STATISTICS AND ANALYSIS OF PHYSICAL PARAMETERS OF ADZUKI BEAN SEEDS
/
红小豆种子物理参数统计及分析

Guoqiang DUN*[1)], Luhan WANG[2)], Huiwen XUE[1)], Xinxin JI[1,2)], Quanbao SHENG[2)], Xinming LI[2)], Chaoxia ZHANG[1)], Yuhan WEI[1)]

[1)] Harbin Cambridge University, Intelligent Agricultural Machinery Equipment Engineering Laboratory, Harbin / China;
[2)] Northeast Forestry University, College of Mechanical and Electrical Engineering, Harbin / China;
Tel: +86 13836027042; E-mail: dunguoqiangpaper@163.com
DOI: https://doi.org/10.35633/inmateh-75-37

Keywords: *Mechanical seed-metering device; Adzuki bean seeds; Physical parameters; Seed shape*

ABSTRACT
To address the issue of seed filling in mechanical seed meters for different varieties of adzuki beans and to provide a basis for designing the shape and size of seed metering plate holes, a statistical analysis of the physical parameters of seeds from 10 adzuki bean varieties with significant morphological differences was conducted. The three-axis dimensions (length, width, and thickness) and the equivalent diameter of the seeds were found to approximately follow a normal distribution. The distribution and dispersion of each physical parameter were analyzed. A linear correlation analysis was performed between the equivalent diameter and the hundred-seed weight, showing a consistent overall trend. By measuring the hundred-seed weight, the relative equivalent diameter was determined, which was then used to select the appropriate seed metering plate diameter. The linear correlation coefficient analysis of the three-axis dimensions of different varieties indicated that, when modeling adzuki bean seeds for simulation, either the width or thickness could be selected as the primary dimension based on specific conditions.

摘要
为解决红小豆机械式排种器对不同品种红小豆的充种问题，提供排种盘型孔结构设计参数依据，选取形态差异较大的 10 种红小豆种植品种的种子物理参数进行数据统计分析。种子的三轴尺寸长、宽、厚及均径均近似服从正态分布，分析确定了各物理参数的分布离散情况，均径与百粒重整体变化趋势基本一致并进行线性相关分析，通过测量百粒重得出相对均径从而选择排种盘直径，不同品种三轴尺寸间线性相关系数分析结果表明，仿真红小豆种子建模时可根据具体情况选取宽或厚作为主尺寸。

INTRODUCTION
Adzuki Bean, or Vermillion Beans, is the leguminous family's annual semi-twining herbaceous plant. The taste of the adzuki bean is sweet, and it is planted all over China. The stability of its production is of great significance in ensuring China's food security. Adzuki bean has a purple-red surface, plump grains, and is rich in protein, vitamins, and carbohydrates *(Li et al., 2023)*, so consumers deeply favor it. Adzuki bean breeding technology *(Liu et al., 2024)* is an essential means of variety improvement and grain production increase. The adzuki bean mechanical plot breeding experiment *(Dun et al., 2022)* is the best method for breeding high-quality and high-yield new varieties, which is focused on the research and development of seeding machinery and equipment *(Shang et al., 2021)*.

At present, the filling problem of the mechanical seed-metering device is still the core technical problem, which mainly studies the internal relationship between the hole of the seed metering plate and the adzuki bean seeds. Different varieties of adzuki bean seeds are sown in the breeding test field in the same region, and these seeds have different geometric dimensions and seed grain shapes. Therefore, it is necessary to measure and statistically analyze the geometric dimensions of different varieties of adzuki beans in the same region as a reference for the design of the hole shape of the seed-metering device *(Lan et al., 2022)*. Domestic and foreign scholars have researched the physical properties of various agricultural materials. *Dun Guoqiang et al., (2024),* conducted EDEM discrete element simulation on the seed filling characteristics of the double swing plate type seed metering device of different soybean varieties and simulated the seeding process; *Zheng Xiaoshuai et al., (2024),* from Qingdao Agricultural University analyzed the geometric shape and size parameters of Cyperus esculentus seeds, measured the precise outline of Cyperus esculentus seeds by using the cross-sectional circular runout method, and established a discrete element simulation particle model of the seeds. They also performed parameter calibration and seeding simulation through simulation experiments, data analysis, and fitting. Based on the geometric characteristics of pumpkin seeds, *Yu Yaxin et al., (2024),* from Zhejiang Sci-Tech University calibrated the discrete element simulation contact parameters of pumpkin seeds and seed metering device, and determined the range of negative pressure and the number of holes in the seed metering plate through single factor tests. *Zhang Shengwei et al., (2022),* used the Hertz-Mindlin with bonding model to establish a seed simulation model and calibrated the simulation parameters between mung bean seeds and contact materials to further optimize seed planting components. *Yan Jianwei et al., (2023),* from Guizhou University took white radish seed particles as the research object, establishing a discrete element model of white radish seed particles using 3D scanning reverse modeling technology and EDEM software. They calibrated simulation parameters through physical tests and virtual simulation experiments. *Li Qichao et al., (2021),* established a discrete element model of vegetable seeds and a seed-metering device model based on the physical parameters of three different types of small-particle vegetable seeds. Using discrete element software EDEM, they analyzed the seeding performance and examined the movement behavior of vegetable seeds during the seed filling process.

Wenxin Zhang et al., (2022), determined the basic physical parameters, contact parameters and angle of repose of germinated American ginseng seeds through physical experiments, and through the steepest climbing test, the optimal range of the significance parameter values was determined. *Ma Wenpeng et al., (2023),* used the discrete element method to simulate and analyze the mechanized seeding process of sesame seeds. The contact parameters of sesame seeds were calibrated by combining the actual seed drop test and the simulated seed drop test. *Xu Bing et al., (2021),* calibrated the simulated discrete element parameters of buckwheat seeds in combination with the simulation optimization design test and physical test. *Karaiev Oleksandr et al., (2021),* mathematically modeled the calibration process of fruit stone culture seeds such as cherry, sweet cherry, cherry plum, almond, and apricot kernel, etc. *Xingye Chen et al., (2024),* calibrated the contact parameters of the bean pod pepper seeds, took the repose angle as the response value, and simulated the discrete element model of the bean pod pepper seeds by using reverse engineering reconstruction technology. *Tianyue Xu et al., (2023),* took ellipsoidal seeds such as soybeans, adzuki beans, and kidney beans as research objects and analyzed their size and shape. The results showed that the normal distribution can approximate the size dispersion, and thus a method of modeling ellipsoidal seeds as particles based on the multi-sphere method was proposed.

In summary, previous studies have conducted in-depth research on the physical parameters, the model establishment, and simulation parameter calibration of agricultural materials. However, there is still room for research on the physical parameters, seed shape measurement, and statistical analysis of a certain number of multi-variety adzuki bean seeds. Since the shape and size of adzuki bean seeds are relatively irregular and small, to ensure the accuracy of the experiment, several adzuki bean seeds were selected as research objects. Their length, width, and thickness were measured, followed by statistical analysis and calculations of their triaxial dimensional relationships, average diameter, sphericity, length-to-width ratio, length-to-thickness ratio, volume, density, and 100-grain weight. This analysis provides a reference for designing the seeding plate hole of the adzuki bean mechanical seed-metering device.

MATERIALS AND METHODS

Determination of material properties of Pak Choi seeds

Ten adzuki bean varieties grown in China were selected, namely, Pearl Red, Xianfeng Extremely Early, Shouhe Acacia, Shengyou, Pangda Agricultural, Kyoto, Jin Wangjie, Red Pearl, Dazhi, and Dahongpao. 100 seeds of each variety were randomly selected, as shown in Figure 1. A digital display vernier caliper (range 200 mm, accuracy 0.01 mm) was used to measure the triaxial dimensions (length l, width w, thickness t) of each adzuki bean seed *(Wang et al., 2018)*. An electronic analytical balance (range 100 g, accuracy 0.001 g) was used to measure the 100-grain weight of adzuki bean seeds. 100 seeds of each variety were respectively taken for measurement, and the average value was taken 5 times *(Bai et al., 2024)*. The actual operation diagram is shown in Figure 2. The average diameter d, sphericity S_p, length-to-width ratio R_{lw}, length-to-thickness ratio R_{lt}, volume v, and density ρ of the adzuki bean seeds were calculated.

The specific calculation formula *(Dun et al., 2023)* is as follows:

$$d = \frac{l+w+t}{3} \tag{1}$$

$$S_p = \frac{\sqrt[3]{lwt}}{\max(l \cdot w \cdot t)} \tag{2}$$

$$R_{lw} = \frac{1}{w} \tag{3}$$

$$R_{lt} = \frac{1}{t} \tag{4}$$

$$v = \frac{1}{6}\pi lwt \tag{5}$$

$$\rho = \frac{m}{v} \tag{6}$$

where: l is the seed length, mm; w is the seed width, mm; t is the seed thickness, mm; m is the seed quality, g; ρ is the seed density, g/cm^3; v is the seed volume,mm^3; S_P is the seed sphericity; R_{lw} is the ratio of seed length to width; R_{lt} is the ratio of seed length to thickness.

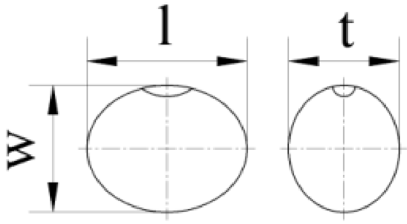
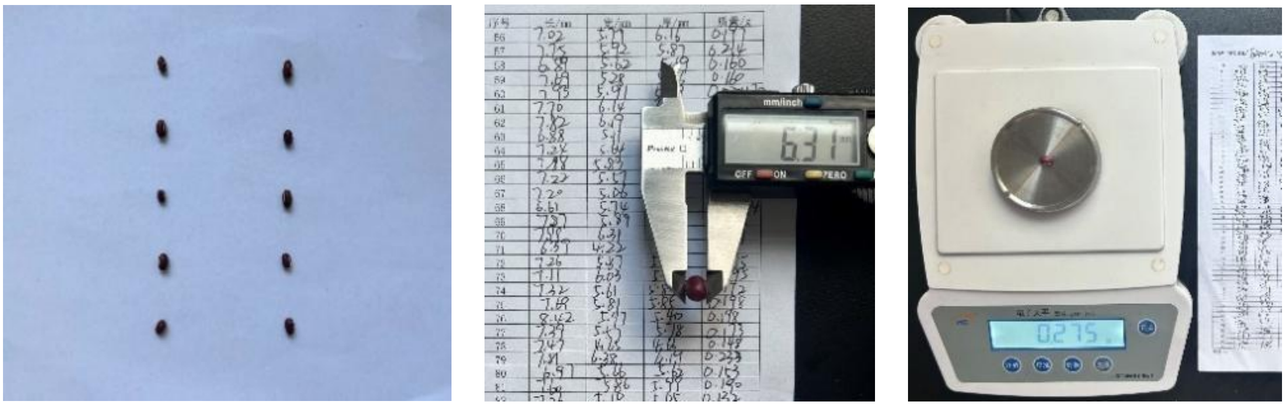


Fig. 1 - Triaxial dimensions of adzuki bean seeds



a) Adzuki been seeds diagram; *(b) Seed triaxial dimension measurement;* *(c) Seed quality measurement diagram*

Fig. 2 - Measured physical parameters of adzuki beans

In order to analyze the population characteristic data of 100 seeds of each adzuki bean variety, the measured values and calculated values of the physical geometric parameters of the above varieties of seeds were calculated by mathematical statistics. The statistical parameters included each parameter's maximum, minimum, mean and coefficient of variation. The maximum and minimum values represented the distribution range limits of the parameter. The coefficient of variation is a commonly used statistic to measure the degree of data variation *(Yang et al., 1993)*. The ratio of standard deviation to the mean value can eliminate the influence of measurement scale and dimension between different varieties of adzuki bean seeds. It is used to compare the dispersion degree of each parameter. The smaller the value, the more concentrated the overall distribution of the data, conversely, the larger the value, the more discrete the overall distribution. The statistical results of seed physical parameters of 10 kinds of adzuki bean seeds, such as Pearl red, Xianfeng Extremely Early and Shouhe Acacia, are shown in Table 1.

Table 1

Statistics of dimensions of adzuki bean seeds

Adzuki bean variety	Value	Length l/mm	Width w/mm	Thick-ness t / mm	Average diameter d / mm	Sphericity S_p	Length - width ratio R_{lw}	Length -thick-ness ratio R_{lt}	Volume v/ mm^3	Density ρ/g/cm^3	hundred-grain weight / g
Pearl red	Maximum value	7.37	5.94	5.78	6.18	0.98	1.37	1.54	121.6	2.402	

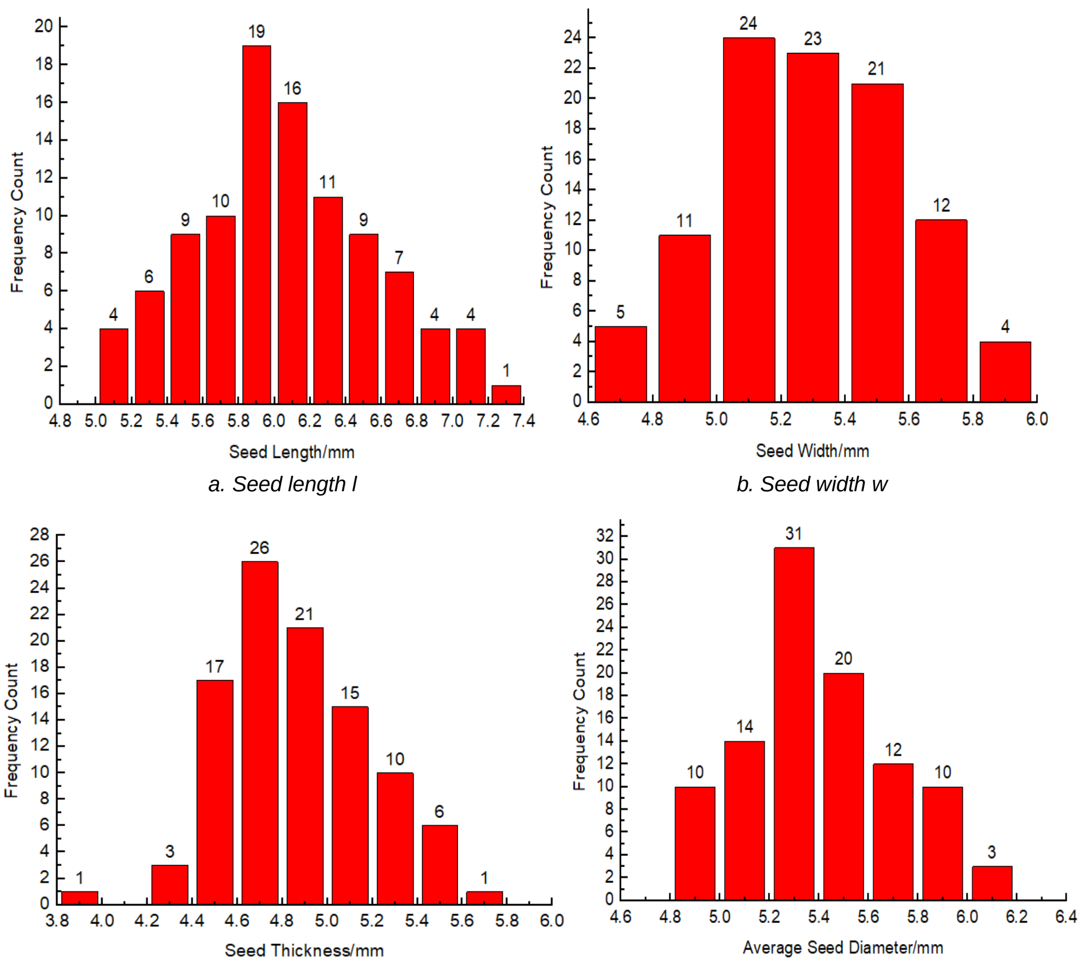
Adzuki bean variety	Value	Length l/mm	Width w/mm	Thick-ness t / mm	Average diameter d / mm	Sphericity S_p	Length - width ratio R_{lw}	Length -thick-ness ratio R_{lt}	Volume v/ mm^3	Density ρ/g/cm^3	hundred-grain weight / g
	Minimum value	5.02	4.70	3.99	4.80	0.79	0.98	1.04	56.58	0.635	
	Average value	6.05	5.29	4.86	5.40	0.89	1.15	1.25	82.017	1.427	
	Coefficient of variation	0.085	0.055	0.069	0.058	0.052	0.078	0.085	0.176	0.134	
	hundred-grain weight										11.597
Xianfeng Extremely Early	Maximum value	9.98	6.94	6.94	7.76	0.98	1.84	1.81	232.22	2.137	
	Minimum value	5.39	5.01	4.50	5.19	0.68	0.93	1.01	73.21	1.022	
	Average value	8.40	5.96	5.91	6.76	0.80	1.41	1.42	156.91	1.461	
	Coefficient of variation	0.104	0.076	0.077	0.075	0.065	0.098	0.098	0.214	0.104	
	hundred-grain weight										22.689
Shouhe Acacia	Maximum value	10.65	6.87	7.69	7.95	0.88	1. 65	1.74	245.32	1.882	
	Minimum value	7.71	5.41	5.06	6.06	0.72	1.20	1.18	110.51	1.170	
	Average value	8.99	6.23	6.24	7.15	0.79	1.45	1.44	183.85	1.480	
	Coefficient of variation	0.072	0.049	0.062	0.051	0.046	0.067	0.074	0.144	0.067	
	hundred-grain weight										27.076
Shengyou	Maximum value	10.12	7.02	6.90	7.71	1.00	1.63	1.69	226.52	2.203	
	Minimum value	6.03	4.99	4.98	5.45	0.73	1.00	1.00	83.14	0.830	
	Average value	8.47	6.17	6.14	6.93	0.81	1.38	1.38	169.51	1.416	
	Coefficient of variation	0.089	0.065	0.068	0.062	0.061	0.087	0.089	0.176	0.098	
	hundred-grain weight										23.894
Pangda	Maximum value	10.04	6.94	7.08	7.88	0.93	1.70	1.69	242.71	2.261	
	Minimum value	5.12	5.10	4.94	5.70	0.70	0.82	0.83	95.53	1.228	
	Average value	8.36	6.04	6.03	6.81	0.81	1.39	1.39	160.85	1.514	
	Coefficient of variation	0.092	0.065	0.074	0.067	0.048	0.080	0.084	0.197	0.084	
	hundred-grain weight										24.175
Kyoto	Maximum value	8.57	7.72	6.80	7.16	0.96	1.61	1.64	186.74	2.061	

Adzuki bean variety	Value	Length l/mm	Width w/mm	Thick-ness t / mm	Average diameter d / mm	Sphericity S_p	Length - width ratio R_{lw}	Length -thick-ness ratio R_{lt}	Volume v/ mm^3	Density $\rho/g/cm^3$	hundred-grain weight / g
	Minimum value	4.81	4.22	4.44	4.76	0.73	0.88	0.97	56.20	0.709	
	Average value	7.31	5.71	5.66	6.23	0.84	1.29	1.30	125.23	1.410	
	Coefficient of variation	0.078	0.099	0.083	0.071	0.050	0.093	0.086	0.208	0.120	
	hundred-grain weight										17.535
Jin Wangjie	Maximum value	9.40	6.85	6.70	7.47	0.96	1.62	1.66	212.25	2.261	
	Minimum value	5.34	4.95	5.00	5.48	0.73	0.94	0.88	86.23	1.085	
	Average value	7.98	5.72	5.69	6.46	0.80	1.40	1.40	137.47	1.433	
	Coefficient of variation	0.083	0.071	0.071	0.065	0.046	0.077	0.077	0.195	0.106	
	hundred-grain weight										19.551
Red Pearl	Maximum value	10.00	8.68	6.90	7.75	0.92	1.72	1.78	232.88	1.689	
	Minimum value	6.26	4.96	4.96	5.47	0.70	1.00	1.11	83.94	1.001	
	Average value	8.24	5.91	5.86	6.67	0.80	1.40	1.41	151.16	1.504	
	Coefficient of variation	0.096	0.081	0.071	0.071	0.055	0.088	0.084	0.206	0.074	
	hundred-grain weight										22.606
Dazhi	Maximum value	9.98	6.94	6.94	7.76	0.98	1.84	1.81	232.22	2.14	
	Minimum value	5.39	5.01	4.50	5.19	0.68	0.93	1.01	73.21	1.02	
	Average value	8.40	5.96	5.91	6.76	0.80	1.41	1.42	156.91	1.46	
	Coefficient of variation	0.104	0.077	0.077	0.075	0.065	0.098	0.098	0.21	0.10	
	hundred-grain weight										22.689
Dahongpao	Maximum value	10.31	7.41	7.36	7.99	0.91	1.60	1.68	256.53	1.543	
	Minimum value	6.07	4.63	4.19	4.96	0.73	1.13	1.11	61.66	1.142	
	Average value	8.65	6.35	6.17	7.05	0.81	1.36	1.41	179.90	1.364	
	Coefficient of variation	0.095	0.075	0.090	0.079	0.046	0.066	0.080	0.216	0.058	
	hundred-grain weight										24.436

RESULTS

Single seed parameter analysis

First, taking Pearl Adzuki beans as an example, the triaxial dimensions and shape parameters of 100 seeds of this variety were statistically analyzed. The statistical results are shown in Table 1. The average values and coefficients of variation of length l, width w, thickness t, and average diameter d of Pearl Adzuki beans are 6.05 mm, 5.29 mm, 4.86 mm, 5.40 mm, and 0.085, 0.055, 0.069 and 0.058, respectively. The triaxial dimensions and average diameter approximately obeyed the normal distribution. The normal distribution of triaxial dimensions of seeds is shown in Figure 3. The length l, width w, thickness t, and average diameter d of Pearl Adzuki seeds showed leapfrog jumps in the first 20%, 16%, 21%, and 24%, and the changes in the last 80%, 84%, 79% and 76% of the seeds were more gradual, indicating that there were fewer small seeds and more large seeds in Pearl Red varieties. The distribution of seed length l, thickness t, and average diameter d was basically consistent and relatively discrete. The sizes were concentrated in 5.5 mm~7.0 mm, 4.5 mm~5.5 mm, and 4.9 mm~5.9 mm, respectively. The size ranges were 2.35 mm, 0.92 mm, and 1.38 mm, respectively. The sizes varied greatly, and a certain proportion of over-large and over-small sizes existed. The seed width w was more concentrated, with a size range of 0.65 mm. The overall distribution was too smooth and basically symmetrical. The coefficients of variation of seed length l, thickness t, and average diameter d were 0.085, 0.069, and 0.058, respectively, while the coefficient of variation of seed width w was 0.055, significantly smaller than the first three. The overall distribution was significantly concentrated. The sphericity S_p of Pearl Red seeds ranged from 0.79 to 0.98, with an average value of 0.89 and a coefficient of variation of 0.052. The average length-to-width ratio R_{lw} and length-to-thickness ratio R_{lt} of the seeds were calculated to be 1.15 and 1.25, respectively. The length l and width w were basically the same, but both were significantly larger than the seed thickness t. The length-width cross-section of the seed was an ellipse, the length-thickness cross-section was an ellipse, and the seed shape was an approximately ellipsoid of unequal diameters.

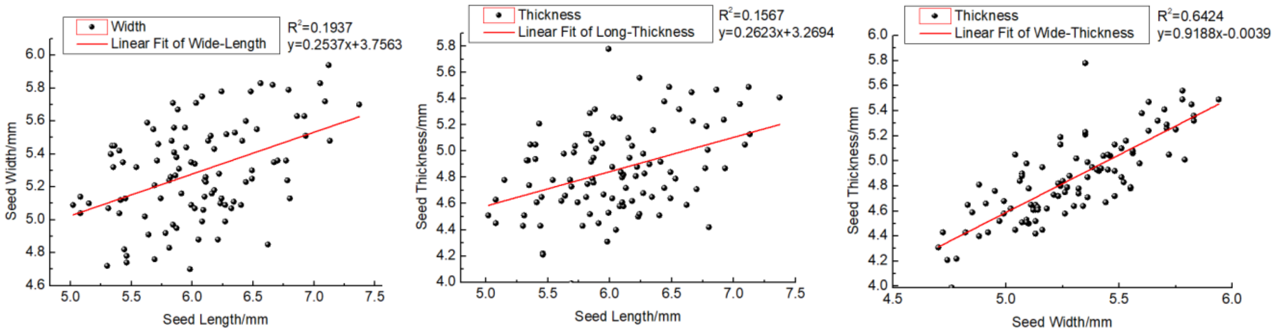


a. Seed length l *b. Seed width w*

c. Seed thickness t *d. Average seed diameter d*

Fig. 3 - Seed grain triaxial and average diameter size distribution

In order to analyze the relationship between the length l, width w, and thickness t of adzuki bean seeds, origin 8.5 was used for parameter mapping *(Chen et al., 2024)*, and scatter plots of seed length and width, length and thickness, and width and thickness were drawn for linear fitting, as shown in Figure 4. The triaxial dimensions of adzuki bean seeds showed a linear positive correlation function relationship. The correlation coefficients of the linear fitting equations between the triaxial dimensions of length-width, length-thickness, and width-thickness were R^2=0.1957, R^2=0.1567, and R^2=0.6424. The Pearson coefficient between length-width and width-thickness was significantly greater than the linear correlation between length-thickness. Therefore, it can be determined that the width of the triaxial dimensions was the main dimension and the thickness was the secondary dimension. The seed width can be randomly generated according to the normal distribution during seed modeling, and the length and thickness dimensions can be calculated according to the functional relationship with the main dimension width. In this way, the size distribution of the adzuki bean seed population generated by simulation was closer to the actual situation.



a) Seed length and width *(b) Seed length and thickness* *(c) Seed width and thickness*

Fig. 4 - Scatter plot of the relationship between the triaxial dimensions of adzuki bean seed

Statistical analysis of different seed parameters

The measurement and statistical results of the parameters of a single variety of Pearl Red cannot represent the overall physical geometric parameters of adzuki bean seeds in the national planting area due to its variety of attributes and the particularity of regional environment planting. Therefore, as shown in Table 1, the physical parameters of 10 kinds of adzuki bean seeds were statistically analyzed. It can be seen from Table 1 that the physical parameters of 100 seeds in each adzuki bean variety obeyed the normal distribution. The coefficient of variation of length, width, thickness, and average diameter ranged from 0.049 to 0.104. The larger the coefficient of variation of the average diameter of adzuki bean seeds, the greater the degree of dispersion of the average diameter of seeds, the more irregular the seed shape, and the more it tends to be ellipsoidal. The coefficient of variation of sphericity ranged from 0.046 to 0. 065, the coefficient of variation of length-to-width ratio and length-to-thickness ratio ranged from 0.066 to 0.098, the coefficient of variation of volume ranged from 0.144 to 0.216, and the coefficient of variation of density ranged from 0.058 to 0.134. The sphericity distribution was concentrated overall, followed by length-to-width and length-to-thickness ratios. The distribution of triaxial dimensions, average diameter and volume was relatively discrete, and the density distribution was the most discrete. The single-factor test method was adopted, and the experimental design expert software design-expert 8.0 was used. The adzuki bean varieties (10 kinds of adzuki bean seeds) and parameter values (maximum value, minimum value, average value) were used as experimental factors, and length, width, thickness, average diameter, sphericity, length-width ratio, length-to-width ratio, length-to-thickness ratio, volume, and density were used as experimental indicators. The statistical analysis of physical parameter tests was carried out, and the statistical results of the experimental indicators are shown in Table 2.

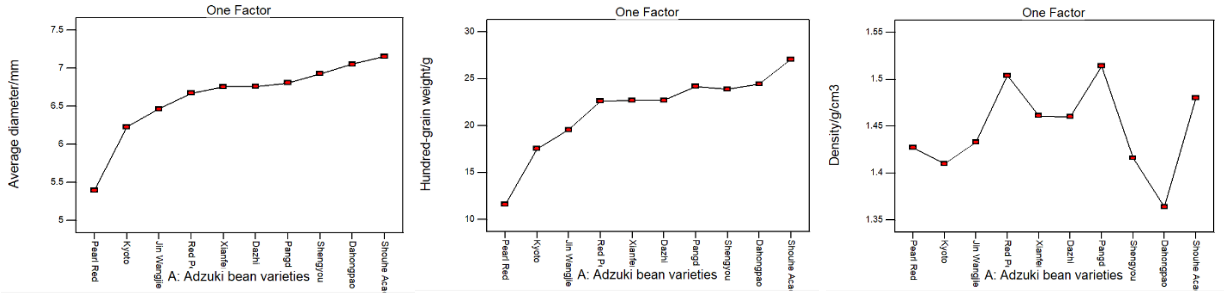
Table 2

Overall statistics of physical parameters of adzuki beans

Parameter	Minimum	Maximum	Average	Standard deviation	Coefficient of variation
Length / mm	4.81	10.65	8.08	1.082	0.134
Width / mm	4.22	8.68	5.93	0.516	0.087
Thickness / mm	3.99	7.69	5.85	0.575	0.098
average diameter / mm	4.76	7.99	6.62	0.658	0.099
Sphericity	0.68	0.997	0.81	0.052	0.064
Length-width ratio	0.82	1.84	1.36	0.141	0.103

Parameter	Minimum	Maximum	Average	Standard deviation	Coefficient of variation
Length-thickness ratio	0.83	1.81	1.38	0.132	0.085
Volume / mm^3	56.20	256.53	150.38	41.104	0.273
Density / g/cm^3	0.63	2.40	1.45	0.147	0.101

As shown in Table 2, the average length, width, thickness, average diameter, and variation range of the 10 kinds of adzuki bean seeds are 8.08 mm, 5.93 mm, 5.85 mm, 6.62 mm, 8.08±1.082 mm, 5.93±0.516 mm, 5.85±0.575 mm, and 6.62±0.658 mm, respectively. The seed length and width are close, and significantly larger than the seed thickness. The average diameter and the width of the seeds are close to each other. The coefficient of variation shows that the seed width distribution is relatively concentrated, and the seed length distribution is the most dispersed. In order to further explore the design structure of the seed metering plate hole, according to Tables 1 and 2, the factor index change trend chart was drawn using design-expert 8.0. The adzuki bean varieties were used as experimental factors, and the average diameter, 100-grain weight, and density of each variety were used as experimental indicators to analyze the changing trend of the adzuki bean seed average diameter, 100-grain weight and density parameters, as shown in Figure 5.



a) Variation trend of average diameter *(b) Variation trend of 100-grain weight* *(c) Variation trend of density thickness*

Fig. 5 - Variation trends of average diameter, 100-grain weight and density

As shown in Figure 5, the average diameter and 100-grain weight of different seeds have basically the same trend. The density of seeds of a few varieties (Shengyou, Dahongpao) is entirely opposite to the average diameter and 100-grain weight. The trends of seeds of other varieties (Kyoto, Red Pearl, Jin wangjie, Xianfeng Extremely Early, Dazhi, Pangda Agriculture, Shouhe Acacia) are basically consistent with their average diameter and 100-grain weight. Among them, the larger the average diameter of each adzuki bean variety, the larger the value of its 100-grain weight. Since the density range between the same beans is small, the density of specific varieties should be analyzed according to the specific variety combined with the average diameter and 100-grain weight. There is also a particular case in analyzing the average diameter and 100-grain weight trend. For example, although the average diameter of Shengyou's seeds is larger than that of Pangda Agriculture, the 100-grain weight is smaller than that of Pangda Agriculture, the floating trend of its value is not obvious. The main reason for this trend is that there are minimal exceptions in Shengyou adzuki bean seeds that lower the value of 100-grain weight, and it can be seen from the triaxial dimensions of the seeds and the range of the average diameter that the seed dimensions vary greatly.

The main parameters for designing the seed metering plate holes of the mechanical seed metering device are based on the average seed diameter increasing from 4.76 mm to 7.99 mm, with a variation of 3.23 mm. Therefore, the measured range of 100-grain weight is different, and the average diameter of each variety of seeds is calculated from the average length, width and thickness. The triaxial dimensions obey the normal distribution. Therefore, the external dimensions of adzuki bean varieties planted in the same area vary significantly, which puts forward necessary design requirements for the adaptability of the mechanical seed metering device to sowing varieties.

The seed metering plate with different hole sizes in the corresponding range can be accurately selected according to the 100-grain weight value in seed cleaning and replacement. As can be seen from Figure 6, there is a stable linear correlation between the 100-grain weight and the average diameter of adzuki bean seeds. Therefore, a linear equation was fitted between the 100-grain weight and the average diameter of 10 varieties of adzuki beans. The 100-grain weight of each variety of adzuki beans was set as the independent variable X, and the average diameter of each variety of seeds was set as the dependent variable Y.

Based on the principle of linear regression equation construction *(Yu et al., 2024)*, the linear fitting equation was obtained as y=0.1138x+4.1607, and the Pearson coefficient R^2 was 0.9728. Therefore, when selecting the seeding plate, the 100-grain weight value x can be directly input to obtain the corresponding average diameter y, to select an appropriate seeding plate.

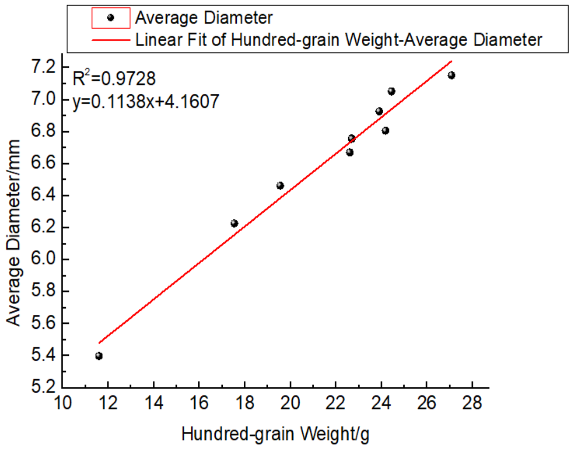


Fig. 6 - Linear fitting diagram of 100-grain weight-average diameter

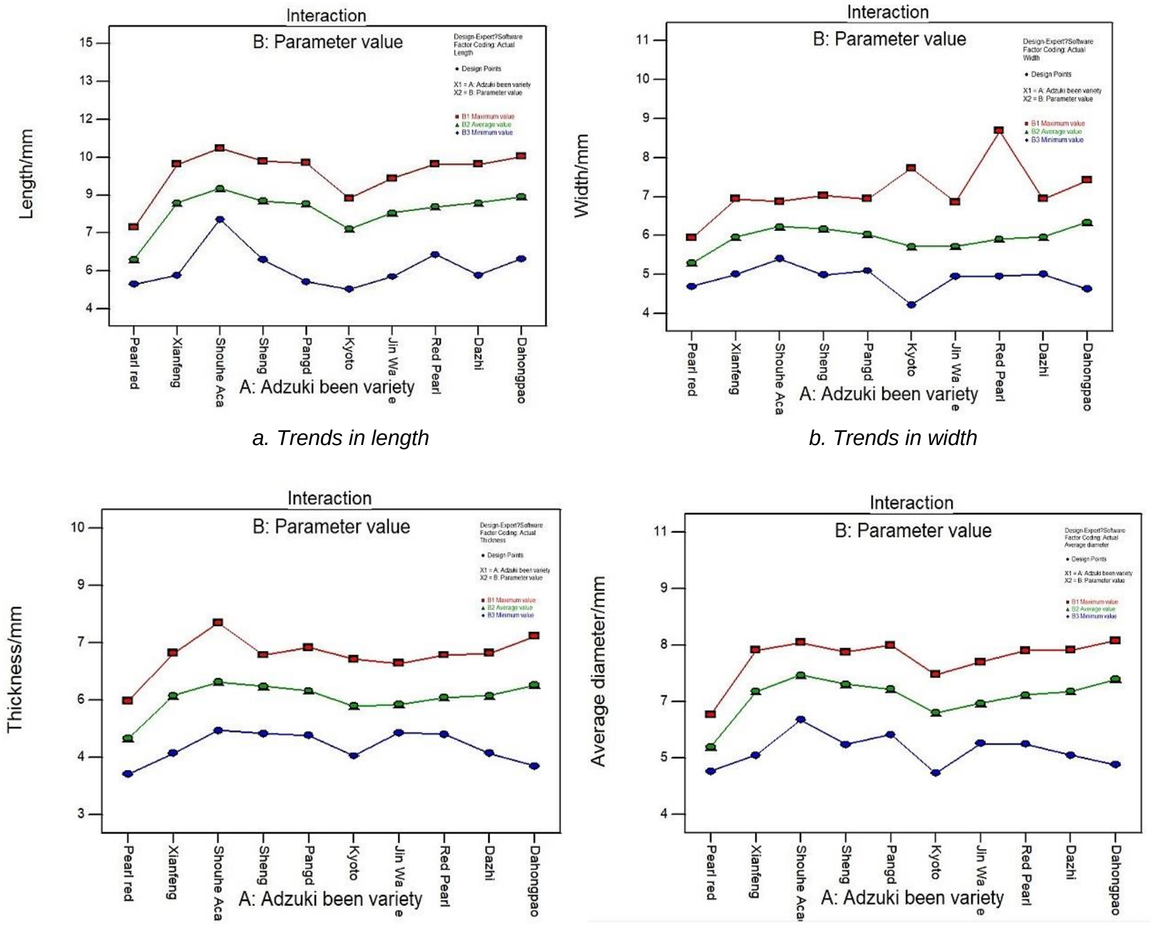
Therefore, it will be very useful to study the overall statistical results of different seed physical parameters in the same region for the design of seed metering plate holes. Table 3 shows the results of the single-factor test ANOVA for physical parameters of different seed sphericity variation ranges.

Table 3

Packett-Burman test protocol and results

Shape parameters	Source of variance	mean square	F value	P value	Significance
Length / mm	Model	8.74	44.38	< 0.0001	**
	Adzuki bean variety	1.99	10.09	< 0.0001	**
	Parameter value	39.13	198.71	< 0.0001	**
	Error	0.20			
Width / mm	Model	2.50	11.93	< 0.0001	**
	Adzuki bean variety	0.28	1.33	0.2908	**
	Parameter value	12.49	59.66	< 0.0001	**
	Error	0.21			
Thickness / mm	Model	2.66	43.95	< 0.0001	**
	Adzuki bean variety	0.42	7.02	0.0002	**
	Parameter value	12.70	210.09	< 0.0001	**
	Error	0.060			
Average diameter / mm	Model	2.82	44.39	< 0.0001	**
	Adzuki bean variety	0.59	9.31	< 0.0001	**
	Parameter value	12.83	202.23	< 0.0001	**
	Error	0.063			
Sphericity	Model	0.026	37.51	< 0.0001	**
	Adzuki bean variety	1.979E-003	2.84	0.0282	**
	Parameter value	0.13	193.51	< 0.0001	**
	Error	6.959E-004			
Length-width ratio	Model	0.22	22.26	< 0.0001	**
	Adzuki bean variety	0.018	1.79	0.1412	**
	Parameter value	1.15	114.42	< 0.0001	**
	Error	0.010			
Length-thickness ratio	Model	0.23	46.91	< 0.0001	**
	Adzuki bean variety	0.012	2.52	0.0456	**
	Parameter value	1.19	246.70	< 0.0001	**
	Error	4.832E-003			
Volume/mm^3	Model	10753.12	34.73	< 0.0001	**
	Adzuki bean variety	2114.72	6.83	0.0003	**
	Parameter value	49625.89	160.27	< 0.0001	**
	Error	309.65			
Density / g/cm^3	Model	0.55	12.61	< 0.0001	**
	Adzuki bean variety	0.028	0.65	0.7434	**
	Parameter value	2.90	66.42	< 0.0001	**
	Error	0.044			

It can be seen from Table 3 that changes in the experimental factors, such as adzuki bean varieties, did not affect width, length-to-width ratio, or density ($P=0.237>0.01$, $P=0.1412>0.01$, $P=0.7434>0.01$). However, they had some effect on seed sphericity and length-to-thickness ratio ($0.01<P=0.0282<0.05$, $0.01<P=0.0456<0.05$), and an extremely significant impact on other physical parameters ($P<0.01$). The test factors had significant effects on all test indexes. In order to analyze the variation trends among the physical parameters of different varieties of adzuki beans, design-expert 8.0 was used to draw the variation trend diagram of factor indicators. The variation trend of the triaxial size and average diameter is shown in Figure 7.



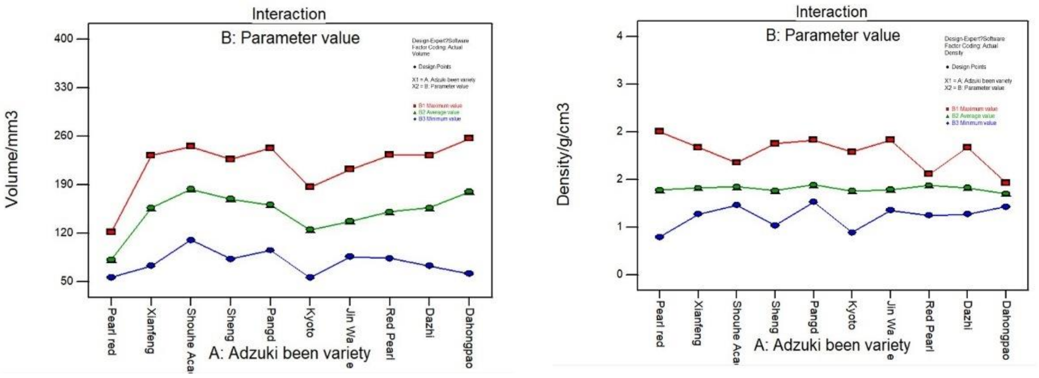
a. Trends in length *b. Trends in width*

c. Trends in thickness *d. Trends in mean diameters*

Fig. 7 - Variation trends diagram among different varieties

As can be seen from Figure 7, there are significant shape differences among different seeds. For each adzuki bean variety, the seed shape size parameter's mean value is basically equal to the mean value of the maximum and minimum values. However, there are some special cases, such as the average seed length of Shengyou, Pangda Agriculture, Kyoto and Jin wangjie tended to the maximum value. The average seed width of Kyoto, Red Pearl and Dazhi tended to the minimum value. The seed thickness of Xianfeng Extremely Early, Shouhe Acacia, Shengyou and Dahongpao tended to the maximum value, while the seed thickness of Jin Wangjie tended to the minimum value.

The main reason for this trend in triaxial size is that some parameters of the length, width and thickness of 100 seeds of each magenta adzuki bean seed obey asymmetric normal distribution. As shown in Figure 3, the length and thickness of Pearl Red seeds are asymmetrical. Seed width is a symmetrical normal distribution. The average diameter of seeds is the characteristic size of each seed population and the primary parameter of seed grain shape. It can be seen from Figure 7 that the overall change trend of the triaxial size of different seeds is basically the same, and the change trend of seed volume is also basically the same as that of the triaxial size, as shown in Figure 8.



a. Trends in volume *b. Trends in density*

Fig. 8 - Variation trends diagram among different varieties

As shown in Figure 8, the volume of the 10 varieties of adzuki beans varies greatly. Except for Jinwangjie and Dahongpao, the average values are closer to the minimum value, and the volume change trend is basically consistent with the trend of the triaxial size change, with the average volume of 150.38 mm^3 and the volume change range of 56.2 mm^3~256.53 mm^3. The coefficient of variation of the volume v of different varieties ranges from 0.052 to 0.216, the dispersion degree varies greatly, the greater the volume difference, the more comprehensive consideration is needed for the design of the seeding plate hole to determine the number of holes filled by the hole-direct seeding number of adzuki beans. The trend of adzuki bean seed density is entirely opposite to seed volume. The maximum and minimum density values are significantly different among different varieties, but the average value of seed density is very small, ranging from 1.364 g/cm^3 to 1.514 g/cm^3. Therefore, the influence of seed density on the seeding plate hole still needs to be considered in many aspects.

The variance analysis of the test results in Table 3 shows that the difference in sphericity among different varieties varies little, and its changing trend is shown in Figure 9.

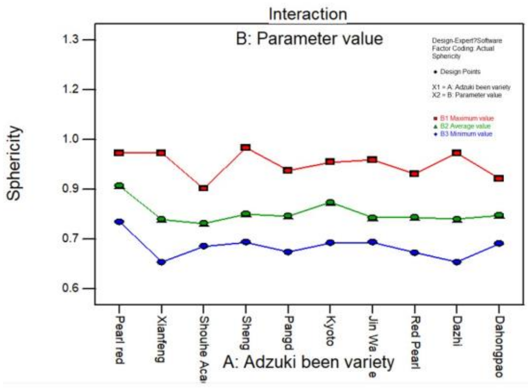
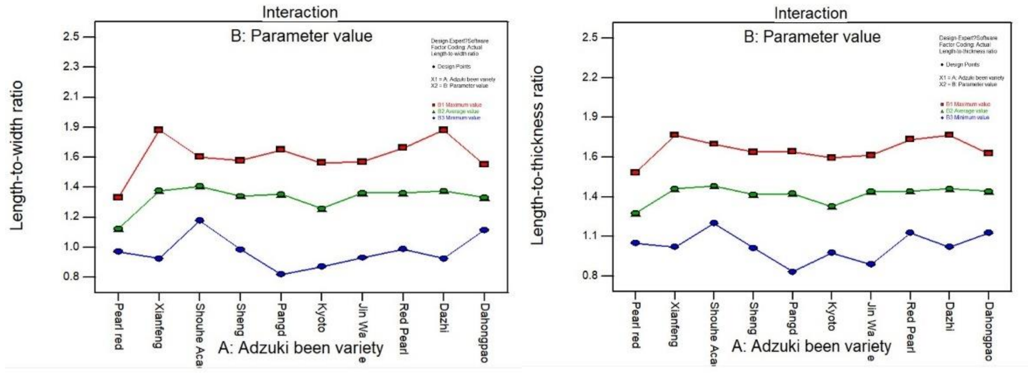


Fig. 9 - Sphericity variation trends among different varieties

It can be seen from Table 3 in Figure 9 that the average sphericity of 1000 seeds of 10 adzuki bean varieties is 0.81, and the sphericity range is 0.68~1.00. A small part of the seeds have a sphericity close to 1.00, which is a pure sphere, but most of them are non-equilinear ellipsoids and the maximum value of sphericity S_p is 1, with no significant change. The maximum and minimum values of sphericity S_p change gradually and obviously. The average value tends to the minimum direction. The variation coefficient of sphericity S_p for different varieties ranged from 0.046 to 0.065, and the dispersion degree changed little. The larger the sphericity, the more obvious the rolling effect of the seeds on the seed metering plate in the seed box, which is more conducive to filling the seed holes.

On the contrary, the smaller the sphericity, the lower the relative motion between seed particles, which is not conducive to filling the holes. For seeds filled into the hole, the smaller the sphericity, the better the seed storage and carrying effect of the hole. Therefore, the size of the seed sphericity requires some comprehensive and dialectical consideration for the design of the seed metering device. The stable state of the seed filling in the hole is the lowest center of gravity of the seed; that is, the smallest of the three axes is vertical, and the other two axes provide a reference for the diameter design of the hole to calculate the length-to-width ratio and length-to-thickness ratio of the seed, as shown in Figure 10.



a. Trends in length-to-width ratio *b. Trends in length-to-thickness ratio*

Fig. 10 - Variation trends diagram among different varieties

As shown in Figure 10, the average length-to-width ratio of the seeds of the 10 adzuki bean varieties is 1.36, the average length-to-thickness ratio is 1.38, the length-to-width ratio ranges from 0.82 to 2.21, and the length-to-thickness ratio ranges from 0.83 to 2.08. All unequal-diameter ellipsoid seeds appear in any shape, that is, the size of any axes of three axes has a maximum or minimum value, but each variety has its characteristics. For the length-to-width ratio of seeds, the overall average value is 1.36, and the length and width are basically equal. The minimum length-to-width ratio of Pearl Red, Xianfeng Extremely Early, Pangda Agriculture, Kyoto, Jinwangjie, and Dazhi Adzuki Bean is less than 1. The minimum values of the other varieties of adzuki beans are more significant than 1, but the maximum length-to-width ratio of all varieties of adzuki beans is greater than 1; For the length-to-thickness ratio of seeds, the average and maximum values are greater than 1 as a whole, and the minimum length-to-thickness ratio is less than 1 in some cases, such as Pangda Agriculture, Kyoto, and Jinwangjie Adzuki Bean, that is, the thickness of a small part of the seeds is greater than the length. In contrast, the length of all seeds of other varieties is greater than the thickness.

As shown in Figure 4, there is a stable linear correlation between the length, width and thickness of adzuki bean seeds. However, the Pearson coefficient R^2 of the fitted linear curve between different varieties' length, width and thickness are different. The fitting correlation coefficient R^2 of width-thickness of each variety is generally more significant than the fitting correlation coefficient of length-width and length-thickness. Most of the R^2 values of length-width are more significant than the R^2 values of length-thickness, and a small part is less than the R^2 value of length-thickness, such as Xianfeng Extremely Early, Kyoto, Red Pearl, and Dazhi Adzuki Bean. Therefore, the primary dimensions of the tri-axial dimensions calculated by different varieties are also different, directly affecting the model establishment of discrete element simulation seeds of the seed metering device. For this reason, the linear equations between the length, width and thickness of 10 kinds of adzuki beans are fitted, and the correlation coefficient R^2 is extracted as shown in Table 4. Except for Xianfeng Extremely Early, Kyoto, Red Pearl, and Dazhi Adzuki Bean, the main dimensions of other varieties are width. Seed modeling can be calculated according to the functional relationship with the actual main dimensions of adzuki beans, so that the size distribution of the simulated adzuki bean population is closer to the actual situation.

Table 4

Correlation coefficient R^2 of the linear equation of adzuki bean seeds

Correlation coefficient R^2 of linear equation				
Adzuki bean variety	**Length-Width**	**Width-Thickness**	**Length-Thickness**	**Main dimension**
Pearl Red	0.1957	0. 6424	0. 1567	Width
Xianfeng	0.2247	0.7200	0.2390	Thickness
Shouhe Acacia	0.1704	0.4571	0.1453	Width
Shengyou	0.1663	0.6262	0.1567	Width
Pangda Agricultural	0.2673	0.6363	0.2497	Width
Kyoto	0.1503	0.4986	0.2175	Thickness
Jin wangjie	0.2583	0.6557	0.2413	Width
Red Pearl	0.2178	0.4040	0.2784	Thickness
Dazhi	0.2356	0.7149	0.2395	Thickness
Dahongpao	0.5258	0.6979	0.3958	Width

CONCLUSIONS

(1) The physical characteristic parameters of seeds of 10 adzuki bean varieties were selected for statistical analysis. Length, width, thickness, average diameter, sphericity, length-to-width ratio, length-to-thickness ratio, volume, density, and 100-grain weight were statistically analyzed, and the maximum, minimum, mean, standard deviation and coefficient of variation of each parameter were obtained.

(2) The results of the analysis of the appearance parameters of Pearl Red Adzuki Beans showed that the triaxial dimensions of the seeds, length, width, thickness and average diameter all approximately obeyed a normal distribution. Subsequently, the statistical analysis of the seeds of multi-varieties adzuki beans, and the statistical test analysis results of different seed parameters showed that the average length and width of adzuki bean seeds of 10 varieties were basically the same and significantly greater than the average seed thickness, the analysis determined the discrete distribution of each physical parameter. Changes in adzuki bean varieties did not affect the width, the length-to-width ratio, or density. However, they had a significant impact on sphericity and the length-thickness ratio and had a very significant impact on other physical parameters. The overall change trend of the three-axis size was basically consistent with the 100-grain weight. For linear fitting of the 100-grain weight-average diameter, the equation and the Pearson correlation coefficient R^2 were obtained. The appropriate one can be directly selected according to the formula on the seeding plate. The volume change trend of seeds was basically consistent with the three-axis size, but the trend of both and density was basically consistent for the most part. There were also very few exceptions and a small part was completely opposite; this requires a specific design for the adzuki bean mechanical seed metering device to achieve the seed filling target of adzuki beans with different sizes. During the seed cleaning process, different hole sizes in the corresponding range can be selected based on the measured 100-grain weight value of the seeding plate.

(3) The average seed sphericity S_p was 0.89, and the average length-width and the length-thickness ratios of the seeds were 1.15 and 1.25, respectively. The length and width were basically the same, but both were significantly larger than the seed thickness t. The seed shape was an approximately ellipsoid of unequal diameters. The three-axis dimensions of the seed grains showed a linear positive correlation function relationship. The linear correlation of length-width was significantly greater than the linear correlation between length-thickness. However, the linear fitting correlation coefficients R^2 of length-width and length-thickness were relatively close. So, in practical applications, the primary size can be calculated based on the functional relationship of the actual size of adzuki beans so that the size distribution of the simulated adzuki bean population is closer to the actual situation.

REFERENCES

[1] Bai Z., Meng H., Peng H., Qi J., Li Y. & Kan Z. (2025). Parameter calibration for discrete element simulation of Cistanche seeds (肉苁蓉种子离散元仿真参数标定). *Journal of Agricultural Mechanization Research* (02), 19-26+53.

[2] Chen X., Wang X., Bai J., Fang W., Hong T., Zang N., Hong T. & Wang G. (2024). Virtual parameter c alibration of pod pepper seeds based on discrete element simulation. *Heliyon* (11), 2405-8440.

[3] Chen Y., Yang W., Tian J., Liao J., Zhao J. & Sun D. (2024). Simulation experimental study of green manure mixed seeder rower in Xinjiang orchard (新疆果园绿肥混合播种机排种器仿真试验研究). *Journal of Agricultural Mechanization Research* (09),157-165.

[4] Dnu G., Mao N., Liu W., Wu X., Zhou C. & JI W. (2022). Design and experiment of four-bar translational seed metering device for soybean plot breeding (四杆平移式大豆小区育种排种器设计与试验). *Transactions of the Chinese Society for Agricultural Machinery* (04), 70-78.

[5] Dun G., Wu X., Ji X., Zhang F., Ji W. & Yang Y. (2024). Simulation and optimization of soybean plot metering device with double swing plate (双摆盘式大豆小区排种器的仿真优化). *Journal of Agricultural Science and Technology* (06), 82-90.

[6] Dun G., Liu W., Mao N., Wu X., Ji W. & Ma Y. (2023). Optimization design and experiment of alternate post changing seed metering device for soybean plot breeding (交替换岗式大豆小区育种排种器优化设计与试验). *Journal of Jilin University (Engineering and Technology Edition)* (01), 285-296.

[7] Karaiev, O., Bondarenko, L., Halko, S., Miroshnyk, O., Vershkov, O., Karaieva, T., Shchur, T., Findura, P. & Prístavka, M. (2021). Mathematical Modelling of the Fruit-Stone Culture Seeds Calibration Proces s Using Flat Sieves. *Acta Technologica Agriculturae.* (3),119-123.

[8] Lan T. (2022). *Design and experimental study on horizontal disc seed metering device of Cyperus esculentus (水平圆盘式油莎豆排种器的设计及试验研究).* [Master's Thesis], Jilin Agricultural University.

[9] Li Q. (2023). *Mechanism analysis and experimental study on scoop type precision seed metering device for small size vegetable seeds (舀勺式小粒径蔬菜种子精量排种器机理分析与试验研究)*. [Doctor's Thesis], Northeast Agricultural University.

[10] Li X., Liu Y. & Gong Y. (2023). Study on the technology of red bean and coix seed cake (红豆薏米蛋糕的工艺研究). *Farm Products Processing*, (22), 53-56.

[11] Liu Z. (2024). High-yield and high-quality cultivation technology of adzuki beans in Muling (黑龙江穆棱红小豆高产优质栽培技术). *Special Economic Animals and Plants* (04), 96-98.

[12] Ma W., Zhang S., Yin X. (2023). A Calibration of the Contact Parameters of a Sesbania Seed Discrete Element Model Based on RSM. *Processes*, (12).

[13] Shang S., Wu X., Yang R., Li G., Yang X. & Chen D. (2021). Research status and prospect of plot-sowing equipment and technology (小区育种播种装备与技术研究现状与展望). *Transactions of the Chinese Society for Agricultural Machinery.* (02), 1-20.

[14] Wang Y., Lv F., Xu T. & Yu J. (2018). Shape and size analysis of soybean kernel and modeling (大豆籽粒形状和尺寸分析及其建模). *Journal of Jilin University (Engineering and Technology Ed.)* (02), 507-517.

[15] Xu B., Zhang Y., Cui Q. (2021). Construction of a discrete element model of buckwheat seeds and calibration of parameters. *INMATEH-Agricultural Engineering.* Vol. 64 (02), 175-184.

[16] Xu T., Fu H., Liu M., Feng W., Zhang R., Wang Y. & Wang J. (2023). Ellipsoidal seed modeling and si mulation parameter selection based on the discrete element method. *Materials Today Communication s*, 37, 2352-4928.

[17] Yan J., Wei S., Zhang W. & Zhang F. (2023). Calibration of discrete element contact parameters for white radish seed particles (白萝卜种子颗粒接触参数标定). *Journal of Chinese Agricultural Mechanization.* (02), 1-11.

[18] Yang Q. (1993). Significance test of the difference of coefficient of variation of two populations (两总体变异系数差异的显著性检验). *China Cattle Science* (01), 285-296.

[19] Yu S., Feng G., Su X., Zhang X., Zuo S. & Zhang X. (2024). Multiple analysis of the relationship between agronomic traits and yield formation in 17 varieties/lines of lolium multiflorum (17 份多花黑麦草品种（系）农艺性状与产量形成关系的多重分析). *Acta Agrestia Sinica.* (09), 2862-2874.

[20] Yu Y., Wang Y., Zhou J. & Pan Y. (2024). Design and test of combined directional seed metering device for pumpkin seed (南瓜种子组合式定向排种器设计与试验). *Transactions of the Chinese Society for Agricultural Machinery,* 1-13.

[21] Zhang S., Zhang R., Chen T., Fu J. & Yuan H. (2022). Calibration of simulation parameters of and mung bean seeds using discrete element method and verification of seed-metering test (绿豆种子离散元仿真参数标定与排种试验). *Transactions of the Chinese Society for Agricultural Machinery* (03), 71-79.

[22] Zhang W., Wang F. (2022). Calibration of American ginseng seeds for discrete element simulation. *International Journal of Agricultural and Biological Engineering*, (06), 16-22.

[23] Zheng X., He X., Shang S., Wang D., Li C., Shi Y., Zhao Z. & Lu Y. (2024). Calibration and experiments for discrete element simulation parameters of Cyperus esculentus seeds (油莎豆种子籽粒离散元仿真参数标定与试验). *Journal of Agricultural Mechanization Research* (02), 172-178.