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RESEARCH ON SOIL FRAGMENTATION CHARACTERISTICS BASED ON FRACTAL DIMENSION AND IMAGE PROCESSING

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KEYWORDS

soil drop fragmentation, fractal dimension, image processing, sandy soil, potato-soil separation.

ABSTRACT

To improve the complex process of judging the degree of soil fragmentation during potato-soil separation and to establish a fast and effective judging method. Soil drop experiments were performed using sandy soil from the potato growing region of Hohhot, Inner Mongolia Autonomous Region, China. The effects of soil moisture content, hardness, volume, drop height, inclination of the separating sieve and composition of the separating sieve rod on soil fragmentation were investigated. The fractal dimension and image processing used to quantify soil fragmentation and scattering and obtain quantitative indicators of soil fragmentation. The results showed that the following factors influenced soil fragmentation in descending order of statistical significance: soil hardness, fall height and soil volume. The softer the soil was, the greater the fall height; the larger the soil volume was, the greater the fragmentation. Meanwhile the correlation between the two indicators is extremely high, simplifying assessment of the degree of soil fragmentation. This study clearly shows the influence of the intrinsic physical properties of soil and the external physical parameters of potato excavators on the characteristics of crushed soil. The results can provide a basis for improving the efficiency of potato-soil separation and designing more efficient devices for harvesting potatoes.

INTRODUCTION

Mechanization of potato harvesting is one of the key examples of mechanized production that increases the efficiency of harvesting compared to manual methods (Kempenaar & Struik, 2007; Lv et al., 2015; Lü et al., 2017). Although the sizes of the areas planted with potatoes and the annual production in China are among the largest in the world, mechanical harvesting processes are not fully utilized in most regions (Yang et al., 2021). In China, potatoes are harvested mainly in sections of fields, and farmers rely primarily on potato excavators to dig soil and plant potatoes in the field; then, potatoes are picked and bagged by hand.

In segmented potato harvesting machines, the potato-soil separation device is the fundamental working component. The 4SW-170 potato harvester, which is a typical segmented potato harvester, uses an oscillating sieve as its soil separation device. The power of the tractor output shaft is transmitted through a two-stage linkage mechanism that drives the two layers of the sieve to undergo reciprocal oscillations at a certain angle. The mixture of potatoes and soil is thrown from the lift chain to the sieve where it is repeatedly tossed until soil falls through the sieve rod gap; the potatoes and some of the soil fall from the end of the sieve. However, if the soil is broken before it separates from the potatoes during this process, very few soil particles land on the sieve surface. This means that there is no buffer of soil between the potatoes and the sieve rod. Instead, the potatoes collide directly with the sieve rod, which commonly increases the rate of damage and breakage of potatoes. However, if the soil does not break easily, then it remains on the sieve surface and does not fall through the sieve rod gap. As a result, the mixture contains significantly more soil than potatoes, and pieces of potatoes are buried again by soil. The obvious rate of harvesting is underestimated, which affects the subjective judgment of workers at the picking stage, and more potatoes are overlooked in the soil instead of harvested. Therefore, current research and analysis of soil fragmentation are particularly important.

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The evaluation of soil fragmentation is usually performed by impact crushing experiments (Wei, 2007; Yang et al., 2021), but this method is used primarily in research that targets soil tillage and loosening and fragmentation properties. After soil is broken by a punch hammer, the mass fractal dimension is used to quantify the breakage of the scattered soil. For the operation of potato harvesters in the potato-soil separation stage, the degree of soil fragmentation can only be subjectively estimated; little is known about the form of indicators, and research is still in the simulation test stage (Wei et al., 2020). During simulations, the Hertz–Mindlin model was used as the main model for physical contact, and the Johnson-Kendall-Roberts (JKR) surface energy or bonding model was used to model soil agglomerates. Assessing the degree of soil fragmentation based on the variation in JKR data or the percentage of bond breakage can effectively explore the effects of different factors on soil fragmentation. Therefore, for the study of the characteristics of soil fragmentation, this paper proposes applying the theory and method of the fractal dimension and image data. However, determining the fractal dimension requires the collection and evaluation of crushed soil, and it is necessary to obtain and process photographs to provide data in the form of images. Then, the results are processed. The environmental conditions are demanding, and this approach cannot be used directly for the study of soil crushing during potato harvesting. Therefore, in this study, experiments were conducted in a laboratory to investigate the breakage pattern of lumpy soil on a potato excavator. The test procedure was soil drop breakage under controlled conditions.

For these reasons, to determine the degree of soil fragmentation during potato-soil separation in the absence of a fast and effective method of evaluation, the soil drop experiment was used to model the process of soil fragmentation, observe the state of soil fragmentation and the degree of fragmentation, and study the influence of different factors on the characteristics of fragmented soil. This was the first study of soil fragmentation during potato-soil separation. An innovative scheme was proposed to correlate the fractal dimension with image processing theory and replace the fractal dimension with image data processing, which simplified the means to assess the degree of soil fragmentation. It is important to enrich the theory and methodology for the evaluation of soil fragmentation and promote the development of potato harvesting machinery.

In this study, the structure and working principle of the potato-soil separation device of the 4SW-170 potato excavator were analyzed. Data for the characteristics of the movement of soil falling from the lifting chain to the separation sieve were used as parameters in the soil drop experiment. Then, experiments were undertaken with a test bed to obtain the variation and pattern of the degree of soil fragmentation with the test parameters. The results of this study provide a theoretical basis and data to guide the development and improvement of the design of potato excavators.

POTATO EXCAVATOR STRUCTURE ANALYSIS

Structure and working principle of the potato excavator

The overall structure of the 4SW-170 potato excavator is shown in Figure 1. The excavator is composed mainly of an excavating shovel, lifting chain and swing separating sieve. The power for both the lifting chain and the swing separating sieve is provided by the tractor. Power is transmitted to the excavator through the drive shaft and then to the lifting chain and separating sieve by the reduction gearbox and the rotating shaft, respectively. The rotating shaft drives the crank to rotate, which in turn drives the rocker to make reciprocal oscillations. The slow movement of the tractor drives the excavator forward, and the digging shovel scoops mixtures of potatoes and soil. Then, the potatoes and soil are lifted by the lift chain, and they fall on the swing separation sieve. As the separation sieve swings continuously, the soil breaks and falls by the gap of the sieve bar, while the potatoes fall from the rear of the excavator under the action of inertia to achieve the separation of potatoes and soil.

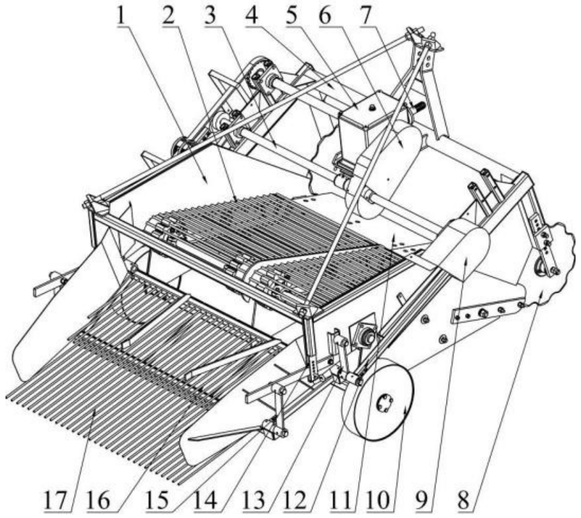


FIGURE. 1 4SW-170 potato excavator overall structure.

1-Side Plate; 2-Lifting Cain; 3-Spool; 4-Frame; 5-Planetary Gearboxes; 6-Housing for Chain Wheel Drive Mechanism; 7-Propshaft; 8-Soil cutting Disc; 9. Housing for Crank Mechanism; 10-Traveling Wheels; 11-Digging Shovel; 12-Connecting Rod; 13-Back Pendulum; 14-Sieve Inclination Adjustment Mechanism; 15-Front Pendulum; 16-Upper Sieve; 17-Lower sieve

Force analysis in the separation phase of a potato excavator

During the operation of the 4SW-170 potato excavator, the mixture of potatoes and soil is transported through the lift chain to its top point A. Due to inertia, the mixture is thrown upward in an oblique direction and follows a trajectory that has the form of a parabola; the schematic diagram is shown in Figure 2. At this time, the speed of the mixture is close to the linear velocity v of the lift chain. After passing the highest point B, the mixture falls to the surface of the separation sieve at point C. According to the classical equation of motion of the parabola, the distance BD that the mixture continues to rise due to inertia after leaving the sieve surface is:

$$\mathrm{BD} = \frac{v^2 \sin^2 \theta}{2\left(\mathrm{g} + \frac{1000 f}{m}\right)} \tag{1}$$

Where:

θ is the lifting chain angle;

v is the speed of the material after leaving the lift chain;

g is the acceleration of gravity (9.8 m/s^2);

f is the air resistance, and

m is the mass of the material.

The time t_{AB} required to travel from point A to point B is:

$$t_{AB} = \frac{v_y}{g + \dfrac{1000f}{m}} \tag{2}$$

The horizontal distance AD from point A to point B is:

$$\mathrm{AD} = \frac{v^2 \sin 2\theta - v^2 \sin^2 \theta}{2\left(g + \dfrac{1000f}{m}\right)} \tag{3}$$

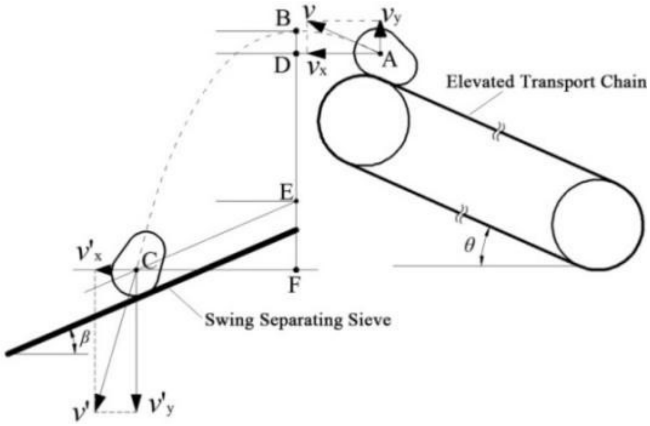


FIGURE. 2 Analysis of potato and soil force during potato-soil separation.

The distance DE between the horizontal position E of the top of the separating sieve and the horizontal position D of the material center of mass is determined by the installation height of the separating sieve and the volume of soil or potatoes. The mixture is thrown down from point A to point C in the process. Due to the presence of air resistance, the horizontal force v_x decays to v'_x. By the joint action of gravity and air resistance, the vertical direction force v_y becomes v'_y. The equation for kinetic energy in the vertical direction shows [eq. (4)].

The kinetic energy in the horizontal direction is subject to a constant resistance size f and calculated by the uniform deceleration formula, which can be obtained from the [eq. (5)].

$$\frac{m}{2}\left[v^2 \sin^2 \theta - v_y'^2\right] = \mathrm{DF} \cdot mg - f\left(\mathrm{BD} + \mathrm{BF}\right) \tag{4}$$

$$\mathrm{AD} + \mathrm{CF} = \frac{vv'_x \cos\theta}{v\cos\theta - a} - \frac{a\left(v'_x\right)^2}{2} \tag{5}$$

Where:

a is the reverse acceleration due to air resistance, and $a = \dfrac{1000f}{m}$.

From the equation, we see that the material in the collision with the sieve surface instantaneous horizontal direction speed as well as vertical direction speed is related to the material mass m, three parts of the fall height (BD, DE, EF) and other factors.

MATERIAL AND METHODS

Materials and Devices

The soil samples were 50 kg of soil from the potato growing area in Wuchuan County, Hohhot City, Inner Mongolia (111°27'E, 41°12'N) (Figure 3). Wang (2019) conducted particle size analysis of the soil at this site. The ratio of sand, powder and clay particles was 0.908:0.0123:0.0794, and the soil type was sandy soil, as indicated by the US soil texture triangle. The effective mechanical undercutting depth during potato harvesting was between 180 and 200 mm (Wu, 2016). This condition was followed during sampling, i.e., only soil within 200 mm of the surface layer was sampled.

The test device used a soil drop test bed (Figure 4) that consisted mainly of a drop part and a shooting part. A height adjustment frame was welded vertically to a flat observation plate with the soil drop frame fixed at the desired height by means of a cam latch. The lower end of the separation sieve was fixed by bolts, and the middle part was supported on a bracket. It was possible to change the inclination of the sieve surface while the height of the middle section of the separation sieve from the drop table remained unchanged. The fixed end of the separation sieve as well as the lens holder was coupled with bearings, which allowed the sieves to be turned over. Before the test, the cam latch was loosened, the sieves were adjusted to the desired height, and then the latch was fastened. The coupling bolts of the separation sieve were loosened and tightened again after determining the inclination of the sieve surface. The prepared soil sample was placed on the soil drop frame, and the lens holder was turned counterclockwise to avoid blocking the dropped soil during the test. The isolation plate on the drop frame was pulled out during the test so that the soil fell freely onto the surface of the separation sieve. After rotating the sieve surface clockwise, the lens mount was lowered, and the scattered condition of the soil was photographed. The soil above the specified size after scattering was weighed and counted so that one test was completed, and subsequent tests could be conducted.

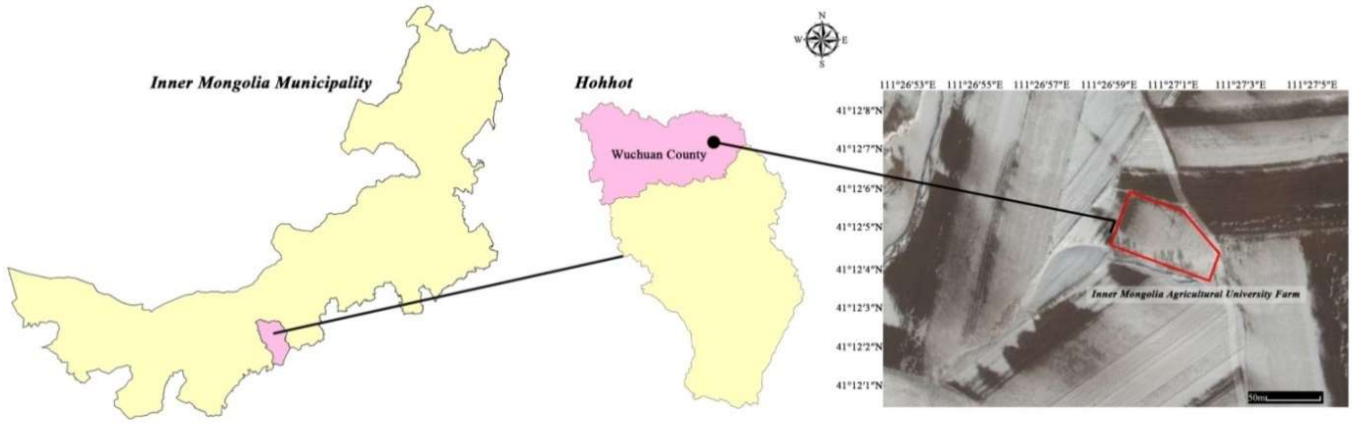


FIGURE. 3 Test field and soil sampling site.

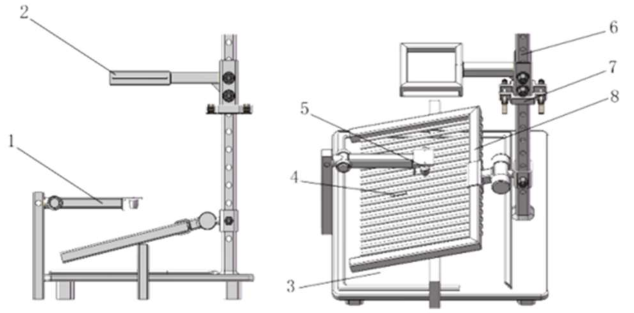


FIGURE. 4 Soil drop analysis test-bed.

1-Lens holder; 2-Soil drop frame; 3-Observation plate; 4-Acceleration sensor adsorption piece; 5-Camera; 6-Height adjustment frame; 7-Cam lock; 8-Separation sieve;

The main instruments used in the test included a DDL200 universal testing machine (Changchun Institute of Machinery Science) with a sensor range of 100 kN, an STR-J-750-Ⅱ soil compactness meter (Shanghai Siwei Instrument Manufacturing Co., Ltd.); DHG-9245A blast drying oven (Shanghai Yiheng Scientific Instruments Co., Ltd.), and temperature range RT+10~300 °C.

Soil sample preparation

In practice, soil hardness has an important influence on the degree of soil fragmentation. Therefore, it is necessary to simulate the soil conditions in real situations by means of soil sample preparation. According to GB/T 27845-2011, the equation for the soil water content is:

$$\omega = \frac{m_w}{m_s} \times 100\% \tag{6}$$

Where:

ω is the soil moisture content, ranging from approximately 0% to 25%;

m_w is the mass of water lost when the soil specimen is baked to a constant volume at 105-110 °C, and

m_s is the dry soil mass of the soil sample after baking to a constant volume.

The collected soil was crushed using a grinding apparatus, placed in a drying oven for two hours, removed, crushed, and then passed through a sieve to separate the gravel and obtain a finely ground powdered soil. The drying oven was then put in place for drying and removed and weighed every hour until the last two consecutive weighs had the same mass to obtain a completely dry soil sample.

If a sample of soil with ω water content was needed, a dry soil of mass m_s was taken, and water of mass m_w was added to it and then mixed. Five soil samples were taken using the five-point sampling method, and the moisture content was detected using a soil moisture sensor (Sensor type: RS-WS-*-TR, reading data using RS-485 serial communication on Arduino-UNO). If the soil moisture content was consistent at each location, then the consistency indicated that the soil was well mixed.

Then, 500 g of soil with a determined moisture content was put into a cling bag and placed in the mold of the universal testing machine (Figure 5). (The role of the cling bag was to facilitate the removal of soil after compression.) The compression was 2~10 kN, the compression speed was 50~100 N/s, the empty speed of travel was 100 mm/min, and the holding time was 20 s.

After compression was completed, the soil block was removed and sealed in a new plastic bag to prevent moisture diffusion and changes in the moisture content. The hardness of the soil compressed under different conditions was measured and recorded by a soil firmness tester, and the data were processed to obtain a regression function of pressure and firmness so that the pressure magnitude for making the desired hardness of the soil could be obtained.

FIGURE. 5 A soil compression mould installing on universal testing machine.

Test method

This study investigated the effects of different factors on the degree of soil fragmentation. In this test, the values of a small number of more significant factors were varied to explore their effects on soil fragmentation; the design of experiment (DOE) approach was used. In actual situations, the kinetic energy at the moment of collision between the soil and the sieve rod, the physical conditions of the sieve surface, and the physical conditions of the soil all affect the final results of crushing. The force analysis shows that the kinetic energy at the moment of falling is influenced by the height of falling as well as mass of the material. The physical conditions of sieve surface and soil were selected as test factors, i.e., sieve surface inclination and sieve rod material, and soil hardness and water content, respectively; the fractal dimension and image processing results werethe test indicators. To prove correlation between the two indicators, the factors were evaluatedby an analysis of variance (ANOVA) of the fractional factorial experiment, and a range analysis was used to explore the influence of the factors. The process is shown in Figure 6.

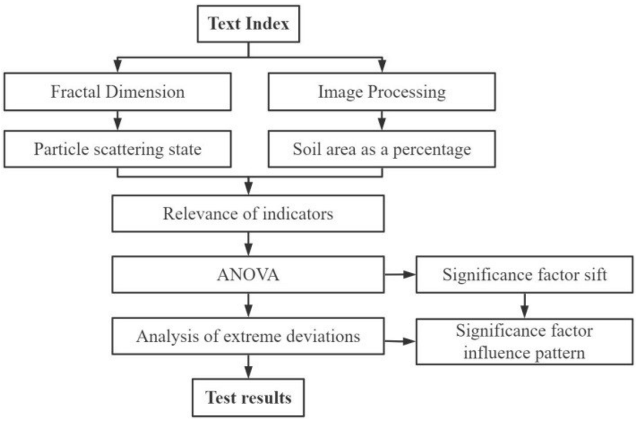


FIGURE. 6 Flow of analysis and processing of test indexes.

We improved soil drop test method mentioned in the literature (Schjønning et al., 2002) by replacing the cubic soil block with a cylindrical soil block that was more consistent with the actual working situation. According to a deeper optimization (Hadas & Wolf ,1984), (Munkholm et al. (2002) suggested sieving crushed soil. We measured the diameters of the scattered clods because sandy soil is prone to secondary crushing during sieving, which affects the final test results.

The test factors were coded, and high and low test levels of all factors were initially proposed according to requirements of test apparatus and esults of pretest, as shown in Table 1.

The experiment was designed using Minitab software, and the design form was represented by +1 and -1 codes. A total of 32 sets of experiments were required using the 2_{VI}^{6-1} experimental design, and its design codes and test results are shown in Table 2, with 10 replicates of each set of experiments.

TABLE 1. Factor levels and codes for the fractional factorial experiment design.

Factor	Code	Coding level	
		Low level (-1)	High level (+1)
Soil Volume (mm³)	X_1	$50^2\pi\cdot 25$	$50^2\pi\cdot 45$
Soil Moisture Content (%)	X_2	6.13	18
Soil Hardness (N/mm²)	X_3	0.34MPa	2.76MPa
Drop Height (mm)	X_4	300	700
Separation Sieve Inclination (°)	X_5	0.5	21.1
Sieve Rod Material	X_6	Rubber	65Mn Steel

Test indicator assessment methods

Evaluation of the test results was performed using two indicators. That is, we combined the fractal dimensional and image processing to guaranteeing the reliability of test results and validity of test indicators. Additionally, the idea that only fractal dimension can be used to evaluate the soil fragmentation state was changed, and the more complex fractal dimension calculation wasreplaced by a simple modular image data processing approach, which improved the efficiency of the experiment.

a) Fractal dimension (FD)

An important indicator for evaluating the degree of soil fragmentation is the fractal dimension (FD) (Turcotte, 1986; Perfect et al., 1992; Meng et al., 2009), which is defined by *fractal* theory for scattered soils. Fractal theory is an effective tool used to characterize complex and irregular spatial forms found in nature (Yang, 2008) . Due to the statistical self-similarity of the grain size of an overengineered sediment, the FD value D_f can be used to quantitatively characterize the fractal features of the grain size (Lu et al., 2021). Similarly, fragmented soils can be evaluated using the FD, but the scale convention that should be followed for soil fragmentation analysis is not yet clearly defined (Meng et al., 2009). Since the application of the FD to the classification of overengineered sediment in hydraulic systems is usually divided by a 2-fold scale (Lu et al., 2021), this method is used in this paper to classify the crushed soil into five classes according to 100, 50, 25, 12.5, and 6.25 mm, where 100 mm is the maximum diameter of the soil sample. After each test, the original sample was photographed in the scattered state, and then the triaxial size of the scattered soil particles was measured by calipers. The average value was taken as the actual scale, excluding particles with largest diameter (measured triaxially)less than 3 mm. The recorded data were graded according to the delineated scales and fitted using the newly defined FD equation (below) (Hallett et al., 1995) to obtain the desired value of D_f.

$$\frac{M\left(\delta<\bar{d}_i\right)}{M_0}=k_c\left(\frac{\bar{d}_i}{\bar{d}_{\max}}\right)^{3-D_f} \tag{7}$$

Where:

$M(\delta<\bar{d}_i)$ is the cumulative mass of soil particles with particle sizes less than $\bar{d}_i$;

M_0 denotes the sum of the weight of each particle class;

$\bar{d}_i$ is the average particle size between two adjacent particle classes d_i and d_{i+1}, i.e., $\bar{d}_i=(d_i+d_{i+1})/2$

$\bar{d}_{\max}$ is the average particle size of the largest particle size class;

k_c is a correction factor, and

D_f is the soil particle FD, which ranges from 0 to 3.

The above formula can be rearranged on a log-log scale, provide a method for determining the FD from the slope of the regression of log $\left[M(\delta<\bar{d}_i)/M_0\right]$ vs. log $\left[\bar{d}_i/\bar{d}_{\max}\right]$. The slope of the graph of log $\left[M(\delta<\bar{d}_i)/M_0\right]$ vs. log $\left[\bar{d}_i/\bar{d}_{\max}\right]$ was(3-D_f). The high FD of the soil particles indicated that the soil has a high degree of fragmentation, i.e., the particle size distribution of the soil contained many small-scale soil aggregates. In contrast, a lower soil particle FD indicated a larger proportion of soil agglomerates onlarger scales (D. Az-Zorita et al., 2002).

b) Image data processing: proportion of soil area (PoSA)

In conclusion, the evaluation of soil fragments can be indexed by image data to determine their dispersion status. Image analysis has the advantage of describing and quantifying soil matrices in a relatively undisturbed state. However, it requires specific and complex equipment, so this method has not been widely used to describe the distribution of soil agglomerates, (D. Az-Zorita et al., 2002), and no one has yet evaluated fragments by means of image processing. In this paper, images of the fragmented soil were obtained, metrics were processed, and the correlation with the values of the FD was checked to verify the coefficients of correlation and prove the feasibility of the approach.

It was necessary to take photographs of the broken state of the soil after falling for subsequent image analysis of the test results. The camera position was fixed directly above the test bed, the error of each shooting position didnot exceed ±5 cm, and the error of the shooting angle did not exceed ±5°. White was selected as the shooting background. The specific process of the image processing method is shown in Figure 7. Photoshop was used to correct the angle of the image, adjust the tonal gradations to make the photograph clearer in terms of lightness and darkness, and crop the edges to ensure that the vertical and horizontal pixel points of each image were consistent. Grayscale processing was performed by MATLAB, the threshold was adjusted to binarize, and two filtering and inversion processes were performed to remove noise from the black and white areas, respectively. The number of black areas and the number of pixels in the whole image were calculated, and their ratio was determined to obtain the result of the proportion of soil area (PoSA) of the original image. The equation for this calculation was:

$$\alpha=\frac{p_s}{p_b+p_s}\times 100\% \tag{8}$$

Where:

P_s is the number of pixels in the soil section;

P_b is the number of pixels in the white background, and

α is the percentage of the area of soil on a white background.

To avoid the interference of the soil volume factor on the soil percentage results, we determined the image cropping ratio by pretesting; the larger the soil volume was, the larger the background image cropping range. Finally, the experimental data were processed by ANOVA using Minitab 19 software to obtain the response relationships of the two indicators of FD and PoSA under different experimental conditions and establish a model of the influence of factors on soil fragmentation.

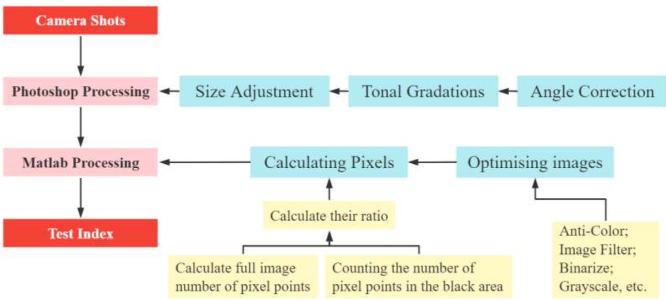


FIGURE. 7 Image Processing Process.

RESULTS AND DISCUSSION

Test results

The results of the fractional factorial experiment are shown in Table 2. Thirty-two sets of tests were conducted with 10 replicates each, and a statistical analysis was performed using the two indicators, FD and PoSA; the test indicators were taken as the mean values after excluding outliers.

TABLE 2. Fractional factorial experiment design and results.

No.	Test parameters						FD[a]	PoSA[b]	No.	Test parameters						FD	PoSA
	X_1	X_2	X_3	X_4	X_5	X_6				X_1	X_2	X_3	X_4	X_5	X_6		
1	1	-1	1	-1	-1	-1	2.55	28%	17	-1	-1	-1	1	-1	1	2.58	18%
2	-1	1	1	-1	1	1	2.31	12%	18	-1	-1	1	1	-1	-1	2.24	10%
3	1	1	1	-1	1	-1	2.52	20%	19	1	-1	1	-1	1	1	2.28	11%
4	-1	-1	-1	-1	-1	-1	2.50	20%	20	-1	-1	-1	-1	1	1	2.52	20%
5	-1	1	1	1	-1	1	2.46	19%	21	-1	-1	1	-1	1	-1	2.39	8%
6	1	-1	-1	-1	1	-1	2.42	16%	22	1	1	-1	1	1	-1	2.90	35%
7	-1	-1	1	1	1	1	2.50	20%	23	1	-1	-1	1	-1	-1	2.83	33%
8	1	1	-1	-1	-1	-1	2.22	15%	24	-1	1	-1	-1	-1	1	2.52	16%
9	1	1	-1	-1	1	1	2.59	18%	25	1	-1	-1	1	1	1	2.86	34%
10	1	-1	1	1	-1	1	2.60	21%	26	-1	1	-1	1	1	1	2.56	22%
11	-1	1	-1	-1	1	-1	2.23	13%	27	1	1	-1	1	-1	1	2.85	34%
12	1	1	1	-1	-1	1	2.24	2%	28	-1	-1	1	-1	-1	1	2.04	2%
13	-1	-1	-1	1	1	-1	2.56	20%	29	-1	1	1	1	1	-1	2.55	21%
14	1	-1	1	1	1	-1	2.28	18%	30	1	-1	-1	-1	-1	1	2.53	15%
15	-1	1	1	-1	-1	-1	2.04	2%	31	-1	1	-1	1	-1	-1	2.35	14%
16	1	1	1	1	1	1	2.51	20%	32	1	1	1	1	-1	-1	2.24	9%

[a]FD: Fractal Dimension;
[b]PoSA: Proportion of Soil Area.

TABLE 3. ANOVA of the fractional factorial experiment.

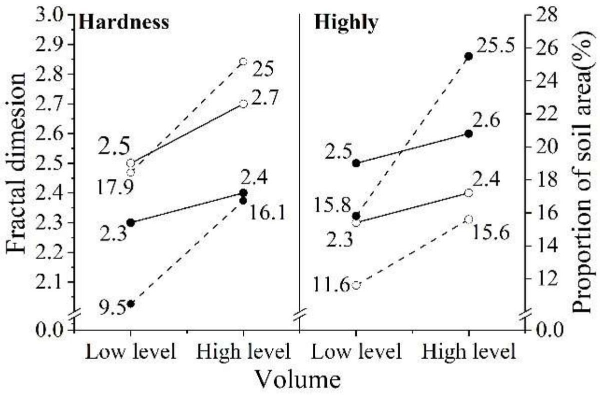
Source			Freedom	FD		PoSA		Significant
				F-value	*P*-value	*F*-value	*P*-value	
Model			6	5.68	<0.001	6.25	<0.001	
	Linear		6	5.68	<0.001	6.25	<0.001	
		Volume	1	5.43	0.028	9.04	0.006	**
		Moisture Content	1	0.46	0.505	1.2	0.285	
		Hardness	1	13.57	<0.001	14.23	<0.001	***
		Drop Height	1	11.4	0.002	9.37	0.005	**
		Sieve Inclination	1	1.65	0.211	3.45	0.075	
		Sieve Rod Material	1	1.58	0.220	0.19	0.666	
Error			25					
Total			31					

Significant factor filtering ANOVA

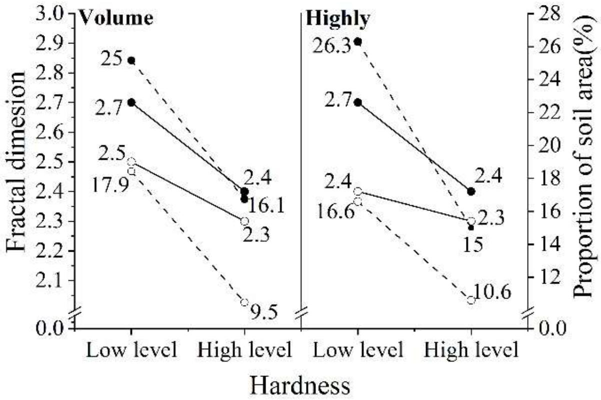
The results of the fractional factorial experiment were analyzed by ANOVA (α = 0.05) using the FD and PoSA as indicators, the results are shown in Table 3. Table GB/T 4086.4-1983 shows that α = 0.05, the project freedom was 1, the number of degrees of freedom of the error was 25, and the critical value of the *F* distribution was $F_{0.05(1,25)}$=4.24. As shown in the table, the soil hardness factor was F_{X3}=14.23>$F_{0.05(1,25)}$ with a highly significant difference and a significance level of 0.1% (P_{X3}≈0.000888<0.001). Here, the *P* value was the mean of the FD ANOVA *P* value and the PoSA ANOVA *P* value, as shown below. The soil volume factor F_{X1}=9.04> $F_{0.05(1,25)}$, and drop height factor F_{X4}> $F_{0.05(1,25)}$, were significantly different with a significance level of 1% (P_{X1}≈0.005943＜0.01, P_{X4}≈0.005943＜0.01). For the soil water content, the *F* values were 0.46 and 1.2 when FD and PoSA were used as indicators, respectively. They were much smaller than $F_{0.05(1,25)}$, so the factor was not significant, which was in agreement with Arvidsson et al. (2004). For the sieve inclination and sieve rod material of the separation sieve, the lowest *F* value was 0.19, and the highest is 3.45, which were less than $F_{0.05(1,25)}$, so their effect on soil fragmentation was not significant. In summary, of the six factors explored in this experiment, oil hardness was a highly significant factor, and soil volume and fall height were significant factors.

Range analysis of soil fragmentation characteristics

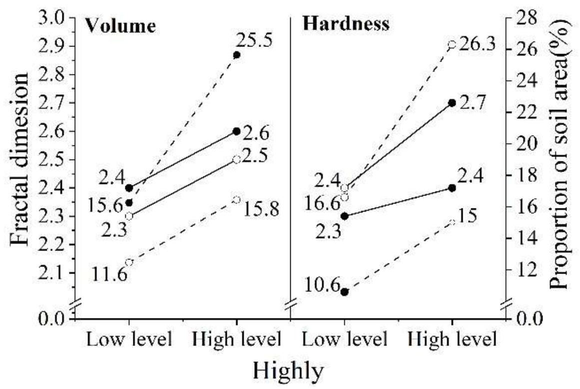
The significant factors filtered by ANOVA were subjected to range analysis, and the trends of the three significant factors, from low to high levels, were obtained. The results of the range analysis are shown in Figure 8(a-c). The left vertical coordinate in the figure is the FD, the right vertical coordinate is the PoSA, and the horizontal coordinates indicate the high and low levels of the three factors that were significant. In the analysis of a factor, we did not consider the effects of the levels of the insignificant factors. We kept the remaining significant factors at fixed levels, and conducted a range analysis of the target factor; the dashed and solid lines in the figure indicated the specific values of the two indicators, PoSA and FD, respectively.



(a) Volume Factor



(b) Hardness Factor



(c) Drop Height Factor

FIGURE. 8 Flow of analysis and processing of test indexes.

a) Relationship between different volumes and soil fragmentation properties

The diagram of the volume factor is shown in Figure 8(a) regarding the effect of the level of insignificant factors. For the left area in the figure, the drop height factor remained constant; the line of hollow circles indicates a low level of soil hardness, while the line of solid circles indicates a high level of soil hardness. The dashed and solid lines indicate the mean values of the two indicators when the soil volume went from low to high levels, respectively. For the area on the right side of the figure, the soil hardness factor remained constant. The line of hollow circles indicates that the soil fall height was low, while the line of solid circles indicates that the soil fall height was high. The dashed and solid lines indicate the mean value of the two indicators when the soil volume went from low to high, respectively.

The figure shows that the FD and PoSA always increased with increasing volume factor, whether the soil fall height factor was kept constant or the soil hardness factor was kept constant. All curves in the graph show such a pattern, indicating that the greater the volume of the soil was, the greater the likelihood that the fragmentation of the soil was significant. The idea that large clods are more likely to break than small ones is consistent with the equation for the kinetic energy of free fall of an object:

$$E_k = mgh \tag{9}$$

Where:

E_k is the kinetic energy of the object;

m is the mass of the object;

g is the acceleration of gravity, and

h is the height of the fall.

The specific size of the soil reduced to a broken clod is determined by the presence of microscopic fatigue cracks inside the clod (Kong & Ruan, 2022).

Our investigation of the soils in the potato crop growing areas revealed a number of reasons for the observations of lumpy soils during harvesting. There were two main reasons. First, for the soil clods that appeared mostly between the furrows, lumpy soil was mainly due to repeated crushing of soil by tractor wheels during potato planting or plant protection (Zhang et al., 2015). Second, for soil clods that appeared on the surface, mainly after rain or watering, soil viscosity was high, which made the soil particles stick together. After drying, the soil contained stronger clumps, which was consistent with the findings of Fubara-Manuel et al. (2021).

Wu (2016) found that most harvesters dug to a depth of approximately 200 mm when harvesting potatoes. The excavation shovel picks up potatoes as well as soil within approximately 200 mm from the ground surface and conveys them by the lift chain to the rear separating sieve. During this process, large pieces of soil were broken into smaller pieces, but these pieces were still not small enough to fall through the gap in the separating sieve, as shown in the schematic drawing in Figure 10(a).

Soil volume is proportional to mass under certain conditions of soil capacity and porosity. The influence of soil volume on the performance of the potato harvester is very significant. According to the test, soil with larger volume broke more easily under the same falling conditions. However, the volume of soil after breaking was not determined. Soil with a small volume did not break easily, but because its initial volume was not large, it might fall from the sieve rod gap after breaking slightly. Therefore, it is necessary to further investigate the actual influence of soil volume factors during potato-soil separation.

b) Relationship between different hardness values and soil fragmentation properties

Factorial plots of the hardness factors are shown in Figure 8(b) without considering the effects of insignificant factor levels. For the left region of the figure, the drop height factor remained constant, and the line of hollow circles indicates a low level of soil volume, while the line of solid circles indicates a high level of soil volume. The dashed and solid lines indicate the mean values of the two indicators when the soil hardness went from low to high levels, respectively. For the area on the right side of the figure, the soil volume factor remained constant, and the line of hollow circles indicates a low level of soil fall height, while the line of solid circles indicates a high level of soil fall height. The dashed and solid lines indicate the mean values of the two indicators when the soil hardness went from low to high levels, respectively.

The graph clearly shows that if the soil hardness was changed while the soil fall height and soil volume were maintained, then the values of the two indicators changed significantly. The two indicators showed an inverse relationship that indicated that the greater the hardness of the soil was, the less the soil fragmentation. These conclusions were the same as those of Usmanov et al. (2014). In very hard soils, the soil particles adhere more closely and are more compact and resistant to damage (Xiao et al., 2019). Additionally, as shown in the region on the right, the slopes of the solid and dashed lines of solid circles were greater than the slopes of the solid and dashed lines of hollow circles. This indicated that the hardness factor had a greater effect on the degree of soil fragmentation when the soil fall height was at a higher level.

Increasing the firmness of the soil is essentially a process of decreasing the porosity and increasing the capacity and density of the soil. Rasmussen (1985) and Mcafee et al. (2010) argued that this reduced the volume fraction and porosity of the soil medium. Larger porosity corresponded to more fragmentable soil, this effect was significant, and this finding was in agreement with Guérif (1990) and Hallett et al. (2010). Usmanov et al. (2014) claimed that it is more difficult to break harder soil because the pressure it receives during a collision is more evenly distributed throughout the soil, which reduces the concentration of the force and weakens the impact of the collision. Hallett et al. (2010) suggested that soil fragmentation depends on not only the amount of porosity but also the geometric characteristics of the cracks, which is consistent with brittle fracture mechanics. The uncontrollable nature of the characteristics of crack geometry during the preparation of the soil samples resulted in test errors and outliers of the index.

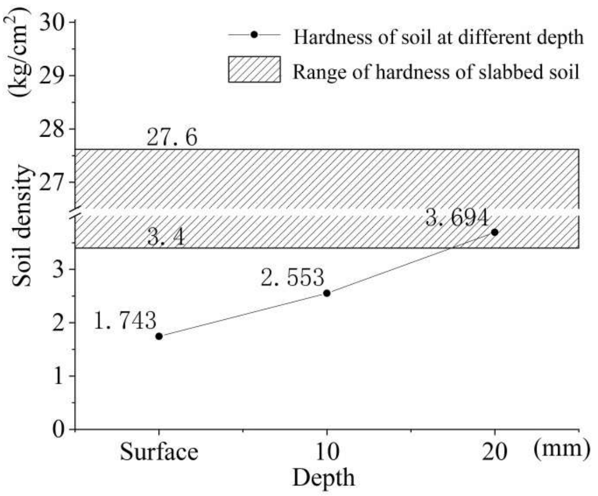


FIGURE. 9 Hardness of soils at different depths as well as blocky soils.

We found that the hardness of the soil at the potato plantation varied considerably at different depths. Specific values were obtained using a soil firmness tester to measure the range of soil firmness and block soil firmness at different depths, as shown in Figure 9. We learned that the firmness of the soil gradually increased with greater depth, which was consistent with the study of Qiao et al. (2021). The soil hardness of the surface of a furrow was approximately 1.743 kg/cm^2. For potato harvesting, the digging shovel normally worked to 200 mm below the furrow, and the soil hardness at this depth was approximately 3.649 kg/cm^2. We also measured the firmness of the block soil dug during the potato harvest and found that it ranged from 3.4 to 27.6 kg/cm^2, i.e., from 0.34 to 2.76 MPa, which was the interval of soil hardness levels explored in this experiment. We found that during the potato harvesting process, the harder soil pieces were not broken to a greater extent by the slight shaking of the lifting chain and the substantial shaking of the separating sieve, as shown in Figure 10(b). Therefore, the potato-soil separation efficiency of the 4SW-170 potato excavator was not high when it operated in fields with large amounts of hard soil. We need to improve the equipment by using the influence of external conditions on the soil crushing characteristics, such as improving the swing speed of the sieve rod and fall height. Soil hardness parameters provide us with the basis for improving the machine so that it is better adapted to the various types of soil in which potatoes are planted.

c) Relationship between different drop heights and soil fragmentation characteristics

Factorial plots of the fall height factors are shown in Figure 8(c) without considering the effects of levels of insignificant factors. For the left area of the figure, the soil hardness factor remained constant, and the line of hollow circles indicates a low level of soil volume, while the line of solid circles indicates a high level of soil volume. The dashed and solid lines indicate the mean values of the two indicators when the soil fall height went from low to high levels, respectively. For the area on the right side of the figure, the soil volume factor remained constant, and the line of hollow circles indicates a low level of soil hardness, while the line of solid circles indicates a high level of soil hardness. The dashed and solid lines indicate the mean values of the two indicators when the soil fall height factor went from low to high levels, respectively.

The figure shows that when the soil volume factor and soil hardness were maintained at a certain level, the values of the two indicators increased with the fall height, which was a positive correlation. This indicated that the higher the fall height was, the greater the degree of soil fragmentation. Similarly, this result was consistent with the equation for the kinetic energy of a freely falling object, $E_k=mgh$. The slope of the line of solid circles on the left side of the image was greater than the slope of the line of hollow circles, while the slope of the line of hollow circles on the right side of the image was greater than the slope of the line of solid circles. This indicated that the greater the volume and the less the hardness of the soil were, the more obvious the relationship between the height of the fall and the effect of soil fragmentation. Assuming that the sieve surface was at rest, the instantaneous velocity of the soil block was the relative velocity between the block and the sieve rod at the moment when the block fell to the sieve surface. This situation was regarded as the stationary soil block being crushed by the impact of its collision with the sieve rod. When the impact resistance of the soil was certain, the greater the impact load was, the more likely the soil was to break. When its impact resistance was exceeded, the actual load continued to increase, and the degree of breakage was greater (Wang et al., 2015). Therefore, when harvesting potatoes in fields with hard soil, it is necessary to control the height of the soil fall by adjusting the speed of the lift chain.

The stage where the potato-soil mixture falls on the separation sieve from the top of the lift chain, as shown in Figure 10(c), is one of the more important stages in the potato-soil separation process. During the potato harvesting process, the digging shovel picks up both potatoes and soil and transports them to the lifting chain with the inertia of the advancing machine (Zhao et al., 2007). The angle of the lifting chain of the 4SW-170 model potato harvester (16° ~ 30°), and the lifting chain line speed (1.3 m/s~1.6 m/s) are generally used (Zhao et al., 2007; Zhao et al., 2020). The force analysis of the model potato excavator shows that the height that the potato and soil are thrown upward is related to the angle and linear speed of the lifting chain, the height of the sieve surface, and other factors. The instantaneous speed of the mixture falling to the sieve surface can be adjusted by altering the linear speed or angle of the lifting chain and the length of the rocker of the swing separation sieve (Lü et al., 2017). In this paper, the kinetic energy of impact at the moment of collision with the sieve rod was controlled by changing the height of the soil fall, which was consistent with this principle. If the height of the fall is too high, then most of the soil is broken to achieve effective separation of potatoes and soil, but this increases the rate of breakage of the skins of potatoes. If the height of the fall is too low, then reducing the rate of breakage of the skins of potatoes reduces the efficiency of potato-soil separation. Therefore, this stage is the most contradictory stage of this potato harvester, and it is important to adjust the structural parameters of the machine for actual soil conditions.

A) Soil clods gathered at the top of the lift chain.

b) Separate large hard clods on the sieve that are difficult to break.

c) The potato-soil mixture is transported to the top of the lift chain and then dropped.

FIGURE. 10 Live view of the harvesting process.

In summary, the three significant factors in the range analysis are shown in Figure 11, where the solid line indicates the FD and the dashed line indicates the area share of the soil according to processed images. The three areas (from left to right) represent the three factors of soil volume, soil hardness and soil fall height. Each area represents the change in the mean value of the two indicators during the increase in the level of the corresponding factor. There is clearly a positive correlation between two factors, soil volume and fall height, and degree of soil fragmentation. However, there is a negative correlation between the soil hardness factor and degree of soil fragmentation. This is mainly due to various factors, such as soil hardness, soil moisture content, and temperature, that affect soil porosity and bulk density. Because soil porosity and bulk density are the main physical parameters of soil, they lead directly to differences in the dynamic physical properties of soil related to impacts.

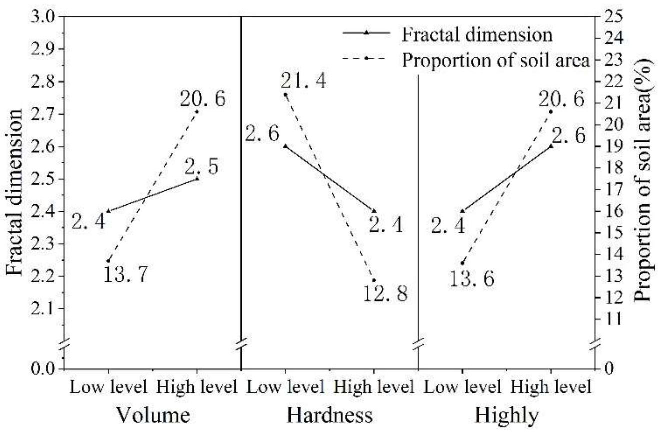


FIGURE. 11 Fractional factorial experiment Range Analysis of significance factors in the test.

Correlation analysis of FD and PoSA

Niu et al. (2018) claimed that the evaluation of two indicators in the experiment made the results more accurate. Thus, we used a combination of two indicators to evaluate and analyze the results of our experiment. Pearson correlation analysis was used to explore the correlation between the FD and PoSA obtained as a result of image processing, and a contour map was plotted. The results are shown in Figure 6. The figure shows that the correlation reached 0.87, which was a strong correlation (0.9>r>0.7) (Hopkins, 2000; Vanzela et al., 2020). The scatter fit image was plotted with the PoSA and FD as indicators, as shown in Figure 7. Approximately 2/3 of the values were within the 95% confidence band. Only test #5 was outside the 95% prediction band, which again indicated that the sample data were statistically significant and relevant (Grossman & Matejka, 2010).

$$POSA = 36.98(\pm 3.77)\times FD - 73.90(\pm 9.33) \quad (10)$$

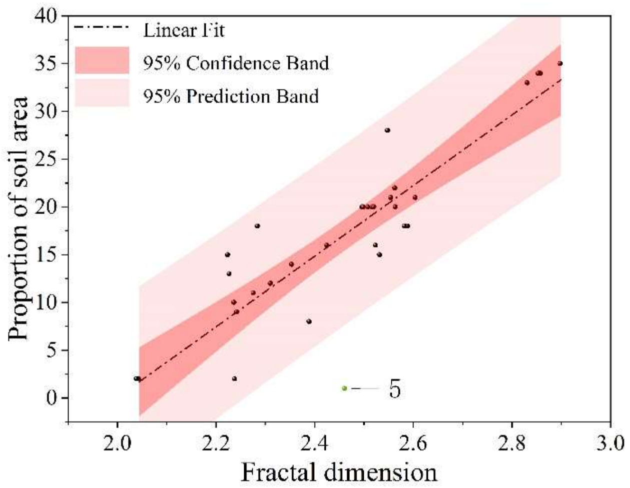


FIGURE. 12 Scatter plot of Fractal Dimension (FD) and Proportion of Soil Area (PoSA).

Although the FD is the more common approach used internationally when assessing the state of scattered soil (Zhang et al., 2016), it is very complex, and recording the data requires measuring the triaxial dimensions of each fragmented body. When analyzing and processing FD data, it is necessary to fit a straight line (Meng et al., 2009). Simplifying this step has always been an enormous challenge. In this study, we found that the two indicators under investigation were strongly correlated, so we adopted the method of real-time image collection and processing, applied a black box model of processing, and focused on the results of processing. This simplified the operation steps and provided a simpler and faster method for future experimental investigations.

CONCLUSIONS

According to the ANOVA of the results of the soil drop experiment for main factors, the factor that had the greatest influence on the degrees of soil crushing was soil hardness, followed by soil volume and soil drop height. In contrast, soil moisture content, sieve inclination, and sieve rod material were statistically nonsignificant. A range analysis showed that soil volume and drop height were positively correlated with degree of soil crushing, while soil hardness was negatively correlated with degree of crushing. To avoid increasing the hardness and volume of soil block and the volume of the slatted soil block, it is necessary to effectively loosen the soil before planting potatoes and try to prevent soil clumping. To determine the difference in height between the potato harvester lift chain and the separation sieve, we should consider the critical height for falling potatoes to ensure that the potatoes are not damage. The damage rate is qualified under the premise of appropriately reducing the height of the separation sieve or increasing line speed of the lift chain transport and then improving the height of the potatoes and soil thrown up so that the soil block effectively breaks to promote potato-soil separation.

We found a significant correlation between the PoSA obtained by image analysis and FD. Thus, the PoSA can be used to index the test results when the FD method is not applicable or when it is necessary to improve the efficiency of evaluating the degree of soil fragmentation. Steps should be taken to simplify the process of determining the degree of soil fragmentation, improve processing efficiency, reduce processing errors, and effectively promote the exploration of soil fragmentation in the field of agricultural mechanization.

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