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Experimental research on shear mechanical properties of tomato stem**

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A b s t r a c t. In order to design a tomato stem crushing and bagging machine and also optimize its operational parameters, knowledge concerning the mechanical properties of harvest-ready tomato stems is required. The mechanical shear properties of the stems were studied by conducting a single-factor experiment, taking the blade angle, moisture content and sampling range as the experimental factors and the peak shear force as the evaluation indexes. The results showed that the blade angle had no significant effect on the mechanical shear properties of tomato stems, while the leaf water content and sampling location had significant effects on the mechanical shear properties of tomato stems. The largest peak force for cutting the tomato stem was observed in the middle of the sampling range, therefore a shear force greater than 411 N should be provided when designing the crushing device. At the same time, the machine should be used to harvest the tomato stalks as early as possible. The study will provide the necessary experimental data and theoretical basis for the development of an optimized tomato stem crushing and bagging machine.

K e y w o r d s: tomato stem, maximum shear force, straight knife

1. INTRODUCTION

The tomato is one of the world’s commercial crops and occupies an important position in the global food trade (Zhang *et al*., 2023; Wu and Song, 2022). With the increasing demand for tomatoes, the scale of the world's total tomato production will continue to expand (Wang *et al*., 2019). China produces more tomatoes than any other country. In 2019, China's tomato harvest area was 1 086 800 ha, and the annual output was 62 869 500 t, accounting for 21.60 and 34.78% of the world's total harvest area and annual output, respectively. The industrial scale of this production has continued to expand (Zeng *et al*., 2021). After the tomato harvest period, the huge amount of residue remaining is an important biomass resource, and its development and utilization are increasingly valued by governments around the world (Guo *et al*., 2018). In the process of returning them to the field, tomato stem are very difficult to break down and decompose because the stems or vine between the plants are creeping and intertwining. It is difficult to deploy operating machinery in order to process tomato plant residues. Crushing and incorporating residues into the soil may exacerbate the occurrence of diseases and pests, while haphazard disposal or incineration may pose a serious threat to transportation safety and cause environmental pollution (Chen *et al*., 2022). Therefore, it is necessary to carry out relevant research concerning the comprehensive utilization of tomato stems, with the purpose of reducing tomato stem waste, improving mechanical collection efficiency, and promoting the resource utilization of crop waste.

The treatment methods for the resource utilization of tomato stems in China are summarized in this study. Stalk cutting is closely related to the efficient and low damage harvesting of crops and also to the comprehensive utilization of stalk resources (Wu and Song, 2022). After the tomato harvest period, the huge amount of residues remaining is an important biomass resource, and the tomato stem must be collected in order to be used for resource utilization, an exception to this process is in situ stem recycling technology. In order to optimize the machinery related to harvesting, knowledge concerning the physical characteristics of tomato stems is required (Kovács and Kerényi, 2019). Tomato straw may be utilized in various ways in

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China. The available options include a direct return to the fields, their use as a fertilizer or a substrate, or else such residues may be used for the production of edible mushrooms, biogas and animal feed (Zhang *et al.*, 2023). Geng *et al.* (2016) employed fermented tomato straw compost mixed with vermiculite to grow tomato seedlings, and their results revealed that the seedlings performed well. Liu *et al.* (2014) and Zhang J. *et al.* (2013) studied the composting performance and fertilizer efficiency of tomato straw compost using composting fungicides and conditioners, respectively. The results showed that the different effects of different composting additives on the composting efficiency of tomato straw compost had a certain impact on the application of tomato straw waste.

The primary step in the comprehensive utilization of tomato stems is stem cutting. Extensive research has been conducted by scholars in China and abroad concerning the mechanical properties of crop stems. Guo *et al.* (2014) explored the energy consumption of cutting mature tomato and eggplant stems using a 40° rake angle sawtooth blade, it was found that the cutting energy consumption was low, the cutting efficiency was high, and the cutting effect was good. Shahbazi *et al.* (2012) studied the relationship between the shear stress and shear energy consumption of safflower and also the moisture content and stem position, and found that the shear stress and shear energy consumption increased with increasing moisture content and also increased from the top to the bottom of the stem. The maximum shear stress and shear energy consumption were 11.04 MPa and 938.33 MJ, respectively, at the lower part of the stem, with a moisture content of 37.16%. Zhang X. *et al.* (2013) found that the average elastic modulus of root cucumber vine stems was 280.58 MPa, which was much higher than the average elastic modulus of 198.81 and 137.22 MPa in the middle and head sections, respectively. The maximum shear force and the critical across-compression failure force were found to be 419.1 and 409.0 N, respectively, with a water content of 10%, the sampling location was the lower part of dwarf-dense-early major cotton variety stalks, and the loading speed was 40 mm min^{-1} (Liang *et al.*, 2020). The maximum shearing force and shearing energy of the *Glycyrrhiza glabra* stalks were found to be 174.03 N and 0.48 J. With increasing water content, the shearing force first decreased and then fluctuated slightly (Wen *et al.*, 2021). The maximum shear forces at different diameters (7, 8, 9, 10, and 11 mm) of wild chrysanthemum stem within the cutting range were determined to be 120.0, 159.2, 213.8, 300.0, and 378.2 N, respectively, through the use of a biomechanical testing machine and a custom-made shear blade (Wang *et al.*, 2022). It was shown that at a distance of 0-15 cm (zone A) and 16-30 cm (zone B) from the top of the cotton plant, the maximum shear force required is higher in zone B (121 N) as compared to zone A (73 N), which suggests that topping should be carried out as close as possible to the ground and that the topping process can be carried out with lower energy consumption. In terms of cutting energy requirements, it was concluded that topping should be completed as early as possible within 100 to 120 days after planting (Aydın and Arslan, 2018). The abovementioned studies concerning the shear force of tomato stems are relatively rare, but the research methods followed and the mechanical properties of these crop stems provide a theoretical support for future research, and also, this study may point to future directions in research concerning the mechanical properties of tomato stems.

Information relating to the physical and mechanical properties of the tomato stem is limited based on the existing foundational research. Therefore, this paper takes the tomato stem as a research subject, and studies the shear mechanical properties of tomato stems and also the factors affecting the magnitude of its shear force, including the blade angle, shearing speed, moisture content, and sampling range of the tomato stem. It is proposed that this study will provide basic data and a theoretical basis for the mechanization of tomato stalk collection and crushing, such as the degree of cutting force required for crushing and the optimal harvesting time period, this will be accomplished through the shear performance test of tomato stalks.

2. MATERIALS AND METHODS

The research was carried out using cherry tomato (*Lycopersicon esculentum* var. Cerasiforme A. Gray) stems from a vegetable production facility in Guli Street, Jiangning District, Nanjing City, Jiangsu Province, on July 7, 2022. Fresh plants that had grown well and were free from disease and insect pests were selected, also mechanical damage to the stems was avoided. The stems were pulled out completely while the tomatoes were still on the hanging vines (Kovács and Kerényi, 2019). The test was carried out immediately after the sample was collected. During the test, 80 samples were selected, the average height of the whole plant stem was 2 100 mm, the leaves and side branches were manually removed, and the stem was equally divided into three regions: top, middle, and bottom (Fig. 1) (Aydın and Arslan, 2018).

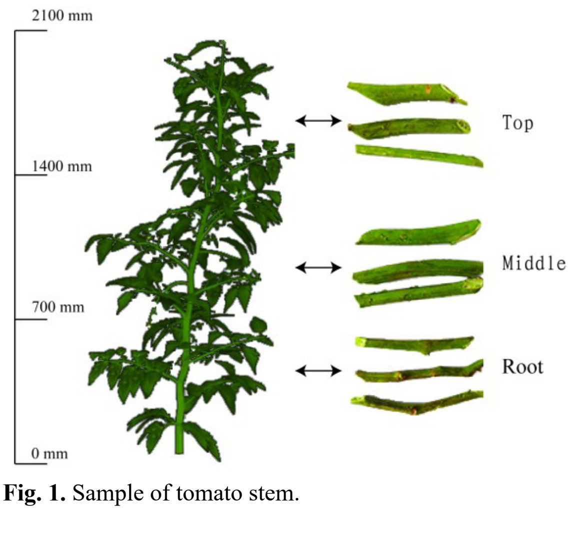

Fig. 1. Sample of tomato stem.

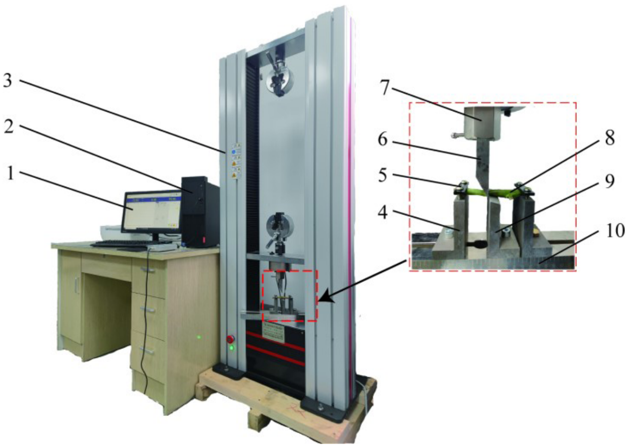

Fig. 2. Tomato stem shear test bench: 1 – display, 2 – computer, 3 – WDW–20 microcomputer–controlled electronic universal testing machine, 4 – block, 5 – press plate, 6 – moving knife, 7 – tool chuck, 8 – stem sample, 9 – fixed knife, 10 – pad block adjustment track.

The diameter of each sample (average diameter at the midpoint) was measured using an electronic digital calliper (GUANGLU, China) with a resolution of 0.01 mm. The WDW-20 microcomputer-controlled electronic universal testing machine (the maximum load of the machine is 10 000 N, its precision is ±0.01 N) from Jinan Chuanbai Instrument Equipment was used for the stem shearing test. The tomato stem shear device consisted of a display, computer, WDW-20 microcomputer-controlled electronic universal testing machine, block, press plate, moving knife, tool chuck, stem sample, fixed knife, and a pad block adjustment track. The experimental diagram and process are shown in Fig. 2. The force, displacement of the contact point, deformation, and loading speed may be recorded in real time during the test process. The test data and report may be saved at the end of the test. The shearing force F_{Smax} (N) of the test was measured using a universal testing machine. Prior to the test, the cushion block 1 and the fixed blade 6 are placed on the guide rail 7. The shearing blade 3 is mounted on the tool clamp 4 and locked with a bolt. The tomato stem is placed on the fixed blade 6 and the two cushion blocks 1, and the stem ends are pressed with a pressure plate 2 in order to enhance the stem's bending resistance and ensure a favourable shearing performance. The thickness of the shearing blade is 15 mm, and there are three different blade angles α, where α equals 20, 30, or 40° (Fig. 3). Studies have shown that the angle of the cutting edge has a significant effect on the cutting forces, and that the preferred cutting edge angle of a tool is in the range of 40-45° (Qian *et al.*, 2023). The higher the cutting angle, the higher the cutting power consumption and peak cutting force, it was found that the cutting power consumption and peak cutting force with an edge angle of 20-25° were the lowest for cutting sesame stalks (He *et al.*, 2021).

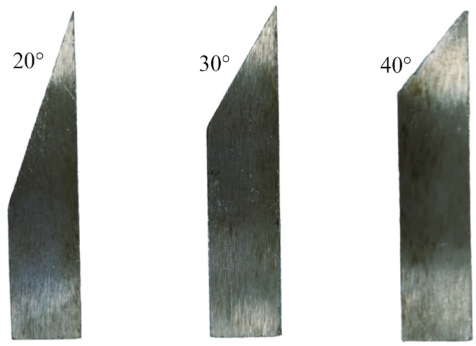

Fig. 3. Different blade angles.

The moisture of the tomato stem was determined by drying each sample in a forced-air oven at 103°C for 24 h (ASABE Standard S358.2, 2008). The samples were dried naturally, sampling occurred every 24 h to measure the moisture content. The moisture content was reported in percentage terms based on the dry material. After the completion of the equilibrium period, the stem moisture content (*SMC*) of the samples for each level of humidity was calculated according to the ASABE S358.2 (2008) method as follows:

$$SMC(dry\ base\ \%) = \frac{|W_1 - W_2|}{W_2} 100\% \,,$$

where: W_1 is the weight of the biomass at the point at which a constant weight (g) is achieved and W_2 is the dry matter of the biomass (g).

In order to study the mechanical shear properties of the tomato stem, the peak shear force was taken as the target value, and the influence of the shearing blade angle, moisture content, and sampling range on the target value was analysed. Based on the test results of moisture content determination (Fig. 4), which revealed a level of around 50% on the 5th day, there is a window of 5-15 days of crop rotation in greenhouse planting. Therefore, the average moisture content of tomato stems needs to be reduced to three different levels: 50, 30, and 10%. In order to ensure the controllability of the moisture content of tomato stem, the samples need to be placed in a chamber with a constant temperature and humidity before the experiment, this has the effect of standardizing their moisture content. In order to minimize the influence of moisture content regulation on the internal structure of the stems, the

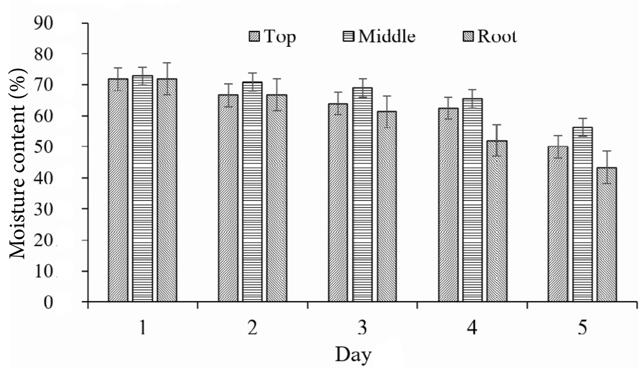

Fig. 4. Changes in moisture content of tomato vines every 24 h.

parameters of the constant temperature and humidity chamber are adjusted to a temperature of 30°C and a relative humidity of 95% (Theerarattananoon *et al*., 2011). Before the experiment, the tomato stem samples were taken out of the constant temperature and humidity chamber and dried at a low temperature of 40°C. The moisture content was measured using a rapid moisture analyser and adjusted to the desired level (Yu *et al*., 2012). Samples were taken from the lower, middle, and upper parts of the stem, that is, 700, 1400 and 2100 mm, with a random 100 mm section being taken from each sampling range for testing. Table 1 shows the factor level table of a single factor experimental design.

The single factor test method was applied in order to study the influence of blade angle on the mechanical shear properties of tomato stem. This was necessary to ensure that other test conditions were consistent, therefore the water content was set at 30% and the sampling range was set at 1400 mm to study the influence of the blade angle at 20, 30, and 40° on the experimental indexes. The test was repeated three times at each level.

The single factor test method was applied to studying the influence of water content on the shear mechanical properties of tomato stems. This was necessary to ensure that the other test conditions were consistent, therefore the blade angle was set at 30° and the sampling position was set at 1400 mm to study the influence of leaf water content at 10, 30, and 50% on the experimental indexes. The test was repeated three times at each level.

The single factor test method was applied to studying the influence of the sampling position on the mechanical shear properties of tomato stem. This was necessary to ensure the consistency of the other test conditions, so the water content was set at 30%, the blade angle was set at 30°, and the degree of influence of the leaf sampling position at 700, 1400, and 2100 mm on the experimental indexes was studied. The test was repeated three times at each level.

The factors affecting the mechanical properties of tomato stem shear were investigated using a one-way test method. The influences considered included the blade angle, moisture content and sampling location, and a total of three factorial tests were set up. The consistency of the test conditions beyond the factors studied had to be ensured for each trial. In the blade angle test, the moisture content was set at 30% and the sampling range was set at 1400 mm in order to investigate the effect of 20, 30 and 40° blade angles on the test parameters. In the water content test, the blade angle was set at 30° and the sampling position was set at 1400 mm to investigate the effect of blade moisture content at 10, 30 and 50%. In the sampling position test, the moisture content was set at 30% and the blade angle was set at 30° to examine the effect of the blade sampling position on the test metrics at 700, 1400 and 2100 mm. All tests were repeated three times at each level.

Table 1. Factor level table of single factor experiment

Levels	Factor		
	Blade angle (°)	Moisture content (%)	Sampling range (mm)
1	20	50	700
2	30	30	1400
3	40	10	2100

3. RESULTS AND DISCUSSION

The results clearly showed that different water content levels and sampling locations had significantly different effects on the physical properties and mechanical behaviour of the tomato stems. Therefore, this study could be used to determine the optimal harvesting time and cutting location of tomato stems. The changes in the moisture contents of the tomato stem samples every 24 h are shown in Fig. 4. The moisture content in the middle part of the stem decreased at the slowest rate, and the moisture content in the lower part of the stem decreased at the fastest rate. The attenuation rate of the moisture content of the whole plant was 5.26%, of which, the attenuation rate in the middle of the stem was 3.83% and the attenuation rate in the lower part of the stem was 7.18%.

The test results of the study concerning the influence of the sampling position on the mechanical shear properties of tomato stem are shown in Table 2. At a significance level of $\alpha=0.05$, IBM SPSS Statistics 24 software was used to conduct a p-value test on the sampling locations of the leaves. The variance analysis is shown in Table 3. The results show that the mechanical shear properties of the sampling locations of the leaves on tomato stems were $0.01<p<0.05$. Therefore, the sampling location of the shear leaves has a significant effect on the mechanical shear properties of tomato stems.

Table 2. Effect of sampling position on shear mechanical properties of tomato stem

Sampling range (mm)	Peak shear force
700	181
700	205.2
700	260.6
1400	287.8
1400	243.8
1400	294.6
2100	188.6
2100	179.6
2100	146.2

Table 3. Variance analysis of the effect of sampling position on shear mechanical properties of tomato stem

Sources	Sum of squares	Degree of freedom	Mean square	F	Significance
Intra-class	16325.929	2	8162.964	8.373	0.018
Interblock	516849.387	6	974.898		
Total	22175.316	8			

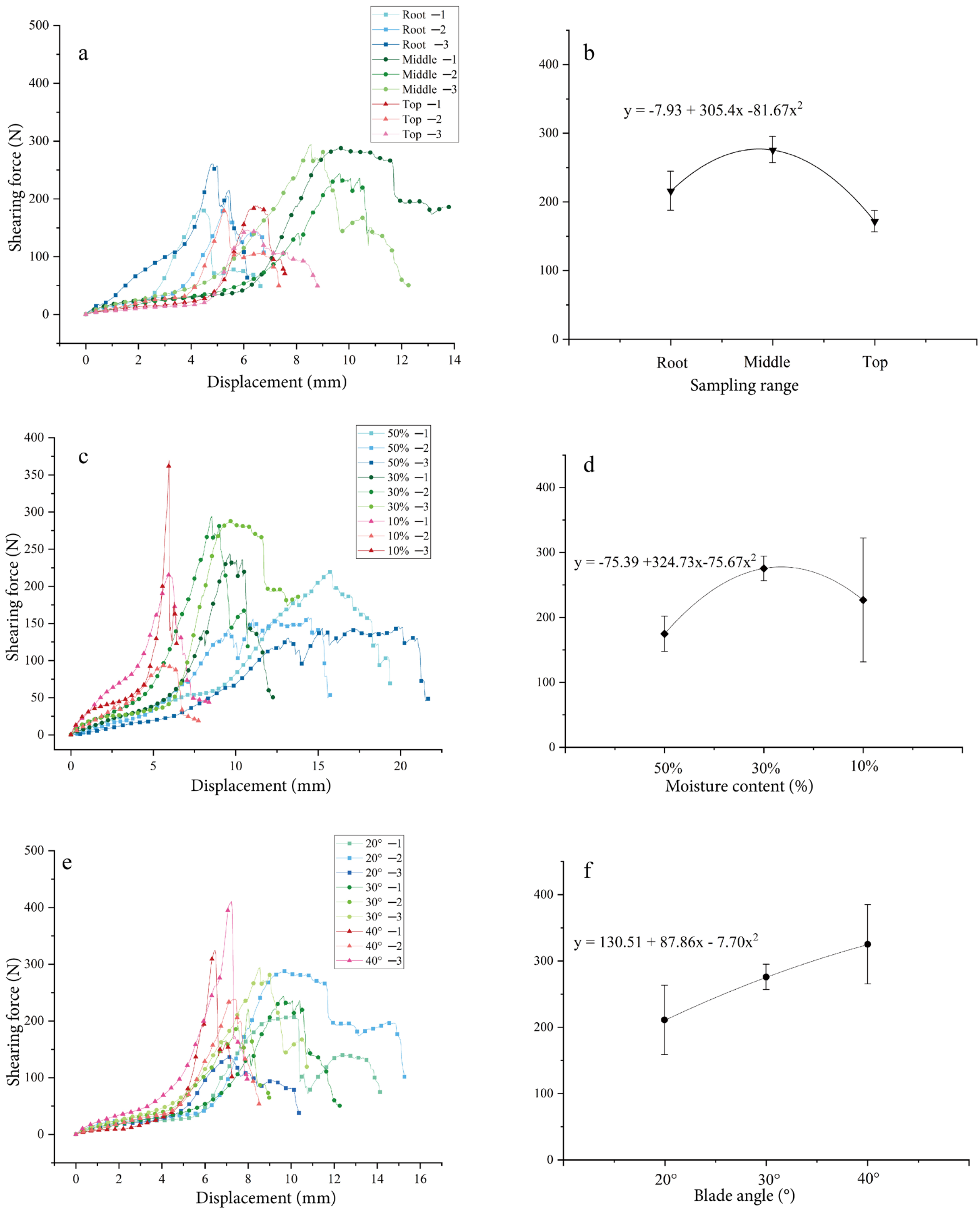

Fig. 5. The influence of various factors on shearing characteristics: (a) curves of shearing force and displacement under sampling range, (b) effect of the sampling range on the shearing force, (c) curves of shearing force and displacement under moisture content, (d) effect of the moisture content on the shearing force, (e) curves of shearing force and displacement under blade angle, (f) effect of the blade angle on the shearing force.

The influence of the sampling range of the shearing force was examined when the stem had a moisture content of 30% and a blade angle of 30°. The displacement curve was drawn with Origin 9.1 (Origin Lab) using real-time data from force variation with displacement produced under three sampling ranges, as shown in Fig. 5a. The highest peak shear force of 294.6 N was observed at the middle sampling range, while the lowest peak shear force of 146.2 N was observed at the top sampling range. As shown in Fig. 5b, the shearing force increased and then dropped as the sampling position moved from the bottom to the top according to the results. The sampling range and shearing force of the tomato stems were analysed using variance analysis and curve fitting under the same water content. The mean diameters of the top, middle, and bottom regions were 6.40, 9.82, and 7.5 mm, and the standard deviations were 0.53, 0.63, and 0.26. Therefore, it was inferred from the results that the shearing force increased with increases in the tomato stem diameter. Previous studies have shown that the fibre fraction forms the main part of the mechanical properties of the stalk (Réquilé *et al*., 2018). Based on this finding, it may be concluded that the fibre fraction is the primary cause of the increase in shear force.

The test results of the study concerning the effect of water content on the mechanical shear properties of tomato stem are shown in Table 4. At a significance level of α=0.05, IBM SPSS Statistics 24 software was used to conduct a p-value test on the water content. The variance analysis is shown in Table 5. The results showed that the water content was $0.01<p<0.05$ regarding the shear mechanical properties of tomato stems. Therefore, leaf moisture content has a significant effect on the mechanical shear properties of tomato stems.

The influence of different water content levels on the shearing force in the middle part of the stem was studied. The real-time data of force variation with displacement under three water contents were obtained, and the resulting displacement curve was drawn using Origin 9.1 (Origin Lab), as shown in Fig. 5c. The maximum peak shear force of 360.6 N was observed at a moisture content of 50%, while the minimum peak shear force of 275.6 N was observed at a moisture content of 10%. As the moisture content decreased, the shearing force increased rapidly, and there was a slight fluctuation when it reached 30%, as shown in Fig. 5d. A decrease in the shearing energy with the increasing stem moisture content of the maize was reported because of the positive relationship between the shearing force and the cellulose and lignin content (Chen *et al*., 2007).

The test results of the study concerning the influence of the blade angle on the mechanical shear properties of tomato stem are shown in Table 6. At a significance level of α=0.05, IBM SPSS Statistics 24 software was used to conduct a p-value test on the blade angle. The variance analysis is shown in Table 7. The results showed that the mechanical shear properties of tomato stem were $p > 0.1$, so the effect of the blade angle (20°~ 40) on the mechanical shear properties of tomato stem was not significant. It was not shown that the blade angle had no significant effect on the shearing performance of tomato stems. In fact, the blade angle had an extremely significant effect on the peak force of sesame stalk cutting (He *et al*., 2021). In the middle of the stem where the moisture content was 30%, the influence of the different blade angles on the shearing force is shown in Fig. 5e. The maximum peak shear force of 411 N was observed at a shearing blade angle of 40°, while the minimum peak shear force of 207.6 N was observed at a shearing blade angle of 20°. The results indicate that the shearing force increased with an increase in the blade angle, as shown in Fig. 5f.

4. CONCLUSIONS

In this paper, the mechanical properties of tomato stems were studied based on an analysis of the physical characteristics of stems of crops grown booth in China and both abroad. The results showed that the blade angle had no significant effect on the mechanical shear properties of tomato stems, while the leaf water content and sampling location

Table 4. Effect of moisture content on shear mechanical properties of tomato stem

Moisture content (%)	Peak shear force
50	94
50	158.6
50	145.91
30	243.8
30	294.6
30	287.8
10	217
10	219.5
10	369.4

Table 5. Variance analysis of effects of moisture content on shear mechanical properties of tomato stem

Sources	Sum of squares	Degree of freedom	Mean square	F	Significance
Intra-class	38810.826	2	19405.413	6.097	0.036
Interblock	19097.915	6	3182.986		
Total	57908.741	8			

Table 6. Effect of shear blade angle on shear mechanical properties of tomato stem

Blade angle (°)	Peak shear force
20	207.6
20	287.8
20	136.6
30	243.8
30	287.8
30	294.6
40	324.8
40	238.4
40	411

Table 7. Variance analysis of the effect of blade angle on the shear mechanical properties of tomato stem

Sources	Sum of squares	Degree of freedom	Mean square	F	Significance
Intra-class	19635.387	2	9817.693	2.114	0.202
Interblock	27861.173	6	4643.529		
Total	47496.560	8			

had significant effects on the mechanical shear properties of tomato stems. The effect of the sampling location was mainly due to the cross-sectional diameters of the different parts of the tomato stalks, and also the moisture content had an effect on the shear force by influencing certain changes in the levels of cellulose and lignin in the stalks.

1. The sampling range of the tomato stems had a great influence on the shearing force. When the sampling range was between 0 and 2 100 mm, the largest peak force which occurred during the cutting of the tomato stem was observed in the middle of the sampling range.

2. Through the moisture content test and mechanical experiments it was established that the shearing force increased when the moisture content increased. Therefore, the machine should harvest as early as possible.

3. Upon analysing all experimental data, it was found that the maximum peak shearing force recorded was 411 N. Therefore, the design of the crushing device should be capable of providing a force greater than 411 N.

This study was aimed at establishing a foundation for understanding the mechanical properties of tomato stems. It will provide the necessary experimental data and a sound theoretical basis for developing efficient crushing and bagging machines for tomato stems. By taking into account the maximum shear force required for tomato stalks as derived from this study, energy wastage can be avoided. Additionally, the study suggests that the machine should operate within 1-5 days after the tomato harvesting period to ensure optimum processing time.

Conflicts of Interest: The authors declare that there is no conflict of interest regarding the publication of this paper.

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