An experimental study on the physical mechanics and collision characteristics of potato tubers in different haulm removal times

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ABSTRACT
Most potato harvesting in China requires haulm removal. The properties of the tubers change after haulm removal. Investigating the effects of different haulm removal times on the physical mechanics and collision damage characteristics of potato tubers during the harvest period can provide a reference for reducing the damage rate of potato tubers during mechanical harvesting. The Longshu No. 7 potato, which is widely grown in northwest China, was selected as the experimental object in this study. The tuber parameters of the physical mechanics and collision damage characteristics for four different haulm removal dates (0, 7, 10 and 14 days before harvesting) were experimentally determined. The results showed that with the increase in haulm removal time before harvesting, the rupture pressure, Young’s modulus, and shear modulus increased significantly. The coefficient of restitution decreased significantly. Additionally, when multiple potato tubers fell on the steel plate in the EDEM simulation test, the maximum force of a single tuber with the largest resultant force and the maximum contact force of all tubers were affected significantly. Both showed significant downward trends. The results of this study can provide a reference for discrete element simulation parameters related to potato harvesting machinery. It can also provide a reference for determining the time to haulm removal during the actual harvest.

INTRODUCTION

The potato (Solanum tuberosum L.) is one of the world’s most important non-grain food crop and is widely planted in many countries, including in China. According to data from the China Rural Statistical Yearbook, in 2020 the Chinese potato planting area was 4.656 million hectares and the yield was 17.983 million tons. Harvesting is a key phase of potato production. Potato haulms usually need to be removed before harvesting the tubers. According to their use principle, the most commonly used methods of haulm removal can be divided into artificial haulm removal, mechanical haulm removal, and chemical haulm removal methods. Removing potato haulms before harvest can accelerate the suberization of the tuber epidermis, which can increase the damage resistance of the tubers. It also makes a big difference to the risk of late blight tuber infection. Removing the aboveground stems and leaves of potatoes can help to avoid mechanical failure caused by winding and blocking, effectively improving the quality of harvest, especially in mechanized harvesting.

The timing of haulm removal during the potato harvest is extremely important. Early removal results in thicker and stronger potato tuber skins, and tuber size, yield and starch content are also affected. Later removal can guarantee sufficient growth time and increase the tuber yield.
the risk of disease transmission from the above-ground parts to the tubers is greatly increased.\cite{7,8} The number of cracked tubers also increases,\cite{13} and it is bad for storage.\cite{13,14} Therefore, haulm removal time of the potato should be considered carefully. According to the technical specifications of potato production\cite{15-17} and practical experience of growers in major producing areas, haulm removal is currently carried out within the two weeks before harvesting in China. The physical mechanics and collision damage characteristics of potato tubers during the harvest period are closely related to the time of haulm removal. However, there are few reports on the physical properties of potato tubers based on different removal times. Most studies have focused on determining the physical mechanics and the collision damage characteristics of tubers during harvest and storage.\cite{18-24}

It is hoped that this study could investigate the effect of different haulm removal times on the physical mechanics and collision damage characteristics of potato tubers at harvest, and clarify how the physical characteristics of tubers change with time after seedling killing. An experiment was conducted with Longshu No. 7 potatoes from China as the object. The moisture content, density, coefficient of restitution, shear modulus, etc. and their change rules for tubers with four different haulm removal times were determined through a series of experiments. The collision characteristics of the potato tubers themselves and that between tubers and a 65 Mn steel plate following different haulm removal times were studied through simulation experiments. We used 65 Mn as the material for the rod of the conveying and separating device in a potato harvester, which was in direct and prolonged contact with potato tubers during harvesting operations. The results of this study can provide a reference for discrete element simulation parameters related to potato harvesting machinery and can briefly provide reliable help for the optimal design of potato harvesting machinery. This can effectively reduce damage during potato harvesting in China. It is also hoped that the results of this study will provide a reference for determining the timing of haulm killing at the actual harvest.

**Materials and methods**

Measurement on the effect of different haulm removal times on physical properties of potato tubers

Raw materials and the setting of different haulm removal times: The potato variety used in the tests was Longshu No. 7. The shape is a long oval. The dry matter content is 25.2%. The starch content is 18.75%, the crude protein content is 2.68%, and the reducing sugar content is 0.18%.\cite{25} The potato was produced in Huining County, Baiyin City, Gansu Province. The agrotype was sandy loam soils. The local potato planting time is April–May, and the potato harvest time is September–October every year. The potatoes used in this experiment were planted at the end of April 2021. They were planted in double rows in a single ridge, with mulch applied after the machine ridging. The top width of the ridge was 45 cm, the height was 20 cm, and the center distance was 145 cm. Tubers were formed at depths between 15 mm and 20 mm. The average soil moisture content in the growing range of the potato tubers was 15.68%. Due to the weather conditions, such as drought, there was low production in the region as a whole in this time period. In this producing area, machine harvesting is generally carried out 7 to 14 days after haulm removal. Based on this we decided to sample potatoes harvested at several different times after haulm removal. The specific procedure was as follows: taking the test date as the benchmark, haulms were removed 14 days, 10 days, and 7 days in advance in each group, with the fourth group undergoing removal on harvesting day. The tubers with similar shapes and qualities were selected for subsequent experiments. The four groups were recorded as D-14, D-10, D-7, and D-0, respectively. The soil and potatoes were dug up in the field, and potatoes encased in the soil were selected and bagged together in each group. We made sure the tubers were still in the soil and firmly attached to the roots of the plant.

**Experimental method and measuring instruments**

A subsequent practical experiment was carried out with four groups of tubers with different removal times of haulm to derive the values of basic physical parameters and collision characteristics
parameters under different conditions. Different potato tubers were selected for each group for eight replicate trials. The results obtained were also subjected to ANOVA and the change curves of the significant terms were fitted accordingly.

The moisture content was measured by the drying method. The potato samples were cut into small slices and weighed with an electronic balance. The temperature of the DGF30/7-1A electric heating air-blowing dryer was set at 105 °C for drying. The mass of the sample would be continuously reduced and drying would be stopped when the mass remained the same. The ratio of the reduced mass to the total mass is the moisture content. The density was measured by the drainage method. The potato samples were cut into cylindrical shapes, which could be placed in the graduated measuring cylinder. The measuring cylinder (measurement range: 50 ml, division value: 1 ml) was filled with a specific amount of water in which the samples could be completely submerged in, and then the potato sample was placed into the measuring cylinder. The volume change was the volume of the tuber. The density is the ratio of mass to volume of the samples.

The collision coefficient of restitution can be obtained by the method of high-speed photography. The measurement method is shown in Figure 1. The process of the tuber dropping and colliding was filmed by a HiSpec5 high-speed camera acquisition system (Fastec Imaging Inc.). A group of images with the same time interval was obtained. And the groups with the velocity vertically upward after the collision were selected for calculation. The obtained image was imported into PS, and comparing the size on the square paper, it can be concluded that each pixel point corresponded to 0.037 cm. Two pictures of the nearest moment before the collision were taken, and the number of pixels between the highest distance of the two tubers was accurately measured, which is the displacement at this time. The ratio of the displacement to the time difference between the two photos is the velocity before the collision. Similarly, the velocity after the collision can be derived. The corresponding value can be solved according to the definition of the collision coefficient of restitution. In this way, the coefficient of restitution between tubers, and between potato and steel can be found.

The compression characteristics of the potatoes were tested with the universal testing machine. Potatoes were selected and sampled along the long axis by a cylindrical sampler with a diameter of 20 mm. The samples were measured by a digital vernier caliper after trimming. Each sample of the tubers was a cylinder with a diameter of 20 ± 1 mm and a height of 40 ± 0.5 mm. The whole was round and smooth, and the section was neat and level. The cylindrical potato samples were compressed by
the UTM6503 electronic universal testing machine (capacity: 5 kN, Grade: 0.5, power: 0.4 kW). The compression test fixture was flat. The loading speed was set as 20 mm/min. The compression was terminated when the sample was broken. The tuber samples and the compression process are shown in Figure 2.

When the compression was finished, the compression characteristic data was obtained and recorded from the control software of the universal testing machine. The calculation equations of Young’s modulus ($E$), Poisson’s ratio ($v$), and the shear modulus ($G$) of the potato tubers are as follows:

$$A = \frac{\pi \cdot d_0^2}{4}$$  \quad (1)

$$\sigma = \frac{F}{A}$$  \quad (2)

$$\varepsilon_1 = \frac{\Delta d}{d} = \frac{d_1 - d_0}{d_0}$$  \quad (3)

$$\varepsilon_2 = \frac{\Delta l}{l_0}$$  \quad (4)

$$E = \frac{\sigma}{\varepsilon_2} = \frac{4F \cdot l}{\pi \cdot \Delta l \cdot d_0^2}$$  \quad (5)

$$v = \frac{\varepsilon_1}{\varepsilon_2} = \frac{(d_1 - d_0) \cdot l}{\Delta l \cdot d_0}$$  \quad (6)

$$G = \frac{E}{2(1 + \mu)}$$  \quad (7)

where $A$ is the cross-sectional area of the potato sample, mm$^2$; $d_0$ is the diameter of the potato sample before compression, mm; $d_1$ is the diameter of the potato sample after compression, mm; $\sigma$ is the stress of the potato sample, N/mm$^2$; $F$ is the pressure of the potato sample, N; $\varepsilon_1$ is the lateral strain of the potato sample; $\varepsilon_2$ is the longitudinal strain of the potato sample; $l_0$ is the height of the potato sample.
before compression, mm; and $\Delta l$ is the change in the height of the potato sample after compression, mm.

Simulation experiment on the effect of different haulm removal times on collision damage characteristics of potato tubers

Establishment and parameter determination of the potato tuber model: A total of 100 potatoes were randomly selected in the field, and their dimensions were measured in the three directions with vernier calipers. The average length, width, and thickness of the sample were 78.274 mm, 51.930 mm, and 43.903 mm, respectively. The potato particle model was simplified to an ellipsoid with a length of 78 mm, a width of 48 mm, and a height of 48 mm, in order to facilitate the simulation modeling and reduce the required calculations. The three-axis direction diagram and simulation model of the potato tuber are shown in Figure 3.

Simulated experiment of multiple potato tubers falling on a steel plate: The simulation experiment was designed as follows. It was used to investigate the influence of the forces on the tuber during collision following different removal times. The simulation experiment was designed as follows in the EDEM software. A 65 Mn steel square plate with a side of 1000 mm was added. A cylindrical container with a baffle at the bottom was arranged 300 mm above the steel plate. A factory of potato particle was set up inside the container which could randomly produce 100 identical tuber particles. When the particles were stable in the container, the baffle was removed. The potato tubers in the container fell freely and collided with the steel plate below. As shown in Figure 4. The particles were produced and fell from the factory with four different haulm removal conditions: 0 days before harvesting, 7 days before harvesting, 10 days before harvesting, and 14 days before harvesting. During the collision process between the particles and the steel plate, the maximum force of the single tuber with the largest resultant force was recorded as $F_1$, the maximum contact force between the tubers colliding with each other was recorded as $F_2$, and the maximum contact force of all tubers as they collided with the steel.
plate was recorded as $F_3$. The contact force generated in the falling process was obtained from the Analyst interface of the software. Each group was repeated 10 times.

**Results**

Measurement of actual on the effect of different haulm removal times on physical and mechanical properties of potato tubers

Effects of moisture content and density of the tubers with different haulm removal times: The experiment results are shown in Figure 5. The moisture content ranges of the potato tubers with four different haulm removal dates (0, 7, 10, and 14 days before harvesting) were, respectively, 74.62\%–80.24\%, 76.44\%–83.44\%, 76.99\%–82.09\%, and 78.82\%–80.35\%. The density ranges of the samples were, respectively, 1.01 \~ 1.12 g·cm\(^{-3}\), 1.00 \~ 1.11 g·cm\(^{-3}\), 1.03 \~ 1.10 g·cm\(^{-3}\), and 1.02 \~ 1.09 g·cm\(^{-3}\). An analysis of variance (ANOVA) was performed on the collected data using SPSS, the P value of both were greater than 0.10. It means there was no significant effect of different haulm removal times on potato tuber moisture content and density.

Effects of different haulm removal times on coefficient of restitution of tubers: According to the experiment results, the ranges of the coefficient of restitution between the potato tubers under the four different haulm removal times (0, 7, 10, and 14 days before harvesting) were, respectively, 0.66 \~ 0.71, 0.65 \~ 0.69, 0.64 \~ 0.69, and 0.63 \~ 0.68. The ranges of the coefficient of restitution between the potato and steel were, respectively, 0.64 \~ 0.69, 0.59 \~ 0.67, 0.56 \~ 0.65, and 0.56 \~ 0.64. The test results were collated and analyzed for ANOVA, and the homogeneity of variance tests were all higher than 0.05. The results are shown in Table 1. Different haulm removal times had highly significant effects on the coefficient of restitution between the tubers and between potato and steel. The mean change chart of the coefficient of restitution of tubers with different haulm removal times before harvesting was obtained. Linear regression analysis of significant terms was carried out by the linear fitting method, as shown in Figure 6. The regression equation between the different haulm removal times before harvesting and the rupture pressure was $y = 8.483 \times 10^{-5}x^2 - 3.860 \times 10^{-3}x + 0.690$, with an $R^2$ of 0.996. The regression equation of the shear modulus was $y = -4.336 \times 10^{-5}x^2 - 4.770 \times 10^{-3}x + 0.659$, with an $R^2$ of 0.959. The $R^2$ of both was close to 1, which indicated good goodness of fit.

![Figure 5](image-url) The experimental result of the moisture content and density of the tubers with different haulm removal times.
Table 1. Analysis of variance for the effect of coefficient of restitution with different haulm removal times.

| Analysis object                                      | Sum of squares | df | Mean square | F value | P    | Significance level |
|------------------------------------------------------|----------------|----|-------------|---------|------|-------------------|
| Coefficient of Restitution between the potato tubers  | 0.006          | 3  | 0.002       | 8.912   | 0.000| **               |
| Coefficient of Restitution between potato and steel   | 0.021          | 3  | 0.007       | 11.377  | 0.000| **               |

P < 0.01 (highly significant, **), P < 0.05 (significant, *)

Effects of different haulm removal times on compression characteristics of tubers: According to the experiment results, the rupture pressure ($F$) ranges of the tubers under the four different haulm removal times (0, 7, 10, and 14 days before harvesting) were, respectively, 307.3 ~ 386.5 N, 295.2 ~ 436.9 N, 337.4 ~ 492.4 N, and 322.6 ~ 496.3 N. The Young’s modulus ($E$) ranges of the samples were, respectively, 2.95 ~ 3.93 MPa, 3.21 ~ 4.02 MPa, 3.30 ~ 4.44 MPa, and 3.50 ~ 4.32 MPa. The Poisson’s ratio ($v$) ranges of the samples were, respectively, 0.35 ~ 0.52, 0.36 ~ 0.60, 0.37 ~ 0.66, and 0.39 ~ 0.54. The shear modulus ranges of the samples ($G$) were, respectively, 0.97 ~ 1.34 MPa, 1.13 ~ 1.38 MPa, 1.13 ~ 1.60 MPa, and 1.14 ~ 1.55 MPa. As compression began to load, the test fixture came into contact with the potato sample. The stress on the sample rose from 0 rapidly, and then with the continuous increase of distance, the growth trend was slightly moderated. Overall, it was still a linear change and rise. When the pressure on the sample reached the maximum, the rupture pressure, the sample broke and the pressure dropped sharply. The results showed that the changes of the compression characteristic curves under different haulm removal times were basically the same. Most samples were fractured into two parts at a certain angle after compression.

The analysis of variance was performed on the collated data, and the homogeneity of variance tests were all higher than 0.05. The results are shown in Table 2. Different haulm removal times had a significant effect on the potato tuber rupture pressure, Young’s modulus, and shear modulus. In particular, it had a highly significant effect on Young’s modulus. On the contrary, the effect was not significant on Poisson’s ratio. The mean change chart of the tuber rupture pressure, Young’s modulus, Poisson’s ratio, and the shear modulus with different haulm removal times before harvesting was obtained. Linear regression analysis of significant terms was carried out by the linear fitting method, as shown in Figure 7. The regression equation between the different haulm removal times before harvesting and the rupture pressure was $y = 0.250x^2 + 1.604x + 347.065$, with an $R^2$ of 0.977. The regression equation of the Young’s modulus was $y = -0.002x^2 + 0.082x + 3.190$, with an $R^2$ of 0.999. The

Figure 6. Mean change chart and fitted curve of coefficient of restitution with different haulm removal times.
regression equation of the shear modulus was $y = -6.998 \times 10^{-4}x^2 + 0.027x + 1.110$, with an $R^2$ of 0.999. The $R^2$ of all three were close to 1, which indicated to a good goodness of fit.

Simulation experiment on the effect of different haulm removal times on collision damage characteristics of potato tubers

Determination of discrete element simulation parameters: The basic physical parameters of the potato tuber were obtained through the mean value of experiment result in 3.1. A pretest found that there were great differences in the friction coefficient of samples under the four haulm removal dates. Wei et al.\textsuperscript{[28]} found that there was a big error between the calibration of the rolling friction coefficient and the real situation. Feng\textsuperscript{[29]} also indicated that the friction coefficient of Longshu No. 7 was greatly influenced by individual surface roughness. Therefore, the same mean value was selected for the simulation after comprehensive consideration. The discrete element simulation parameters were finally obtained based on actual test results and relevant literature,\textsuperscript{[28–31]} as shown in Table 3.

Effects of forces generated by multiple potato tubers falling onto the steel plate with different haulm removal times: According to the experiment results, multiple tubers fell vertically from the top along the long axis and collided with the steel plate, which generated forces. The ranges of $F_1$, the maximum force of the single tuber with the largest resultant force, for four different haulm killing dates were $182.5 \sim 200.1$ N, $177.1 \sim 195.1$ N, $173.0 \sim 194.0$ N, and $172.4 \sim 185.1$ N, respectively. The ranges of $F_2$, the maximum contact force between tubers for the tubers colliding with each other, for four different haulm killing dates, were $72.4 \sim 93.3$ N, $63.5 \sim 89.2$ N, $71.3 \sim 83.6$ N, and $61.0 \sim 80.2$ N, respectively. The ranges of $F_3$, the maximum contact force of all tubers colliding with the steel plate, for four different haulm killing dates, were $137.1 \sim 166.6$ N, $134.8 \sim 147.6$ N, $135.1 \sim 146.7$ N, and $138.2 \sim 146.6$ N, respectively. The changes of several forces over time for a particular drop collision is shown in Figure 8. During the collisions, the contact frequency between the potato and the steel plate was higher than that between the potato and the potato, and the contact collision force was greater. The main reason for this was the hardness of the steel plate. The contact area of the collision was small. The tuber had less
The maximum force of the single tuber with the largest resultant force was greater than the contact force. Presumably, the reason for this is that the tuber was simultaneously affected by the combined effect of the steel plate and other potato tubers.

An analysis of variance was performed on the collated data, with homogeneity of variance tests higher than 0.05. The results are shown in Table 4. Different haulm removal times had a significant effect on $F_1$ and $F_3$; in particular, they had a highly significant effect on $F_1$. On the contrary, the effect was not significant on $F_2$. The mean change chart of $F_1, F_2$ and $F_3$ with different haulm removal times before harvesting was obtained, as shown in Figure 9. The linear regression analysis of significant terms was carried out by the linear fitting method. The regression equation between the different haulm removal times before harvesting and $F_1$ was $y = -0.006x^2 - 0.572x + 187.184$, with an $R^2$ of 0.999. The regression equation of $F_3$ was $y = 0.021x^2 - 0.752x + 147.581$, with an $R^2$ of 0.999. The $R^2$ of both were close to 1, which indicated to a good goodness of fit.

![Table 3. The discrete element simulation parameters.](image)

| Parameter                                      | D-0        | D-7        | D-10       | D-14       | 65Mn/ |
|------------------------------------------------|------------|------------|------------|------------|-------|
| Density                                        | 1064 kg/m³ | 1058 kg/m³ | 1057 kg/m³ | 1056 kg/m³ | 7810 kg/m³ |
| Poisson’s ratio                                | 0.436      | 0.451      | 0.460      | 0.472      |       |
| Shear modulus                                  | $1.108 \times 10^6$ Pa | $1.268 \times 10^6$ Pa | $1.313 \times 10^6$ Pa | $1.360 \times 10^6$ Pa | $8.010 \times 10^10$ Pa |
| Coefficient of Restitution between potato tubers| 0.690      | 0.668      | 0.659      | 0.653      |       |
| Coefficient of Restitution between potato and steel| 0.658      | 0.634      | 0.602      | 0.594      |       |
| Coefficient of Static Friction between potato tubers | 0.452      | 0.452      | 0.452      | 0.452      |       |
| Coefficient of Rolling Friction between potato tubers | 0.024      | 0.024      | 0.024      | 0.024      |       |
| Coefficient of Static Friction between potato and steel | 0.445      | 0.445      | 0.445      | 0.445      |       |
| Coefficient of Rolling Friction between potato and steel | 0.269      | 0.269      | 0.269      | 0.269      |       |

![Figure 8. The changes of several forces during the collision.](image)


**Discussion**

In China, removing potato haulms 1 to 2 weeks prior to harvesting tubers is recommended.\(^{[2,6,15–17]}\) It can be seen from production and practical experience that haulm removal before the potato harvest is beneficial for both mechanized harvesting and preventing tuber infection.\(^{[2–14,32]}\) Removing of haulm changes the growth of potato plants, possibly also changing their physical mechanics and collision damage characteristics correspondingly. Most of the existing studies on the effects of haulm killing on potatoes focus on the disease and yield aspects of potatoes. And most of the studies on the physical properties of tubers have focused on the post-harvest and storage periods. In this paper, the physical and collision characteristics of the tubers were investigated using different haulm removal times as influencing factors during the harvesting period. After sampling in the field, a series of practical experiments were conducted to measure the relevant parameters of the potato blocks, and their collision characteristics were investigated with the help of discrete element simulation software.

After haulm removal, the green tissues, such as the stems and leaves above the soil, were greatly reduced, which reduced water loss. However, for the whole potato, the moisture change was relatively small. As the haulm removal time increased the moisture content of the potatoes showed an upward trend, but it was not significant. The potatoes without haulms were still breathing and accumulating nutrients underground. The density was decreasing, but the change for the potato as a whole was still small. Therefore, the density showed a downward trend, the effect of which was not significant. With the increase of time after haulm removal, the rupture pressure, Young’s modulus, and shear modulus of the potato tuber were all increased significantly. This was possibly because the green tissues, such as the stems and leaves above the soil, were reduced, mulch protection affected the enzyme activity inside the tuber, and the accumulation of starch was slowing down. Additionally, the tubers were still undergoing metabolism and interchange of material. In contrast, potatoes stored after harvest were
affected by respiration, which depleted the accumulated nutrients unidirectionally. This also suggested that the internal structure and composition of stored potatoes may be different from that of fresh potatoes harvested from soil. Haulm removal could not only delay the continuous growth and development of tubers,\textsuperscript{[12,13]} but also promote the thickening and suberization of the epidermis.\textsuperscript{[2]} The moisture content of the tubers tended to increase with an earlier haulm removal time. Tubers with high moisture content show greater stickiness when colliding.\textsuperscript{[18]} The amount of deformation caused by collisions was also greater, which resulted in a larger area of contact between the potato and the steel plate. The increase in energy lost in the collision led to a decrease in the post-collision velocity, which made the coefficient of restitution decrease. This could effectively reduce the impact, which would also reduce the contact force of the collision effectively. This also suggested that the earlier haulms are removed, the more resistant the tubers are to mechanical damage.

According to the results of discrete element simulation tests, it can be found that Multiple potato tubers falling on the steel plate generated forces. With later haulm removal times, both $F_1$ and $F_3$ gradually decreased and were significantly affected. When falling from the same height, the contact force of a single potato colliding with the steel plate was obviously greater than that of multiple tubers colliding with the steel plate. A possible reason for this may be that during the collision, the tubers were cushioned against each other, which reduced the impact on the steel plate. The collision between potato tubers was random due to the uncertainty of the particle formation position and falling process. Therefore, as haulm removal times were delayed, the effect on $F_2$ was not significant. Discrete element method simulation experiments also showed that early haulm removal helped to reduce the tubers damage during mechanical harvesting, bagging, transportation and storage. Therefore, appropriately increasing the date of haulm removal before harvesting will accelerate the suberization of the epidermis, which is helpful to reduce damage to potatoes and the transmission of potato viruses to tubers during mechanical harvesting. However, the starch content, yield, and the proportion of large potatoes is decreased by this. For this reason, it is important to determine the haulm removal time by comprehensively considering the use and yield of potato tubers. For example, for starchy potatoes, the haulm removal time can be appropriately reduced to ensure the starch content and yield; for edible potatoes, the haulm removal time can be appropriately extended to ensure the integrity of the potato tuber and reduce the damage to the potato peels.

**Conclusion**

With the increase in haulm removal time before harvesting, the effect of moisture content, Poisson’s ratio, and density are not significant. However, the rupture pressure, Young’s modulus, and shear modulus increase significantly. The coefficient of restitution between the potato tubers, and the coefficient of restitution between the potato and steel decrease significantly. In simulation experiment with multiple potato tubers falling on the steel plate, with the increase in haulm removal time before harvesting, the maximum force of a single tuber with the largest resultant force ($F_1$) and the maximum contact force of all tubers colliding with the steel plate ($F_3$) decreased significantly. The maximum contact force between tubers colliding with each other ($F_2$) was not significantly affected. With the increase in the haulm removal time before harvesting, the impact contact force of potato tubers falling from the same height became smaller. The values of the tuber-related parameters measured in this experiment can be used as a reference for simulation parameters of potato harvesting machinery design optimization. With the increase of haulm removal time before harvesting, the potato is more resistant to mechanical damage. Therefore, the extension of haulm killing time before harvesting should be appropriated, which may reduce losses in mechanical harvesting while ensuring yield.
Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This research was funded by Natural Science Foundation of Jiangsu Province, grant number BK20201124; Central Public Interest Scientific Institution Basal Research Fund S202110-02,S202110-03, grant number S202110-02, S202110-03.

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