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Research Article

Effect of Mechanical Properties of Sweet Potato Seedlings on Quality of Mechanized Processing and Recycling Work

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Abstract: To research and understand the mechanical properties of sweet potato seedlings, and to provide relevant data for the development of machinery related to sweet potato seedlings processing and recycling, this paper used Shangshu 19 sweet potato seedlings in harvesting period as the test material, the shear test and moisture content of sweet potato seedlings were tested, the influence of moisture content and loading rate on the shear force of sweet potato seedlings were studied, and the influence of mechanical properties of sweet potato seedlings on the operation efficiency was verified.Â At the beginning of experience harvest period, the results showed that the moisture content of sweet potato seedlings was 83.28%, when the loading rate was 10 and 20 mm/min the shear force was 72.1 and 82.7N respectively. With the increase in growth time, it is concluded that the moisture content of sweet potato seedlings decreases, and the shear force increases with the increase in growth time and cutting speed. The test results provide the theoretical basis for the design of related structures and the operation parameters determination.

Keywords: Sweet Potato Seedlings, Mechanical Properties, Test, Shear, Moisture Content,

Introduction

Sweet potato is an annual or perennial herbaceous plant (Lan, 2024). They are important food, feed, industrial raw materials, new energy materials, and high-quality anti-cancer health food. Sweet potatoes are grown in vast regions around the world (Wu *et al.*, 2018; Tan *et al.*, 2024), and China is the largest producer of sweet potatoes in the world. The annual sweet potato cultivation area is over 6 million hectares, accounting for 4.2% of China's total arable land and accounting for approximately 60% of the world's total. According to FAO data, Total Sweet Potato Production in China was 5.2×10^{10} kg in 2019, accounting for 56.62% of the global sweet potato production (FAO, 2021; International Trade Center, 2021). The sweet potato production in 2019 was 14.5×10^{8} kg in the United States (Potter, 2019). Sweet potato is a long seedling crop with high yields and lush growth. The seedlings have fibrous roots and grow close to the ground, covering the entire ridge and ground. The stems and seedlings between rows are intertwined and difficult to separate (Gibson, 2013). Manual cutting of seedlings is labor-intensive, costly, and inefficient (Wang *et al.*, 2021a; Shen *et al.*, 2019). Insufficient equipment support leads to an increase in planting costs, seriously affecting the enthusiasm of potato farmers (Hrushetsky et *al*., 2019). If the seedlings are not removed first, During machine harvesting, There will be phenomena such as seedlings entangled rod, Cluster seedlings blocking the separation and impurity removal components, etc, resulting in high impurity content (Boydston *et al.*, 2018), which leads to unsatisfactory separation effect of potato soil and seedlings. This is the key factor affecting the efficiency of machine operation and harvest quality (Geng *et al.*, 2021; Ahangarnezhad *et al.*, 2019) because it will further lead to the damage rate of sweet potatoes, skin breakage rate, and sweet potato disease rate (Kuyu *et al.*, 2019). Therefore, the mechanization of sweet potato harvesting must consider the handling of sweet potato seedlings. Before excavating and harvesting sweet potatoes, the seedlings must be cleared (Phesatcha and Wanapat, 2013). It is of significant importance for the development of the sweet potato industry in China to develop a sweet potato seedlings recycling machine with advanced technology and reliable performance (Mu *et al.*, 2019).

Abroad, agricultural mechanization research started earlier (Kumar Sahu *et al.*, 2018; Ahmad *et al.*, 2021; Bulgakov *et al.*, 2021). Japan's self-propelled sweet potato pruning machine and South Korea's small sweet potato pruning machine use a rotary wheel crusher to crush the seedlings. However, this type of sweet potato pruning machine cannot meet the requirements of seedlings recycling and is prone to damaging the potato chunks. The United States has developed a mechanical seedlings rolling machine that crushes and collects after harvesting, which is not suitable for China's planting and production mode. Another tracked sweet potato seedlings processing harvester in Japan with seedlings crushing function has a complex structure and high price (Wang *et al.*, 2020). Bulgakov, Olt, and others have conducted extensive research and optimized design in the separation of potato soil and seedling impurities (Olt *et al.*, 2021; Bogue, 2017; Wu & Song, 2022; Zheng *et al.*, 2019). In China, the overall development of mechanization technology in sweet potato production is relatively backward. In recent years, with the continuous emergence of intensive sweet potato cultivation and the increasing shortage of rural labor, the demand for sweet potato machinery has been increasing. Some research institutes and production enterprises have also accelerated the research and development of new technologies and models (Wu *et al.*, 2017a). Wang Xiangyou, Yang Ranbing, and others have effectively improved the quality of operations through their research on the design of potato harvester separation devices and potato impurity detection methods (Wang *et al.*, 2021b; Yang *et al.*, 2023). In terms of mechanized treatment of sweet potato seedlings, the technology of processing and recycling sweet potato seedlings in the field is mostly adopted in China (Mu *et al.*, 2018). Wu *et al.* (2017b) developed a walking sweet potato shredding and returning machine, but this machine directly returns sweet potato seedlings after crushing them, which cannot achieve sweet potato seedlings recycling and use as feed and also exacerbates the spread of sweet potato diseases and pests (Mu *et al.*, 2019). There are still common problems in the current sweet potato pruning machine, such as high working resistance, high energy consumption, low net removal rate of ridge and furrow seedlings, high potato damage rate, long stubble length on the ridge surface, and low qualified crushing rate, which have not been effectively solved. These problems seriously restrict the application and promotion of sweet potato recycling machinery (Wu *et al.*, 2017a).

The mechanical characteristics of sweet potato seedlings during the harvest period are important factors affecting the main operating indicators of the sweet potato seedlings treatment and recycling machine, such as the recovery rate of seedlings, the qualified rate of crushing length, and the height of stubble left at the top of the ridge. Studying the mechanical properties of sweet potato seedlings is the basis for establishing material models and constitutive relationships of sweet potato seedlings under various loads. It has crucial references and is of guiding significance for the structural optimization design and operation parameter determination of sweet potato seedling processing and recycling machinery. In recent years, research on the mechanical properties of crop stems has received widespread attention, and related studies are also increasing. Xin *et al.* (2018) used a universal testing machine and tensile tests to test the mechanical properties of mature garlic main stems, such as tensile strength, extrusion strength, and pull-out force. They studied the effects of straight stems, moisture content, and loading speed on the tensile strength of garlic main stems. However, few studies have mentioned the relationship between mechanical properties and the mechanized processing effect of agricultural straws. In this study, sweet potato seedlings were taken as research objects to study their mechanical properties with diverse time and moisture content, revealing the relationship between the seedling's moisture content, shear force, and the quality of mechanized collection work. It has significant meanings in promoting stem resourceful, comprehensive utilization.

Materials and Methods

Experimental Materials

Sweet potato seedling samples were taken from the Shandong Agricultural University sweet potato planting base. Taking Shangshu 19 as the experimental object, the sweet potato seedlings during the harvest period are shown in Figure (1). They are planted in early May, harvested in the middle of October, and planted once a year. The planting mode is single ridge and single row planting, with a ridge spacing of 900 mm and a plant spacing of 250 mm. The annual harvest time for sweet potato chunks starts on October 13th. In order to make the research more comprehensive, this sampling time starts on October 7th and ends on October 28th. Samples are taken every 3 days, with a total of 9 batches sampled. Cut off the root canal 2cm away from the ground during sampling, remove branches and leaves in the laboratory, and leave the main stem as the test object. The diameter of the seedlings of the collected Shangshu 19 ranged from 0.58-0.96 cm.

Experimental Equipment

The experimental equipment used in this experiment mainly includes an electronic universal testing machine of microcomputer controlled (WDW-5E type, Jinan Shijin Group Co., Ltd.), an electric heating drying oven (202-2 type, Shanghai Second Hardware Factory), a sweet potato seedlings processing and recycling machine of Mechanical and Electrical Engineering in Shandong Agricultural University, an electronic balance (0.001g, JA5003A type, Shanghai Jingtian Electronic Instrument Co., Ltd.), as well as a vernier caliper, tape measure, etc.

Fig. 1: Sweet potato seedlings in harvesting period

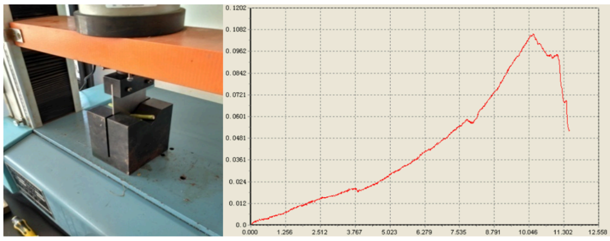

Fig. 2: Shear test of sweet potato seedlings

Experimental Methods

Sweet Potato Seedlings Shear Test

The sweet potato seedlings shear test was conducted on the WDW-5E electronic universal testing machine of microcomputer controlled, with an accuracy of the force sensor and displacement sensor within ± 1%, respectively. Take a sweet potato seedling with a length of 50mm, place the sample on a V-shaped positioning block, and perform two sets of shear tests on each collected sample on a WDW-5E microcomputer-controlled electronic universal testing machine at loading speeds of 10 mm/min and 20 mm/min, respectively (Figure 2). The microcomputer automatically records the relevant data. Each experiment is tested 5 times, and the average value is taken to compare the impact of different loading speeds on the variation of shear force.

Moisture Content Measurement Test

A moisture content measurement test is immediately conducted on the sample after measuring its shear characteristics. In the moisture content measurement experiment, the samples that have completed the experiment are labeled and weighed and then placed in an electric drying oven to dry at a temperature of 100-105°C for 8 h. Then, 2-3 samples are selected for the first weighing. Weigh every 2 h until the difference between the last two measurements does not exceed 0.002g, indicating that the sample has reached full dryness. After removal, place it in a drying dish to recover to room temperature and weigh it. The moisture content of sweet potato seedlings is calculated using the following formula:

$$w = \frac{m - m_s}{m} \times 100\% \tag{1}$$

In the formula: W-moisture content, %; m- Sample weight, *g;* m_s- Mass after drying, g.

Results and Analysis

Results of Moisture Content Test

The results of the moisture content test for sweet potato seedlings are shown in Figure (3). The moisture content of sweet potato seedlings was 85.82% during the sampling on October 7th and 70.21% during the sampling on October 28th. Within 21 days, the moisture content of sweet potato seedlings decreased by 15.61%. The moisture content of sweet potato seedlings decreased slowly in the early stage of ripening and decreased faster in the later stage of ripening, indicating that the moisture content of sweet potato seedlings during the harvest period decreased with the growth time. The moisture content of sweet potato seedlings during the experienced harvest period on October 13th is 83.28%.

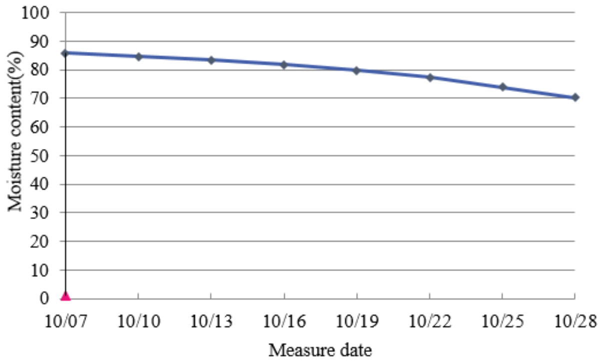

Fig. 3: Moisture content of sweet potato seedlings changes with time

Results of Shear Test

In the shear test, when the loading speed of the universal testing machine tool is 10 and 20 mm/min, respectively, the shear force data is obtained, as shown in Figure (4). When the loading speed is 10 mm/min, the shear force at the sampling on October 7th is 68.9N, and the shear force at the sampling on October 28th is 118.4N. Within 21 days, the shear force of sweet potato seedlings increased by 39.5N. In the early stage of sweet potato ripening, the shear force of sweet potato seedlings increased slowly, while in the later stage, it increased faster. This indicates that the shear force of sweet potato seedlings during the harvest period increases with the growth time, essentially increasing with the decrease of moisture content. As the growth period increases, the moisture content of sweet potato seedlings decreases. Due to the decrease in moisture, sweet potato seedlings gradually age and lose their activity. The toughness of the seedlings continues to increase, so the shear force shows an increasing trend. The sheer force of sweet potato seedlings during the experienced harvest period on October 13th is 72.1N. When the loading speed is 20 mm/min, the shear force during sampling on October 7th was 79.6N, and the shear force during sampling on October 28th was 121.9N. Within 21 days, the shear force of sweet potato seedlings increased by 43.8N, and the shear force of sweet potato seedlings during the harvest period on October 13th was 82.7N. Comparing the curve graph, it can be seen that the shear force generated increases as the cutting speed increases.

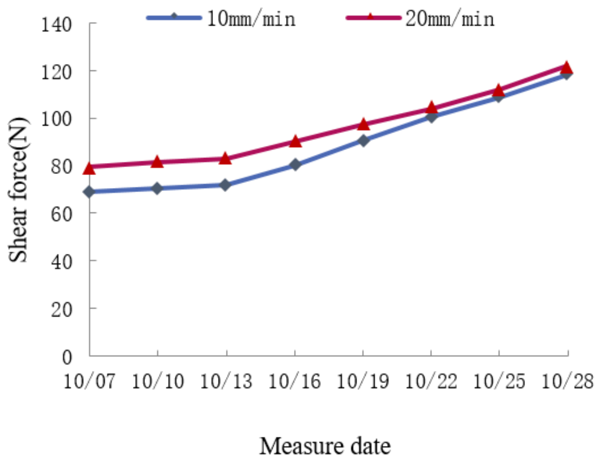

Fig. 4: The shear force of sweet potato seedlings changes with time

Relationship between Moisture Content and Mechanical Properties of Sweet Potato Seedlings

The moisture content has a great influence on the shear force of sweet potato seedlings. Due to the reduction of water, sweet potato seedlings gradually age and lose activity. Their toughness and shear strength have been increasing, so the shear force is also increasing. Therefore, in order to further reflect the change law between moisture content and shear force of sweet potato seedlings for Shangshu 19, the relationship between them was obtained by Matlab software, as shown in Eq. (2):

$$F_1 = 0.372x^2 + 2.206x + 74.87\ R^2 = 0.998 \tag{2}$$

Where F represents shear force, *N*; x represents moisture content, %. According to the formula, the relationship between the shear force and the moisture content of sweet potato seedlings is similar to the quadratic function regression equations, and the fitting coefficient of determination R^2 both reached above 0.99.

Field Trial of Sweet Potato Seedlings Treatment and Recycling Machine

To further investigate and verify the influence of mechanical properties of sweet potato seedlings on sweet potato seedlings crushing processing, sweet potato seedlings crushing processing machine was used to conduct operational tests on the harvested variety Shangshu 19. The main tests were conducted on the qualified rate of sweet potato seedlings' crushing length and the indicators of ridge top stubble length. During each test, the experimental field was divided into five blocks, each with a length of 10 meters. Five batches of test data were tested each time, and the average value was taken. Two sets of operating parameters are selected for the sweet potato seedlings processing and recycling machine: In the first set, the forward speed of the machine is 0.69 m/s, and the blade shaft speed is 2000 r/min. In the second group, with a forward speed of 0.69 m/s and a blade shaft speed of 2200 r/min, the qualified rate of sweet potato seedlings crushing length and the length of stubble left at the top of the ridge were obtained for two sets of operating parameters.

After the operation, pick out the sweet potato seedlings whose crushing length (the qualified crushing length is not more than 150 mm) is unqualified and weigh them, taking the average value as the unqualified seedlings quality M_b, then calculating the qualified rate of sweet potato seedlings crushing length, as shown in the following formula:

$$Y1 = 1 - \frac{Mb}{Mz} \times 100\% \tag{3}$$

In the formula: The qualified rate of sweet potato seedlings crushing length, %; M_b - the quality of seedlings whose crushing length is unqualified after the operation, kg; M_z - the total quality of the seedlings before the operation, kg.

The top ridge stubble length means the distance from the top of the stubble to the ground after the collecting operation. After the operation, 10 stubble lengths were randomly measured in the test area, and the mean value was taken as the stubble length, as shown in the following formula:

$$Y_2 = \frac{\sum_{i=1}^{10} l_i}{10} \tag{4}$$

In the formula: Y_2 - the top ridge stubble length, mm; l_i - the total stubble height of each sweet potato seedling measured.

The test results are shown in Figure (5).

From Figure (5), it can be seen that as the growth period of sweet potatoes increases, the qualified rate of seedlings crushing length for both sets of operation parameters shows a downward trend, while the length of stubble at the top of the ridge shows an upward trend. When the blade shaft speed is 2000 r/min and 2200 r/min, the qualified rate of the crushed length of seedlings decreases from 97.1 and 98.5 to 88.9 and 89.8%, respectively. The length of stubble left at the top of the ridge increases from 2.1 and 2.3cm to 6.3 and 6.9cm, respectively. The qualified rate of seedling crushing length for the second set of operating parameters is slightly higher than that for the first set of operating parameters. After October 25th, the qualified rate of seedlings crushing length for both sets of operating parameters is less than 90%. The length of ridge top stubble for the second set of operating parameters is slightly higher than that for the first set of operating parameters. After October 25th, the length of ridge top stubble for both sets of operating parameters is greater than 5 cm. The results showed that with the increase of the growth period and the rise of the seedling's shear force, the work quality of sweet potato seedlings processing and recycling machines declined. With the increase of the growth period, the shear force and the working load of the machine increased, the line speed of the flail cutter decreased, so long sweet potato seedlings increased, and the qualified rate of sweet potato seedlings crushing length decreased. In addition, with the increasing of the growth period, sweet potato seedlings gradually aged and lost activity; their toughness and shear strength have been increasing and led to the root of sweet potato seedlings not easy to cut off, so the flail cutter cut the slightly soft part which away from the roots, and lead to the top ridge stubble height is getting longer and the collected rate decreased.

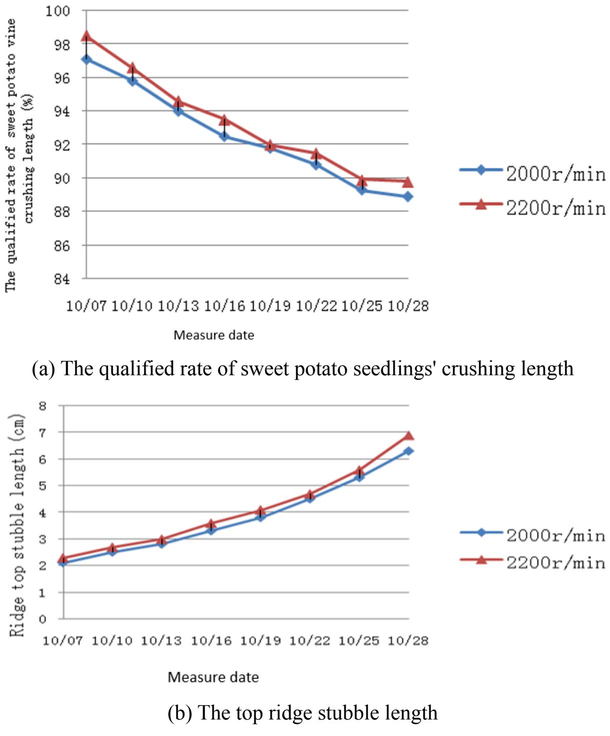

Fig. 5: Changes in major operation quality technical indexes of sweet potato seedlings processing and recycling machine

Discussion

The moisture content of sweet potato seedlings was 85.82% on October 7th and 70.21% on October 28th, respectively. Within 21 days, the moisture content of sweet potato seedlings decreased by 15.61%, indicating that the moisture content of sweet potato seedlings during the harvest period decreased with the growth time.

When conducting shear tests, when the loading speed is 10 and 20 mm/min, the shear force shows an upward trend, indicating that the shear force of sweet potato seedlings during the harvest period increases with the growth time, that is, increases with the decrease of moisture content. The shear force at a loading speed of 20 mm/min is greater than that at a loading speed of 10 mm/min, indicating that the shear force of sweet potato seedlings increases with the increase of cutting speed.

Field experiments were conducted using a sweet potato seedlings processing and recycling machine. As the growth period of sweet potatoes increased, the qualified rate of sweet potato seedlings crushing length and recycling rate decreased, while the length of stubble at the top of the ridge increased, indicating that the operational quality of the sweet potato seedlings processing and recycling machine decreased with the growth period.

According to relevant information, Chen *et al.* (2016) studied the mechanical properties of sorghum straw; Liang and Luan (2013) studied the mechanical properties of peanut plants; Liu *et al.* (2009) studied the mechanical properties of rapeseed stems. There are also related studies on sweet potato vine treating and recycling machinery from other aspects. This study focuses on the impact of sweet potato vine mechanical properties on operation efficiency from the perspective of treating and recycling. Through long-term experiments, a large amount of data has been obtained, and some new patterns have been discovered. These data and patterns provide theoretical basis for the development of new high-efficiency processing machines. Due to the limitation of sweet potato ripening time, more sampling, more experiments, and more thorough steps are needed to further verify the accuracy of the data, the inherent correlation with various changes, and discover more mechanical properties and their changing patterns. Further research on the determination of the influence of mechanical characteristic parameters of sweet potato seedlings on operational efficiency is to be used in the design and development of new sweet potato seedlings processing and recycling machinery.

Conclusion

Shear tests and moisture content measurements were conducted on the harvested variety Shangshu 19 sweet potato seedlings using an electric heating drying oven and an electronic universal testing machine. The effects of moisture content and blade loading rate on the shear force were studied, and the influence of mechanical properties of sweet potato seedlings on operational efficiency was verified through a sweet potato seedlings treatment and recovery machine.

According to the method described in this article, a more extensive and thorough experiment will be conducted to verify the accuracy and regularity of the data, which will be used for the design and development of relevant new agricultural machinery, improve efficiency, increase production and income, reduce labor burden, and achieve better modernization of sweet potato recycling operations.

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Author's Contributions

Junming Liu: Prepared the paper, performed the experiments, and analyzed the data.

Tao Zhang, Jian Sun, Dong Zhao, Dahai Ye, Shumei Qiao, Peng Cheng and Wenxiu Zheng: Performed the experiments and analyzed the data.

Wenlong Zhao: Designed and performed the experiments and revised the manuscript.

Ethics

Participants in this study have the right to refuse to participate or withdraw midway. The results are used to develop new and efficient processors. The conduct and funding of this study comply with ethical standards and ensure its objectivity and scientific validity. The data obtained through experiments will be properly processed and stored.

Conflict of Interest

The authors declare that they have no competing interests. The corresponding author affirms that all of the authors have read and approved the manuscript.

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