角度。当含水率为 50±2%，剪切角度为 0°，剪切速度为 90mm·min^{-1}时，进行切片预处理工序最为适宜。

INTRODUCTION
Licorice, alternatively known as Gan Cao, sweet grass, or sweet root, acquires its name due to the sweet flavor of its root. Licorice is taxonomically classified within the Fabaceae family, specifically residing in the subfamily Faboideae, the tribe Galegeae, and the subtribe Glycyrrhiza. It is a perennial herbaceous plant that is grouped under the genus Glycyrrhiza. Licorice, which is widely acknowledged as one of the earliest plant species enlisted in China's inventory of medicinal and edible resources, also serves as a significant natural resource in arid and semi-arid regions *(He et al., 2024)*. Licorice is mainly distributed in arid and semi-arid areas around 40° north latitude. The major cultivation areas are concentrated in Central Asia, North America, and Eastern Europe. In China, licorice is one of the major economic crops. It has a relatively large cultivation area that is mainly spread across the northeastern, northern, and northwestern provinces. The key production areas encompass Xinjiang, Inner Mongolia, Ningxia, and Gansu *(Li et al., 2015).* The cultivation of licorice spans a period of two to four years from planting to harvesting. And it is generally necessary to conduct pretreatment on the roots prior to their utilization in medicinal applications. The cutting procedure is essential in the pretreatment stage, as it enhances the surface area interaction between the substrate and the solvent, thereby promoting the extraction of the drug and its subsequent delivery.

Shear strength, as one of the critical mechanical properties of agricultural materials, can provide theoretical foundations and effective parameters for the design, manufacturing, and optimization of licorice cutting devices and harvesting machinery.

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Currently, relevant research focuses on the shear mechanical properties of various plant organs and crops, covering the main roots of Panax notoginseng *(Yang et al., 2016)* and the rhizomes of Coptis chinensis *(Li et al., 2023)* as medicinal plants, the root systems of maize *(Zhao et al., 2021; Guo et al., 2016)* as a food crop, as well as common categories such as fruits *(Wu et al., 2022),* seeds *(Bao et al., 2022; Huang et al., 2021; Guo et al., 2016)*, vegetables *(Yang et al., 2022)* and crop stalks *(Yang et al., 2016; Li et al., 2020)*. Moreover, the shear mechanical properties of tea tree new shoots *(Wang et al., 2022)* also fall within the scope of research. In contrast, studies concerning the shear characteristics of Glycyrrhiza uralensis are notably scarce.

Therefore, this study opts for the roots of licorice harvested at the appropriate time as the research object, with cutting force serving as the evaluation criterion. It dissects the influences of moisture content, root diameter, shear speed, and other factors on the cutting force of licorice roots. Through the application of orthogonal experimental methodologies, the predominant influencing factors during the licorice cutting process are pinpointed, and the fluctuations in its shear mechanical properties are investigated. This offers a requisite theoretical groundwork for the design and optimization of the preliminary processing techniques and equipment for licorice.

MATERIALS AND METHODS

Materials

This study focuses on Glycyrrhiza uralensis as the principal experimental subject. The samples were obtained from a comprehensive demonstration practice base specialized in Glycyrrhiza uralensis cultivation in the Northeast region. The selected Glycyrrhiza uralensis plants were of four-year-old age and possessed a root system composed of both vertical and horizontal roots (as depicted in Figure 1). The vertical roots of the Glycyrrhiza uralensis (hereinafter denoted as Glycyrrhiza uralensis roots) had diameters spanning approximately from 1.5 to 3 cm, and their epidermis exhibited a coarse texture. Solely healthy Glycyrrhiza uralensis roots, demonstrating optimal growth status and being free from pests and diseases, were selected for this study. The lateral roots were trimmed and all residual debris was removed. The Glycyrrhiza uralensis roots are illustrated in Figure 2.

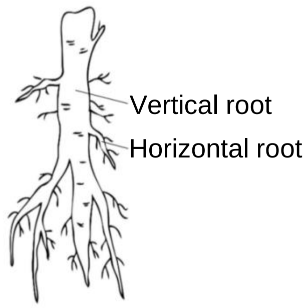


Fig. 1 - Schematic Diagram of the Structure of Licorice Root

Fig. 2 - Glycyrrhiza uralensis root

Equipment

The experimental apparatuses and implements employed in this study comprise a Model 101 electric blast drying oven (with a temperature range of 0 - 300°C and a voltage of 220 V), an Instron 3344 series microcomputer-controlled electronic universal testing machine, a stereo electron microscope (Nexcope NSZ606), a digital vernier caliper (having a measuring range of 150 mm and an accuracy of 0.01 mm), an electronic balance (with a capacity of 500 g and an accuracy of 0.001 g), an angle square, scissors, and sealing bags, among other items.

Experimental Methods

Determination of Physical Parameters and Tissue Structure

The simple random sampling method was adopted to randomly select samples of licorice roots for testing purposes. For each individual root, its length was measured three times, and then the average value was calculated. Subsequently, the licorice root was sectioned into five discrete portions, specifically designated as the upper, upper-middle, middle, lower-middle, and lower segments. The diameter measurements corresponding to each segment are presented in Figure 3. The average diameter of the licorice root was computed using Formula (1), which is as follows:

$$d_j = \frac{1}{6}\sum_{i=1}^{2}\left(d_{1i} + d_{2i} + d_{3i}\right) \tag{1}$$

where:

d_j represents the mean diameter of the cross-sectional area of the licorice root, mm;

d_{1i} represents the length of the major axis of the cross-section of the licorice root recorded during the i-th measurement, mm;

d_{2i} represents the length of the minor axis of the cross-section of the licorice root recorded during the i -th measurement, mm;

d_{3i} represents the length of the shortest axis of the cross-section of the licorice root recorded during the i -th measurement, mm.

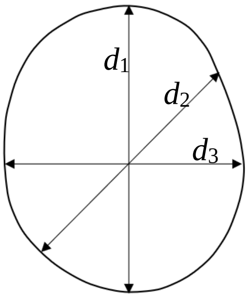


Fig. 3 - Schematic diagram of measurement positions for the diameter of licorice root cross-sections

Scissors and a scalpel were utilized to obtain cross-sectional specimens of licorice root with differing moisture content levels. The moisture content levels were adjusted by subjecting the licorice roots to different drying durations in a controlled environment. Subsequently, high-quality digital microscopy was employed to examine the tissue architecture within the cross-sections of the licorice root, focusing particularly on features such as the cell arrangement, vascular bundle structure, and parenchyma tissue morphology.

Determination of moisture content and density

The entire licorice roots were cut with scissors to determine of the moisture content of freshly harvested licorice and were then grouped accordingly. An electronic balance was employed to weigh each group of licorice roots separately, and the measurements were recorded. After weighing, the samples were placed in a drying box and then transferred into a vacuum drying oven, as depicted in Figure 4. The temperature was set at 110°C, and the weight was recorded every 2 hours until the mass stabilized with a relative change of less than 0.1% between consecutive measurements, indicating the end of the experiment. The average of the weights recorded every 2 hours during the drying process was calculated. Upon the completion of the drying process, the samples were weighed again to calculate the absolute moisture content using the following formula:

$$M = \frac{m_1 - m_2}{m_1} \times 100\% \tag{2}$$

where: M represents the moisture content of licorice root, %;

m_1 is the wet mass of the sample before drying, g;

m_2 is the dry mass of the sample after drying, g.

Fig. 4 - Licorice root drying test

The freshly harvested licorice roots were meticulously cleaned to remove any adhered soil and debris. After allowing the roots to air-dry for 30 minutes, until the surface appeared dry to the touch, a utility knife was used to cut the licorice roots into numerous small fragments. These fragments were then randomly divided into ten groups to ensure sample diversity and representativeness for subsequent measurements. The mass of each group was precisely measured using an electronic balance and denoted as M. A 500-milliliter beaker was selected, and 300 milliliters of water were initially added. The licorice root samples were then weighed and carefully placed into the beaker, ensuring complete submersion in the water. At this point, the change in water level was meticulously observed and recorded. The density of the licorice roots was subsequently calculated using formula (3), as follows:

$$\rho_{\mathrm{g}} = \frac{M_{\mathrm{g}}}{V_{\mathrm{g}}} \tag{3}$$

where: ρ_{g} represents the density of licorice root, g/cm^3; M_g is the total mass of licorice root obtained through direct weighing, g; V_g is the total volume measured by the pycnometer method, mL.

Shear testing methodology

To explore the impacts of shear angle, shear speed, and moisture content of licorice root on its shear strength, based on preliminary investigations, licorice roots with a diameter of approximately 15 mm were selected and samples with a length of 80 mm were fabricated to ensure the representativeness and uniformity of samples for subsequent shear tests. Figure 5 clearly illustrates the schematic diagram of the sample.

Fig. 5 - Licorice root cutting test sampling

Single-factor experiment

The moisture content of the licorice root was adjusted to (50 ± 2)%, and the shear speed was set at 60 mm/s. The shear angles were arranged as shown in Figure 6, which were divided into 0°, 15°, 30°, 45°, and 60°. The 0° angle represents the shear test carried out on the transverse section of the licorice root. Five sets of repeated tests were performed for each shear speed, and the results were averaged.

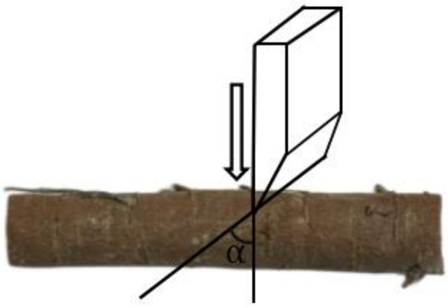


Fig. 6 - Cutting diagram

The shear speed was set to 60 mm/s and the shear angle to 0°. The moisture content of licorice was selected as (50 ± 2)%, (40 ± 2)%, (30 ± 2)%, (20 ± 2)%, and (10 ± 2%) for the cutting tests. Five sets of replicated experiments were conducted for each moisture content, and the average of the results was obtained.

For licorice root with a moisture content of (50 ± 2)% and a shear angle of 0°, the shear speeds were adjusted to 30 mm/min, 60 mm/min, 90 mm/min, 120 mm/min, and 150 mm/min for the cutting tests. Five sets of replicated experiments were performed at each shear speed, and the average of the results was calculated. The cutting process is depicted in Figure 7.

Fig. 7 - Cutting process

Multifactorial experiment

By incorporating single-factor experiments, multifactorial orthogonal tests taking into account moisture content, shear angle, and shear speed were conducted. The multifactorial orthogonal test scheme is presented in Table 1.

Table 1

Experimental factors and levels

Test No.	Moisture content / %	Shear angle / °	Shear speed / (mm/min)
1	20±2	0	30
2	30±2	15	60
3	40±2	30	90
4	50±2	45	120

Evaluation indicators

During the experiment, the licorice root specimen was precisely positioned on the testing platform of a universal testing machine. The sampling frequency was meticulously set to 50 Hz, and the base span was accurately configured to 30 mm. A 1000 N sensor in conjunction with its corresponding shear fixture was employed, featuring a double shear surface. The research primarily focused on investigating the effects of shear angle, moisture content, and shear rate on the maximum cutting force of licorice root stems. The computer software interfaced with the testing machine automatically recorded the data and generated a cutting force - displacement curve.

RESULTS AND ANALYSIS

The physical parameters and structural characteristics

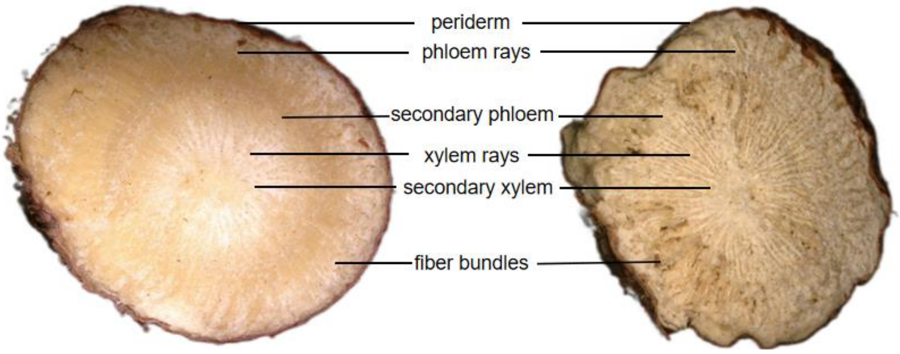
The mean length of four-year-old Ural licorice root was determined to be 41.78 mm, and the average diameter was measured as 15.054 mm. The direct measurements for each section are tabulated in Table 2.

Table 2

The physical parameters of Licorice root

Sampling location	Diameter / mm	Average diameter / mm	Average length / mm
Upper section	20.41	15.054	41.78
Upper-middle section	17.73		
Middle section	14.39		
Lower-middle section	12.72		
Lower section	10.02		

Figures 8 (a) and (b) depict the microscopic structural organization of licorice root under two distinct moisture content conditions, namely 52% and 11.6%. It is conspicuous that the principal constituents of the licorice root comprise the periderm, phloem rays, secondary phloem, xylem rays, secondary xylem, cambium, and fiber bundles. With a reduction in moisture content, the texture of the periderm becomes more pronounced and compact, the interstices between the phloem rays are marginally reduced, the secondary phloem displays wrinkling, the xylem rays undergo a darkening in coloration, and the lignification of the secondary xylem is enhanced.



（a）The water content is 52% （b）The water content is 11.6%

Fig. 8- Structure of cross-section of the internode of corn stalk

Moisture content and density

Based on the in-depth analysis of the experimental outcomes, the quality of ten groups of fresh licorice roots was found to stabilize subsequent to being dried for 12 hours at a temperature of 120°C. The initial moisture content of the fresh licorice roots was precisely measured and calculated, with a resultant moisture content of 52.36%. Moreover, the density of the licorice roots was ascertained by means of the specific gravity bottle method. Upon averaging the results, the final density of the fresh licorice roots was determined to be 1031 kg·m^{-3}.

Analysis of the cutting process

When the moisture content was within the range of (50 ± 3)%, the loading speed was set at 60 mm/min, and the shear angle was 0°. The cutting force-displacement curve of licorice root is presented in Figure 9. The cutting process of licorice root can be categorized into three distinct phases. In the initial phase (segment OA), the licorice root is in a compressive state, and the cutting force displays an approximately linear increment with respect to the displacement. In the intermediate phase (segment AB), as the displacement continuously augments, the cutting force exhibits a fluctuating upward trend. With further progression of displacement, the load surges sharply, attaining a peak value, which signifies the critical state at which the licorice root is severed. In the final phase (segment BC), the licorice root stem is entirely severed by the tool, leading to a rapid attenuation in cutting force until it approaches zero. Research findings suggest that although substantial differences exist in cutting force under diverse moisture contents, loading rates, and shear angles, the overall tendency of the cutting force - displacement curve for licorice root invariably shows an initial increase, subsequent fluctuations, and ultimately a precipitous decrease.

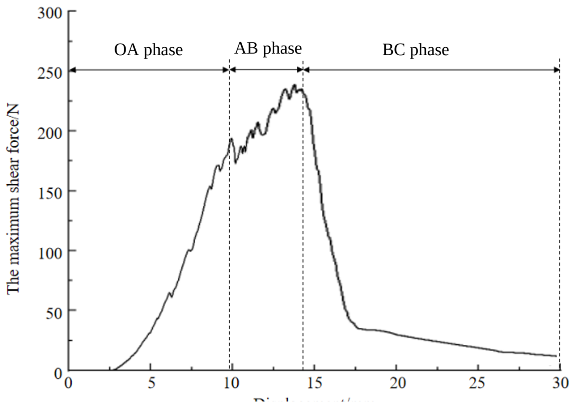


Fig. 9 - Cutting force-displacement curve

Analysis of Single-Factor Experimental Results

Analysis of the Influence of Moisture Content on the Maximum Shear Strength of Licorice Root

The variation in the impact of moisture content on shear strength is depicted in Figure 10. At a moisture content of (50 ± 2)%, the average maximum shear force was measured as 240.23 N. When the moisture content was adjusted to (40 ± 2)%, the average maximum shear force escalated to 312.87 N; at (30 ± 2)%, it further augmented to 357.95 N. At (20 ± 2)%, the average maximum shear force attained 397.65 N, and at (10 ± 2)%, the maximum shear force peaked at 447.87 N.

These data show a trend of increasing shear force as the moisture content in licorice root decreases. It can be inferred that at a moisture content of (50 ± 2)%, the shear force reaches its minimum, indicating that this moisture level is optimal for preprocessing operations such as slicing and root trimming.

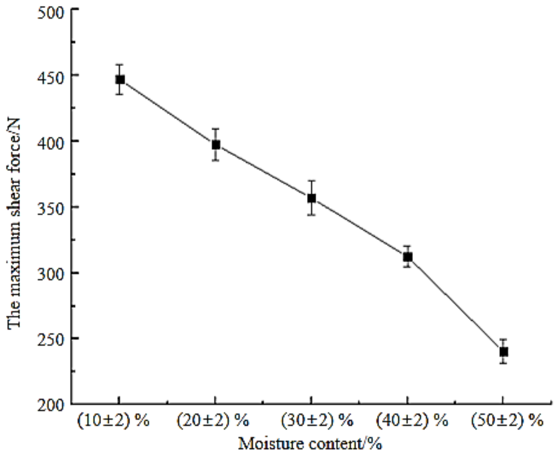


Fig. 10 - The effect of different moisture contents on cutting force

Analysis of the Influence of Shear Angle on the Maximum Shear Strength of Licorice Root

The variation in the impact of shear angle on shear strength is depicted in Figure 11. When the shear angle was set at 0º, the average value of the maximum shear force was measured as 292.398 N. Subsequently, when the shear angle was adjusted to 15º, the average value of the maximum shear force increased to 318.262 N. At a shear angle of 30º, the average value of the maximum shear force was 385.41 N. When the shear angle reached 45º, the average value of the maximum shear force was 426.366 N. And when the shear angle was set to 60°, the maximum shear force was 468.32 N. Within the range of shear angles from 0º to 60º, it was observed that the maximum shear force of licorice root exhibited a gradually increasing trend with the augmentation of the shear angle.

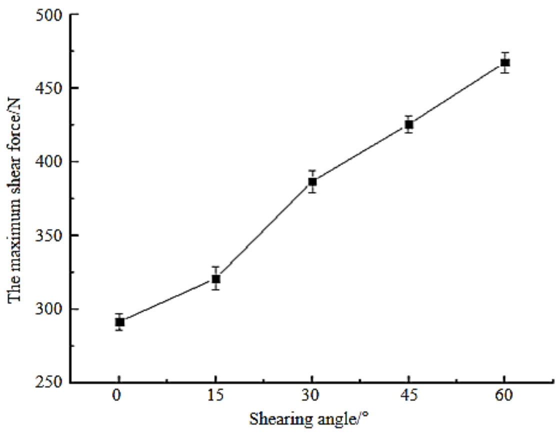


Fig. 11 - The effect of different shear angles on cutting force

Analysis of the Influence of Shear Speed on the Maximum Shear Strength of Licorice Root

The variation in the impact of shear speed on shear strength is depicted in Figure 12. When the shear speed was set at 150 mm/min, the average value of the maximum shear force of licorice root was measured as 290.398 N. Subsequently, when the shear speed was adjusted to 120 mm/min, the average value of the maximum shear force increased to 322.262 N. At a shear speed of 90 mm/min, the average value of the maximum shear force was 387.21 N. When the shear speed was reduced to 60 mm/min, the average value of the maximum shear force was 426.166 N. And when the shear speed was further decreased to 30 mm/min, the average value of the maximum shear force reached 476.32 N. It can be clearly seen that within the range of shear speed s set in the experiment, the shear force of licorice root exhibited a decreasing trend with the increase of the shear speed.

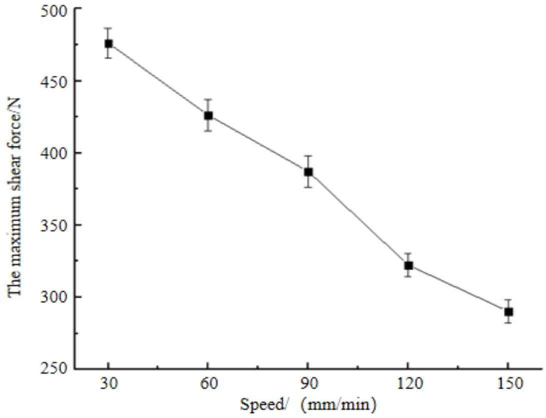


Fig. 12 - The effect of different shear speeds on cutting force

Multifactorial test analysis

After performing a univariate analysis of moisture content, shear angle, and shear rate, it is crucial to take into account the possible interactive effects among these factors, since they might have a cumulative influence on the shear strength of licorice root. Hence, combining these three factors for a multifactorial comprehensive analysis is justified. In this research, moisture content, shear angle, and shear rate were chosen as experimental variables, with the maximum shear strength as the experimental parameter. An orthogonal experiment was designed and carried out accordingly. The specific experimental protocol and corresponding results are shown in Table 3.

Table 3

Experimental factors and levels

Test No.	Moisture content A/%	shear angle B/°	shear speed C/(mm/min-^{1})	Maximum cutting Force /N
1	1	1	1	487.36
2	1	2	2	439.35
3	1	3	3	470.25
4	1	4	4	397.24
5	2	1	2	488.75
6	2	2	1	290.22
7	2	3	4	300.55
8	2	4	3	491.22
9	3	1	3	450.33
10	3	2	4	400.11
11	3	3	1	268.45
12	3	4	2	481.06
13	4	1	4	308.55
14	4	2	3	331.39
15	4	3	2	277.19
16	4	4	1	266.13

Analysis of variance, as an effective statistical method, allows for an in-depth examination of the fluctuations in experimental indicators caused by variations in the levels of experimental factors, thereby determining the significance of each factor's impact on the experimental outcomes. Data from Table 3 indicates that among the experimental factors considered in this study, the order of significance affecting the maximum shear force is as follows: moisture content, shear rate, and shear angle. The variation in moisture content of licorice has a highly significant effect on the shear force of licorice roots, dominating the entire influence framework. Additionally, the shear rate also significantly impacts the shear force of licorice roots, exhibiting a clear pattern of change with varying shear rates. In contrast, while the shear angle does have some effect on the shear force of licorice roots, its significance is relatively weak, suggesting a secondary role within the multifactorial interaction system. Nevertheless, its influence should not be entirely disregarded when conducting precise analyses and optimizing the shear processing of licorice roots.

Table 4

Analysis of Variance

Sources	SS	df	MS	F	P-value	Significance
Moisture content/A	49096.228	3	16365.409	7.704	0.018	*
shear angle/B	25835.984	3	8611.995	4.054	0.068	
shear speed/C	33104.015	3	11034.672	5.195	0.042	*
Error	12745.125	6	2124.188			
Total sum	120781.352	15				

*Note: *, significance level 0.01 < P < 0.05; **, significance level P < 0.01.*

From Table 5, it can be observed that the influence of various experimental factors on the maximum shear force follows a descending order of significance: A>C>B, which translates to moisture content > shear rate > shear angle. The intuitive analysis results regarding the maximum shear force are in strong agreement with the results of the variance analysis.

Table 5

Intuitive analysis results

Index	A	B	C
mean 1	448.6	433.7	328
mean 2	392.7	365.3	421.6
mean 3	400	329.1	435.8
mean 4	295.8	408.9	351.6
Range	152.7	104.6	107.8
Primary and secondary factors	A>C>B		
A relatively optimal combination	$A_4B_3C_1$		

For the determination of the optimal combination of factor levels, the present study endeavors to minimize the experimental index of maximum shear force. Via a visual analysis of the maximum shear force of licorice root, the level associated with the minimum value of the evaluation index was chosen. The optimal factor level combination with respect to maximum shear force was determined as $A_4B_3C_1$, which represents a moisture content of 50±2%, a shear angle of 0°, and a shear rate of 90 mm·min^{-1}. This optimal factor level combination offers a critical reference for the optimization of the licorice root shearing process and bears substantial guiding significance for subsequent related research and practical applications.

CONCLUSIONS

This study systematically analyzes the physical parameters, structural organization, and shear characteristics of four-year-old licorice, thereby providing a theoretical foundation for optimizing post-harvest treatment and processing techniques. The specific conclusions are as follows:

(1) Measurements demonstrate that the average length of the roots of four-year-old Ural licorice is approximately 41.78 mm, with an average diameter of around 15.054 mm. The diameters at the upper, upper-middle, middle, lower-middle, and lower sections are approximately 20.41 mm, 17.73 mm, 14.39 mm, 12.72 mm, and 10.02 mm, respectively. Moreover, the moisture content of fresh licorice roots is determined to be 52.36%, and the density is 1031 kg·m^{-3}.

(2) Shear tests on licorice roots disclose that the shear process mainly comprises three distinct stages: compression, shear, and unloading. This process reflects the mechanical response characteristics of licorice roots under shear forces, which is essential for a more profound understanding of their shear resistance.

(3) Results from single-factor experiments suggest that the shear force of licorice roots rises with increasing moisture content and shear angle, whereas it declines with a growing shear speed. Multi-factor experiments reveal the relative impact of various factors on the shear force of licorice roots in the following order: moisture content > shear speed > shear angle. The optimal combination of shear factors is identified as

$A_4B_3C_1$, corresponding to a moisture content of 50 ± 2%, a shear angle of 0°, and a shear speed of 90 mm·min^{-1}.

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