Development of the magnetic separation device for surface cracks of delinted cottonseed

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Abstract: In seed processing for commercial production, the collision or friction between mechanical parts and seed is inevitable. These collisions or friction can cause cracks on the surface of the seed, which can affect germination rates and ultimately reduce crop yields. Using the difference of the seed motion trajectories with different crack degrees in the magnetic field, the grading of the surface crack seed can be realized. In this study, the motion law of seed in a non-uniform magnetic field was analyzed by taking the delinted cottonseed as an object. A magnetic separation device for crop seeds was developed. This device was essentially composed of the feed throat, magnetic roller, conveyor belt, and variable-frequency adjustable-speed motor. The magnetic powder adhering seeds enter the magnetic separation device through the feed throat and are conveyed to the magnetic roller through the conveyor belt. The magnetic roller has different adsorption forces on seeds with different degrees of cracking, and seeds fall into different outlets, thus completing the grading of the seeds. By adjusting working parameters such as the magnetic field strength and the speed of the conveyor belt, magnetic separation could be made. In order to verify the grading effect, the magnetic separation accuracy was taken as the inspection index, the magnetic powder's mesh number, the mass mixing ratio between magnetic powder and delinted cottonseed, and the rotation speed of the magnetic roller were taken as the inspection factors. The response surface methodology was used to optimize the working parameters of the experimental device. The results showed that the optimal process parameters of the magnetic separation device were as follows: the number of magnetic powder meshes was 250, the mass mixing ratio between magnetic powder and delinted cottonseed was 1:20, and when the rotational speed of the magnetic separation roller was 20 r/min, the detection rate reached 92.5%. The designed magnetic separation device can realize the non-destructive batch detection of seed surface cracks with high work efficiency and has guiding significance for the high-precision and low-damage classification detection and classification of commercial seed.

Keywords: magnetic separation, delinted cottonseed, surface crack, response surface design
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1 Introduction

China is an agricultural country. Cotton is the largest cash crop among China's agricultural products, and its production, circulation, and consumption are closely related to the national economy and social development[1,2]. Cottonseed is the foundation of the whole cotton industry, which directly affects cotton yield and quality. Therefore, using modern production methods to grade cottonseed with high efficiency and low damage is of great significance in enhancing the competitiveness of the Chinese cotton industry in the global market[3,4]. At present, from being harvested to processing into products for sale, cottonseed needs to go through processes such as pluck, cleaning, embossing, depilation, coating pellet, and other processes. During these processes, various production machinery will repeatedly squeeze and rub cottonseed, which will cause severe cracks on the cottonseed's surface[5]. These cracks are vulnerable to pests or molds, which reduce the germination rate of seed and cotton yield. Therefore, it is necessary to detect external cracks on the surface of cottonseeds after they are delinted and before coating and to grade the seeds according to the degree of cracks. Traditional seed grading mainly utilizes the differences in specific gravity, size, or shape of seeds of different grades and adopts airflow, buoyancy, or weighing methods to achieve this[6-8]. However, these grading techniques mainly remove debris or broken grain from the seed. For delinted cottonseed with surface cracks, the differences between their geometrical, physical parameters, and elite varieties are so subtle that these methods cannot distinguish them. The principal method for detecting exterior crack seed is manual classification, which has high labor intensity and low production efficiency. Therefore, it is vital to study and develop an efficient and low-damage method for exterior surface crack detection and grading[9].

Currently, much research has been carried out on the surface crack grading of delinted cottonseed based on machine vision technology. Machine vision uses computers, cameras, and digital

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processing to analyze and determine the condition of the surface of delinted cottonseeds[10,11]. Huang et al.[12] and Zhang et al.[13] used a fusion method of hyperspectral image and image feature information to discriminate the varieties of cotton and wheat seeds. The results showed that the spectral and image information of the fusion hyperspectral image could effectively improve the classification and detection accuracy of those varieties seed in a few spectral bands. Liu et al.[14] studied hybrid rice strain type identification using near-infrared hyperspectral imaging, chemometric methods, and image processing techniques. The results show that near-infrared hyperspectral imaging technology could realize line identification and visual prediction of hybrid rice. Wang et al.[15] have used digital image processing technology to analyze the image of the Jatropha seed. The arithmetic operation fusion of the color components was carried out for its features. According to the adaptive threshold selection of the OTSU method, the image was processed into a binary image, and the edge extraction of the image was realized by using the Laplacian of Gaussian (LOG) operator and the partial morphological feature parameter value of Jatropha seeds was obtained. Lu et al.[16] proposed a machine vision-based method for line detection of buckwheat grains and impurities. Firstly, the buckwheat image is processed by edge adaptive interpolation algorithm. The seed labeling after adhesion segmentation is performed using the watershed algorithm, and finally the buckwheat grains are processed and identified by neural network online testing. By the work above, the base, therefore, could be set up in seed crack identification technology. However, machine vision technology was to identify and analyze seeds in sequence, resulting in a large amount of data, and processing and analysis take a long time. These could affect detection speed, so machine vision was still difficult to detect the larger quantity of seed.

Currently, magnetic grading is mainly applied to ore element classification[17-19], where ore grading is accomplished according to magnetic content of the particle powder in the ore. Moreover, the ore powder magnetic separator is divided into wet and dry separators[20-22]. Among them, the dry magnetic separator mainly relies on the ore particles' gravity and magnetic force size offset for grading. The wet magnetic separator is to mix the liquid with the ore particles, and grading is done by adsorbing the flowing ore particles. Kozlova et al.[23] proposed an aeromagnetic separation method for forestry seed grading by observing the trajectory of seeds coated with magnetic powder in an airfield. The above study provided some inspiration for the magnetic grading of seeds. However, there are fewer relevant studies on the magnetic grading of seeds, and the process and principles deserve further discussion. This paper proposed a new magnetic separation grading method, which utilizes the magnetic difference between superior and exterior crack seeds to classify cracks in large quantities of delinted cottonseed by setting a magnetic field. This method's advantage is that there is no need to inspect the seeds one by one, and no data was generated during the grading process, so it can greatly improve grading efficiency and will not cause damage to seeds. The research results of this paper have certain reference significance for the commercial production of high-quality seeds.

2 Materials and methods

2.1 Theoretical model of cottonseed magnetic separation

The theoretical basis of magnetic separation represents the difference in magnetic properties caused by different internal components of the graded particles. The more significant the difference in magnetic force between these particles, the more significant the difference in the magnetic force they experience in the magnetic field. Therefore, the more significant the difference in the motion trajectories between particles, the better the separation effect. If different magnetic particles are to be graded, it must be conducted in a non-uniform magnetic field[24-26].

Methods for delinted cottonseed magnetic separation grading were shown in Figure 1.

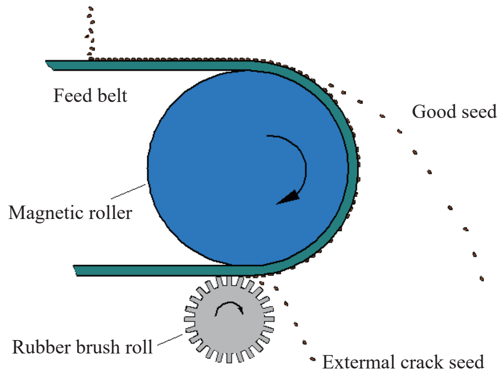


Figure 1 Schematic diagram of magnetic separation of surface cracks in delinted cottonseed

In order to achieve the separation of superior and exterior crack cottonseeds, a series of pre-tests were conducted. It was found that under the condition of no addition of magnetic powder, only exterior crack seeds with a significant difference in quality could be screened out. In contrast, the grading effect between superior and exterior crack cottonseeds was not noticeable. After adding the magnetic powder and then conducting the test, a noticeable grading effect appeared between the two kinds of cottonseeds, which shows that the magnetic powder has a more significant influence on the trajectory of superior seeds and exterior crack cottonseeds in the magnetic field. The principle is as follows:

1) Increase the magnetic difference between the superior and exterior crack seeds. Since cottonseeds don't contain a magnetically conductive component and do not generate a magnetic field, the magnetic difference between the superior seed and the exterior crack seed is minimal. This difference is not sufficient to achieve seed grading. Therefore, it is necessary to use special methods to increase the magnetic difference between these seeds. One approach that can be taken is to add the magnetic powder to the surface of the seeds. Because the adsorption capacity of the seed's surface of the magnetic powder is relatively weak, and the cracked part of the seed's epidermis can accommodate more magnetic powders, the magnetic properties of the seed with exterior cracks will be higher than that of the superior seed.

2) Let the seed-adsorbed magnetic powder move in a magnetic field. Under the attraction of the magnetic force in the non-uniform magnetic field, the seed will move to the place with high magnetic field intensity and finally be attracted by the magnetic pole due to the different amounts of magnetic powder adsorbed by the superior seed and the exterior crack seed in a non-uniform magnetic field. These seeds are subjected to different magnetic forces in the non-uniform magnetic field and move along different trajectories to realize the separation between the superior seed and the exterior crack seed separation.

2.2 Force analysis of cottonseed magnetic separation

2.2.1 Magnetic field spatial characteristics

In an open magnetic system, the variation of magnetic induction intensity of each coordinate point in space along the magnetic pole or pole clearance's symmetry plane conforms to the exponential form[27,28], which can be expressed as:

$$H_x = H_0 e^{-cx} \tag{1}$$

where, x is the distance from the coordinate point to the center of the magnetic pole, m; H_x is the magnetic induction intensity at a distance of x from magnetic pole face, A/m; H_0 is the magnetic intensity on magnetic pole face, A/m, in other words, H_0 is the magnetic induction intensity at x=0; e is the base of natural logarithms; c is the inhomogeneous coefficient of a magnetic field.

The magnetic field gradient can be obtained by derivative of Equation (1), as shown in Equation (2):

$$\mathrm{grad}(H) = \frac{\mathrm{d}H_x}{\mathrm{d}x} = H_0 \frac{\mathrm{d}e^{-cx}}{\mathrm{d}x} = -cH_x \tag{2}$$

The H×grad(H) is magnetic field force, which can be calculated as:

$$H \times \mathrm{grad}(H) = -cH_0^2 e^{-2cx} \tag{3}$$

Therefore, the following conclusions can be obtained from Equation (3):

1) If x=0, then H_x=H_0, H×grad(H)=cH_0^2. This suggests that the magnetic field force on the magnetic surface reaches the maximum

2) If the inhomogeneous coefficient of magnetic field c=0, then the magnetic field force H×grad(H)=0. This explains why the magnetic separation of seed must be conducted in an inhomogeneous magnetic field.

2.2.2 Magnetic field force and intensity

In a magnetic field, the magnetic field force of a grain of delinted cottonseed on a magnetic roller can be written as:

$$F_m = \mu_0 \chi_0 m H \times \mathrm{grad}(H) \tag{4}$$

where, μ_0 is space permeability, and its value is 4π×10^{-7} H/Am; χ_0 is specific susceptibility of seed, m^3/kg; H is magnetic intensity, A/m; the grad(H) is magnetic field gradient; H×grad(H) is magnetic field force, N; m is delinted cottonseed mass after magnetic particle attachment, kg.

2.2.3 Intensity of magnetic separation

Because the specific susceptibility will be affected by the change in the applied magnetic field, the specific susceptibility values of the delinted cottonseed are different under different magnetic intensities. The experimental method of specific susceptibility can be used Gouy-magnetic-balance method[29,30]. The principle of the Gouy-magnetic-balance method is: if an extended sample with an equal cross-sectional area is hung at one end of the balance. Furthermore, the bottom of the sample is in the region with the most vigorous magnetic intensity (expressed in H_1), then the sample tube is in a non-uniform magnetic field. The magnetic field force can be calculated by Equation (5):

$$F_m = \frac{1}{2}\chi_0 A\left(H_1^2 - H_0^2\right) = (\Delta W - \Delta W')g \tag{5}$$

where, A is the cross-sectional area of the sample, m^2; H_1 is the magnetic intensity at the center of the magnetic pole, A/m; H_0 is magnetic intensity at the top of the sample, A/m; ΔW is the weighing difference of sample and fixture between the magnetic field and non-magnetic field, m; ΔW' is weighing difference of fixture between the magnetic field and non-magnetic field, m; g is the acceleration of gravity, m/s^2.

Therefore, the magnetic field force of the sample can be calculated by the result of weighing the sample twice when there is a magnetic field and a non-magnetic field. $A(H_1^2$-$H_0^2)$ can be directly measured using a Gaussmeter. Then the specific susceptibility is obtained according to Equation (5). Previous tests concluded that the specific susceptibility after mixed magnetic powder of delinted cottonseed should be (1.189-3.360)×10^{-5} cm^3/g.

Suppose the magnetic field force Fm can absorb the delinted cottonseed. In that case, it is necessary to ensure that the magnetic field force of the delinted cottonseed exceeds its gravity, that is, F_m≥G. G is the gravity on the cottonseed, N. In practice, the number of samples delinted cottonseed is huge. Each cottonseed is not equal to the magnetic absorption force, so the magnetic absorption force takes the most stressed cottonseed. The magnetic suction force should take the cottonseed with the highest stress, so the load coefficient K=1.3 is introduced, and F_m≥1.3G is obtained[31,32]. After several experiments and weighing, the maximum mass of the magnetic powder-coated cottonseed is 0.097 g, and the preliminary calculation showed that F_m≥0.001 24 N.

Let F_m=0.001 24 N, m=0.097 g, vacuum permeability μ_0=4π×10^{-7} H/Am, and delinted cottonseed specific susceptibility χ_0=1.189×10^{-5} cm^3/g be substituted into Equation (4). Then it can be obtained H×grad(H)=0.855×10^6 N.

2.3 Motion analysis of seed magnetic separation

In general, delinted cottonseed, waiting to be graded, is dropped above the magnetic roller. From the contact of cottonseed and magnetic roller to the completion of grading, the application of cottonseed can be divided into three stages: transition, detachment, and separation. A detailed analysis of these three stages is shown below.

2.3.1 Transitional stage of cottonseed grading

The transition stage refers to the beginning of the delinted cottonseed falling on the magnetic separation roller until it is adsorbed on the surface of the roller relatively static. When the delinted cottonseed is in contact with the surface of the magnetic separator roller, the cottonseed might be impacted by the surface of the roller and bounce. Therefore, it is generally used to coat the surface of the magnetic roller with flexible material to alleviate this problem. The magnetic roller speed and the magnetic strength of the magnetic roller also affect the adsorption process of the seeds by the magnetic roller during the transitional stage. The magnetic roller speed varies the impact of the cottonseeds when they fall, and the time they enter the stable state changes. The magnetic roller's strength will increase the cottonseeds' adsorption capacity so that the seeds can enter a stable state quickly. Therefore, the above factors need to be considered in the design process on the impact of grading.

2.3.2 Detachment stage of cottonseed grading

When the delinted cottonseed is in the highest position of the roller, the direction of gravity and magnetic action are the same. At this moment, cottonseed of different magnetism does not produce differential motion. Thus, this position is a critical point in the cottonseed grading process. When the delinted cottonseed begins to move downward through the highest point, the angle between gravity and magnetic force gradually increases, and the cottonseed enters the stable stage.

Force analysis of cottonseed at this stage is shown in Figure 2. The cottonseed is subjected to a total of five forces: gravity (G), the magnetic field force (F_m), the supporting force (N), the frictional force of the magnetic separation roller to cottonseed (F_f), the centrifugal force (F_1).

$$F_1 = m\omega^2(r + r') \approx m\omega^2 r \tag{6}$$

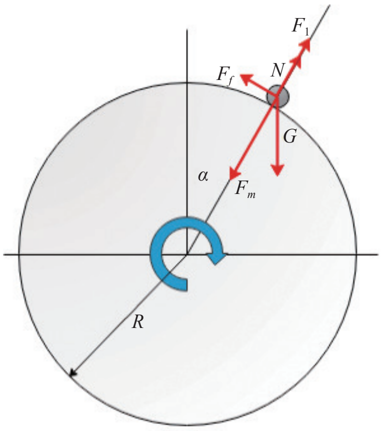


Figure 2 Delinted cottonseed stress diagrams stable stages

where, ω is the angular velocity of the magnetic separation roller, rad/s; r is the curvature radius magnetic separation roller, m; r' is the curvature radius of the cottonseed, m. Because $r' \ll r$, so $(r+r')\approx r$.

In the stable stage, the delinted cottonseed is adsorbed on the magnetic separation roller and the relative velocity with the roller is zero. According to the basic principles of mechanics, the delinted cottonseed should then satisfy the Equations (7) and (8):

$$F_m + mg\cos\alpha - N - mr\omega^2 = 0 \tag{7}$$

$$mg\sin\alpha - fN = 0 \tag{8}$$

where, α is the angle between the diameter of the cottonseed position and the vertical axis, (°).

From Equation (7) and Equation (8), the initial angle of the slide α_0 can be calculated from:

$$\alpha_0 = \alpha_2 + \arcsin\left[\left(F_m/mg - r\omega^2/g\right)\sin\alpha_x\right] \tag{9}$$

where, α_s is minus the maximum static friction angle.

$$\alpha_s = \mathrm{arctg} f$$

where, f is cottonseed's static friction coefficient, f=0.47[33].

As the rolls rotate, the gravitational component force along the tangential direction of the roll increases, and the frictional force of the cottonseeds increases to maintain equilibrium. When the component force of gravity exceeds the friction force of the cottonseed, it enters the stage of sliding off. The friction force of the cottonseed is mainly related to the friction coefficient, magnetic field force, centrifugal force, and other factors of the cottonseed.

During the movement of the cottonseed with the roller, the supporting force N is smaller and smaller. When N=0, the cottonseed would fall off the roller, and the initial sliding angle obtained would become the escape angle.

Equation (9) shows that when the magnetic separator is determined, the main factors affecting cottonseed detachment are magnetic field force, cottonseed mass, and roller speed.

2.3.3 Separation stage of cottonseed grading

When delinted cottonseed is off the surface of the roller, the supporting force N=0. When the delinted cottonseed out of the roller moment, the relationship between F_f and G can be obtained from:

$$F_f \le G\sin\alpha$$

or

$$(F_m G\cos\alpha - mr\omega^2)\tan\varphi \le G\sin\alpha$$

Therefore, the following equation can be obtained:

$$F_m \le mr\omega^2 + G\sin(\alpha-\varphi)/\sin\varphi \tag{10}$$

where, φ is the static friction angle between the delinted cottonseed and the roller surface, (°).

When dF_m/dα=0, the magnetic field force F_m reaches its maximum value. Derivation of α in Equation (10), it can be obtained:

$$\mathrm{d}F_m/\mathrm{d}\alpha = G\cos(\alpha-\varphi)/\sin\varphi$$

Let dα/dβ be equal to 0°, because G/sinα squared does not equal 0. That is, cos(α–β) = 0 means α–β=0°. So, when α=90°+φ, the delinted cottonseed by the most significant magnetic field force F, for the magnetic roller cover had a rough belt, generally taken 30°. The value can be calculated by Equation (11).

$$F_m = mr\omega^2 + G/\sin\varphi = mr\omega^2 + 2G \tag{11}$$

That is, when the position angle of the cottonseed is 120°, the magnetic field force is the maximum.

2.4 Experimental device

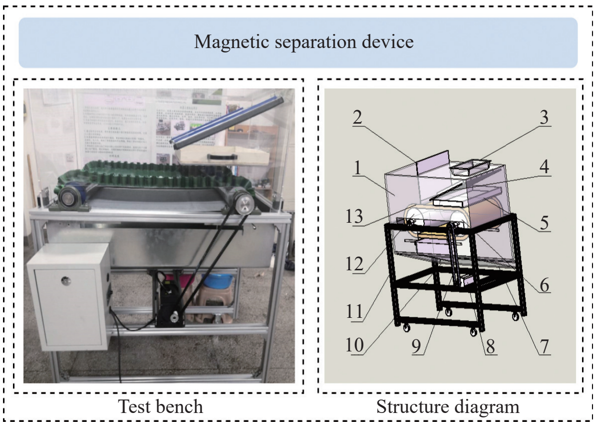
The magnetic separation experimental apparatus was carried out indoors in the laboratory. The main test instruments were:

1) The cottonseeds after being delinted, the variety of cottonseed is GK-10, which is delinted by mechanical method. Mechanical lint removal uses the pulling force of the machine to strip the short lint from the cottonseeds, such as a brush wheel-type lint removal machine, and the magnetic powder can adhere to the cottonseeds better after lint removal.

2) A JJ1000 electronic balance. Its rate capacity was 0.01-1000 g, and its measurement accuracy was 0.01 g.

3) The magnetic separation device was independently developed by Henan University of Science and Technology.

In order to verify the theoretical model, a magnetic separation experimental device was built. Its structure is shown in Figure 3. The experimental device included a feed throat, mesh, solid magnetic roller, a roller, the superior seed outlet, the exterior crack seed outlet, and variable frequency speed motor, etc. The shell of the experimental device was made of transparent plexiglass so that the magnetic separation process could be observed. A mesh was arranged below the feed throat, which was used to reduce the impact force of the seed falling on the conveyor belt and make the seed evenly distributed on the conveyor belt. The experimental platform consists of a solid magnetic drum and a magnetic field



1. Shell 2. Baffle 3. Feed throat 4. Mesh 5. Magnetic powder collection box 6. Roller 7. Exterior crack seed outlet 8. Variable-frequency adjustable-speed motor 9. Belt 10. Superior seed outlet 11. Wheeled support 12. Strong magnetic roller 13. Conveyor belt

Figure 3 Magnetic separation device

without a magnetic field drum connected by a conveyor belt. A variable frequency motor controlled the roller speed. The conveyor belt was made of rubber to reduce damage when the seed fell. In the lower part of the experimental device, there were two seed outlets separated by baffles, which were used to screen out superior seed and exterior crack seed, respectively. The sieved seed and cracked seed contain magnetic powder. A vibrating screen was used to recover the magnetic powder in the seed.

2.4.1 Selection of magnetic materials

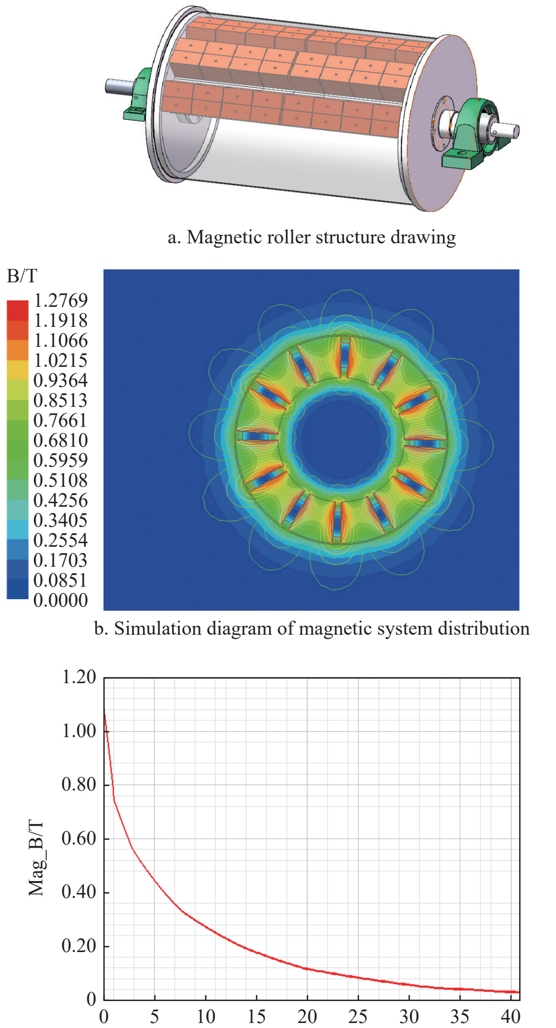
The magnetic field of the magnetic separator was generated by the magnetic system, which was the core part of the magnetic separator. Currently, the magnetic materials widely used in the market are mainly ferrite and neodymium-iron-boron (Nd2Fe14B). Generally speaking, ferrite's maximum magnetic induction intensity does not exceed 2000 Gs, while the magnetic induction intensity of Nd2Fe14B material could be increased to more than 8000 Gs[34,35]. Ferrite material was used in the magnetic powder of this experimental device, and Nd2Fe14B material was used in the magnetic roller system. Its brand was N40. Its coercive force was 900 kA/m, and remanent magnetism was 1200 mT.

2.4.2 Key components of magnetic separator

If the graded material was a small particle, the magnetic system with a small polar distance could be used because the particle moves close to the surface of the magnetic system. On the contrary, if the size of the graded material was large, the magnetic system with a significant polar distance should be adopted. According to the magnetic field force requirements of the magnetic separator in the separation process, this machine designed the polar width to be 75 mm, the polar width was 30 mm, and the polar width ratio was 2.5.

The structure of the magnetic roller is shown in Figure 4a. The driving force was transmitted to the end cover and the shell of the roller through the short shaft to drive the cylinder body to rotate. The magnetic roller was 300 mm in diameter and 600 mm in length. The material of the roller was 304 stainless steel, and a rubber layer with a thickness of 2 mm was pasted on the outer wall of the roller. This way could reduce the roller wear and be conducive to delinted cottonseed adhesion. In order to prevent the magnetic lines of force from forming a closed loop in the roller material, the end cover of the roller was cast with aluminum alloy. The magnetic poles were made of blocks made by a permanent magnet system. Each block was fixed to the magnetic guide plate by copper screws through the center of the magnet, and the magnetic guide plate was fixed to the support shaft of the cylinder by a bracket. Therefore, the magnetic system of the roller was fixed and did not rotate. The polarity of the magnetic system was arranged alternately along the circumference, and the magnetic field was uniformly distributed along the axis.

The spatial distribution of the magnetic field around the magnetic pole was simulated by ANSYS Maxwell Low-Frequency EM-Field Simulation software. The simulation model used Balloon boundary conditions to avoid outside interference. The outer space of the magnetic pole was set as the vacuum. The ferrite material was Nd2Fe14B, with a coercive force of 900 kA/m and remanence of 1200 mT. An adaptive method was used in ANSYS Maxwell to divide cell mesh. The shape of the cell mesh was triangular, in which the grid in the vacuum region was the widest, the shielding layer was the highest, and the magnetic pole part was the densest. The simulation results are shown in Figures 4b and 4c. Figure 4b shows that the magnetic roller system's magnetic field intensity reaches the highest at the edge of the magnetic pole. The farther the space position was from the edge of the magnetic pole, the lower the magnetic field intensity. Figure 4c shows the relationship between the magnetic system's radial magnetic induction intensity curve and the distance to the center of the magnetic system. It could be seen that the magnetic induction intensity of the magnetic system of the magnetic roller was up to 1200 mT, and the magnetic induction intensity of the magnetic system 2 mm away from the magnetic system was up to 1000 mT, which could meet the requirements of seed grading. However, magnetic induction intensity drops rapidly, about 5-10 mm from the magnetic system.



a. Magnetic roller structure drawing

b. Simulation diagram of magnetic system distribution

c. Relationship between magnetic field intensity and distance

Figure 4 Structure of magnetic roller

2.4.3 Magnetic separation electromechanical control

Control cabinet after accepting the touch screen, after the CPU logic transformation, the formation of square-wave PWM signal, to 380 V power amplification, Drive the variable frequency motor to drive the magnetic roller rotation. The drive motor was generally with selection. The machine speed control requirements were 20 to 80 r/min, and the moment of inertia of the load of 0.35 kg·m^2 was a typical high torque and low speed. To install the pulley on a variable frequency motor for deceleration, the motor output of high speed, low torque reducer ratio, low speed, high torque load output.

3 Results and discussion

The experimental location was in Henan University of Science and Technology, China. The experiment time was October 2021.

3.1 Determination of 100-seed weight

The 100-seed weight is an indicator that reflects the seed's size and fullness. The larger the value of the 100-seed weight, the plumper the seed, and the stronger the vitality[36]. Firstly, five groups of samples were randomly selected from the experimental delinted cottonseed, with 100 grains in each group. Secondly, as shown in Figure 5, weigh the sample on the electronic balance and record the experimental result. Thirdly, calculate the mean value, standard deviation, and coefficient of variation for each group of samples, as listed in Table 1.

Figure 5 100-seed weight

Table 1 100-seed weight of experiments

Repeat/g					Average/g	Standard deviation/g	Variable coefficient
1	2	3	4	5			
8.3	7.9	8.4	8.4	8.0	8.25	0.2380	0.0288
8.6	8.4	8.3	8.4	8.5	8.44	0.1140	0.0135
8.8	8.6	8.5	8.6	8.5	8.60	0.1225	0.0142
8.7	8.5	8.5	8.6	8.2	8.50	0.1871	0.0220
8.8	8.7	8.7	8.8	8.8	8.76	0.0548	0.0063
8.4	8.0	8.1	8.2	8.3	8.24	0.1517	0.0184

It can be seen from Table 1 that the average 100-seed weight of the delinted cottonseed samples was between 8.24 g and 8.76 g, and the standard deviation and coefficient of variation of seeds were minimal. The average 100-seed weight for all sample seeds was 8.47 g.

3.2 Response surface analysis of factors of magnetic separation

In order to find out the primary and secondary factors affecting the experiment and determine the optimal combination of magnetic separation parameters, a four-factor, and three-level response surface test was designed. The mesh size is the screen's number of holes per inch (25.4 mm). The higher the mesh size, the more holes there are, and the finer the granularity of the material. In this paper, the Taylor standard sieve system is used, and its indexing is based on the 200-mesh sieve hole size of 0.074 mm. By consulting Taylor's standard sieve system sieve hole and the corresponding relationship between the labeled mesh: 100-mesh sieve size 0.150 mm, 300-mesh sieve size 0.050 mm. Magnetic powders with different mesh numbers have different adsorption properties to seeds, affecting the separation accuracy. In this study, a single-factor pre-experiment was conducted to investigate the effect of magnetic powder mesh. The results showed that the magnetic powder's mesh number significantly affected the separation accuracy. The mesh number of the magnetic powder, the mass mixing ratio between magnetic powder and delinted cottonseed, the magnetic field strength, and the rotation speed of the magnetic roller were taken as the experimental factors, and the weight of one hundred grains was taken as the experiment index. The horizontal values of the mesh number of magnetic powder (Experimental factor A) were 100 mesh, 200 mesh, and 300 mesh, respectively. The mass mixing ratio between magnetic powder and delinted cottonseed (Experimental factor B) was 1:10, 1:20, and 1:30, respectively. The horizontal values of the rotating speed of the magnetic separation roller (Experimental factor C) were respectively 20 r/min, 30 r/min, and 40 r/min.

3.2.1 Experimental preparation

In order to experiment with the performance of the delinted cottonseed grading device, 20 groups of 100 delinted cottonseed were prepared in advance. Each of the 100 delinted cottonseeds comprised 90 fine delinted cottonseed and 10 cracked delinted cottonseed. Exterior crack delinted cottonseed refers to a long crack within the edge[37]. The cracked delinted cottonseed was treated with dye to allow visual differentiation.

Selecting the mesh number of magnetic powder (Experimental factor *A*), the mass mixing ratio between magnetic powder and delinted cottonseed (Experimental factor *B*), and the horizontal values of the rotating speed of the magnetic separation roller (Experimental factor *C*) as test factors. The response surface analysis design was adopted in the experiment, as listed in Table 2 and Table 3.

Table 2 Coding of test factors

Levels	Factors		
	Magnetic powder A/mesh	Mixing ratio B/%	Rotating speed C/r·min^{-1}
–1.682	100	1:10	20
–1	150	1:14	24
0	200	1:20	30
1	250	1:26	36
1.682	300	1:30	40

Table 3 Test design scheme and test results

No.	A	B	C	Magnetic separation accuracy/%
1	1	1	1	83.1
2	1	1	–1	88.3
3	1	–1	1	78.7
4	1	–1	–1	85.6
5	–1	1	1	80.2
6	–1	1	–1	85.3
7	–1	–1	1	77.3
8	–1	–1	–1	84.2
9	–1.682	0	0	78.3
10	1.682	0	0	88.7
11	0	–1.682	0	80.4
12	0	1.682	0	91.6
13	0	0	–1.682	92.5
14	0	0	1.682	78.2
15	0	0	0	89.2
16	0	0	0	90.1
17	0	0	0	88.1
18	0	0	0	91.2
19	0	0	0	90.2
20	0	0	0	87.2

3.2.2 Regression analysis

Using Design-Expert 12 software, the experimental data were fitted by multiple regression, the regression equation of detection rate was obtained, and the significance test was carried out, as listed in Table 4. The accuracy of magnetic separation means that after the magnetic separator is fed and stabilized, at the beginning of the test, during the test, and before the end of the test, not less than 100 g of cottonseeds are picked up at the outlet of superior seeds and mixed thoroughly respectively. The exterior crack cottonseeds were selected from the mixed samples and weighed to calculate the ratio of the exterior crack cottonseeds to the weight of the mixed samples, calculated according to Equation (12). The measurement was carried out three times, and the average value of three times was taken as the magnetic separation accuracy of the sample.

$$\alpha = 100 - \frac{W_h}{W_z} \times 100\% \quad (12)$$

where, α is the magnetic separation accuracy, %; W_h is the mass of exterior crack cottonseeds of the mixed sample, g; W_z is the total mass of the picked up mixed sample, g.

Table 4 Results of variance analysis

Source	Magnetic separation accuracy/%			
	Sum of squares	df	*F*	*P*
Model	448.55	9	14.28	0.0001
A	76.33	1	21.87	0.0009
B	94.57	1	27.10	0.0004
C	156.31	1	44.78	<0.0001
AB	18.32	1	5.25	0.0449
AC	0.03	1	0.0087	0.9275
BC	0.49	1	0.1414	0.7147
A^2	62.55	1	17.92	0.0017
B^2	18.03	1	5.16	0.0464
C^2	39.00	1	11.17	0.0075
Lack of fit	23.99	5	2.20	0.2038

Regression equation of influence of test factors on detection rate was obtained by multiple regression fitting

$$y_1 = 89.02 + 2.77A + 3.09B - 3.46C + 2.31AB + 0.076AC + 0.302BC - 2.22A^2 - 1.15B^2 \quad (13)$$

Table 4 lists that the regression model, p<0.01, was very significantly fitting. However, the interaction terms of magnetic powder and rotating speed, mixing ratio, and rotating speed p>0.05, and the influence was insignificant. The impact was very significant for magnetic powder, mixing ratio, rotating speed, magnetic powder quadratic, and rotating speed quadratic p<0.01. The interaction term of magnetic powder and mixing ratio and the quadratic term of mixing ratio were 0.01<p<0.05, which have significant effects. Lack of fit p>0.05, the difference was insignificant, indicating that the regression model fitting effect was good. The new regression equation was:

$$y_1 = 89.02 + 2.77A + 3.09B - 3.5C + 2.31AB - 2.22A^2 - 1.15B^2 - 1.68C^4 \quad (14)$$

According to the regression equation, the influence curve of single factor on detection rate can be obtained, as shown in Figure 6.

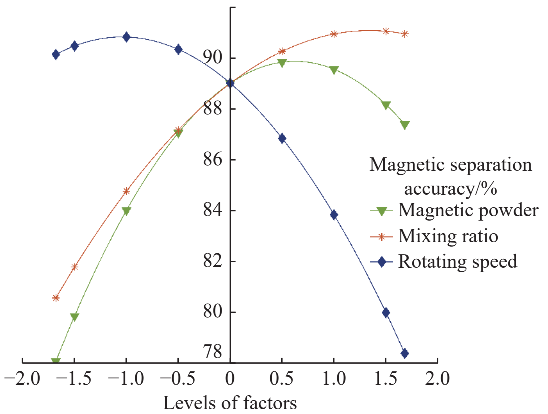
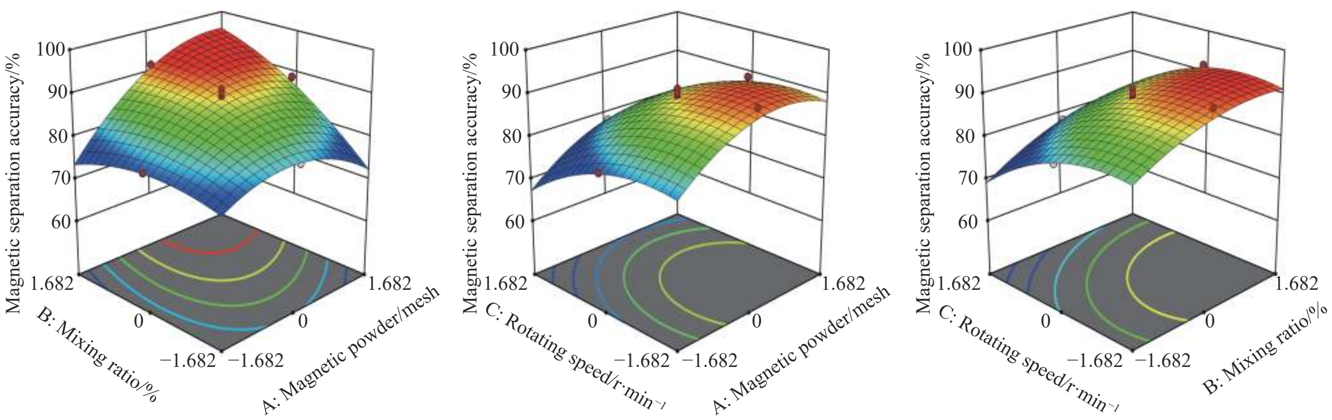


Figure 6 Effect of single factor

It was not difficult to see from Figure 6 that the detection rate increases first and then decreases with the increase of magnetic powder and tends to be flat with the increase of mixing ratio. This was similar to the adhesion experiment of magnetic powder results, while the detection rate decreased with the increased rotating speed.

3.2.3 Response surface analysis

The results of the response surface analysis are shown in Figure 7. Figure 7a shows that when the rotation speed was fixed at 30 r/min, the detection rate increased with the mixing ratio and magnetic powder increase. The detection rate will decrease when one of the two facts is low. When the rotational speed increases, the detection rate will decrease. The interaction between rotational speed and the other two factors was not apparent, as shown in Figures 7b and 7c. Therefore, increasing the magnetic powder mesh and the number of magnetic powders can effectively improve the detection rate when the rotational speed is reduced as much as possible. However, when there were too many magnetic powders or the magnetic powder mesh was too high, the improvement of the seed grading success rate was limited. From the perspective of cost reduction, the optimal number of magnetic powder mesh and mixing ratios were 200-250 and 1:18.6-1:23.7.



a. Mixing ratio and magnetic power relationship

b. Rotating speed and magnetic power relationship

c. Rotating speed andmixing ratio relationship

Figure 7 Response surface analysis

3.3 Prototyping testing

The prototyping testing was at Henan University of Science and Technology, China. Test treatment was the same as above. In the experiment, the rotating speed was 20 r/min, the magnetic particle mush was 250, and the mixing ratio was 1:20. The experimental site is shown in Figure 8.

Figure 8 Photos from the test site

After testing, the detection rate was 92.5%, meeting operational requirements. So it was feasible to classify seeds by magnetic principle to ensure seed quality.

4 Discussion

In the test of the test bench, we found the following three reasons affecting the classification effect and analyzed them:

1) When the rotating speed of the magnetic separation roller increases, it means greater centrifugal force. In this case, seeds with more minor surface cracks were thrown out in advance because of less magnetic powder adsorbed and less magnetic force, which leads to misclassification.

2) When the magnetic field intensity was insufficient, the adsorption capacity of the seed was weakened. In this case, even if the rotational speed were deficient, the seed with cracks on the surface would still be thrown out in advance due to the low adsorption capacity. When the magnetic field intensity is too large, the adsorption capacity of the improved species increases, and the falling of the improved species is not timely, which will also affect the detection rate.

3) When the magnetic powder and seed were mixed unevenly, due to the different numbers of magnetic powder adhered to each seed surface, it will have a particular impact on the results of seed grading.

For the second problem, we added a two-stage magnetic roller to the prototype and used the weak magnetic field to screen out the seed with cracks on the surface in advance, which achieved good results. The author believes there was a specific relationship between the magnetic roller speed and the magnetic field intensity. In the follow-up work, the electromagnet with a variable magnetic field can be added to find the matching value of the two. At the same time, the use of machine stirring magnetic powder and seed ensures its uniformity but also ensures that the moving process will not cause damage to the seed.

5 Conclusions

For the low efficiency of traditional cottonseed quality grading, the magnetic separation device designed in this paper is based on the different movement patterns of the magnetic powder-coated cottonseed in the inhomogeneous magnetic field to screen out superior cottonseeds and exterior crack cottonseeds. The cottonseeds' batch-processing operation was realized by optimizing and analyzing the magnetic separator's working parameters. The magnetic separator is simple and efficient compared with the traditional grading method, realizes batch testing, and does not cause damage to GK-10 cottonseeds during the testing. At the 250-mesh magnetic powder, the mass mixing ratio of magnetic powder and delinted cottonseeds was 1:20, and the rotational speed was 20 r/min. The exterior crack cottonseeds could be effectively removed, and the separation accuracy could reach 92.5%. The test results showed that the magnetic separator's design meets the cottonseed grading requirements, has high grading stability and magnetic separation accuracy, and provides an effective means for producing high-quality cottonseed selection. In addition, the versatility of this magnetic separator for corn, peanut, and soybean seed screening can be explored in the following work by adjusting the main parameters, such as the number of magnetic powder mesh, the magnetic field strength of the magnetic roller, and magnetic roll speed.

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[References]

[1] Yang G, Li F, Tian L, He X, Ren F. Soil physicochemical properties and cotton (*Gossypium hirsutum* L.) yield under brackish water mulched drip irrigation. Soil and Tillage Research, 2020; 199: 104592.

[2] Li H J, Wang J W, Ali S, Iqbal B, Zhang H, Wang S S, et al. Agronomic traits at the seedling stage, yield, and fiber quality in two cotton (*Gossypium hirsutum* L.) cultivars in response to phosphorus deficiency. Soil Science and Plant Nutrition, 2019; 1709543.

[3] Du X M, Liu S Y, Sun J L, Zhang G Y, Jia Y H, Pan Z E, et al. Dissection of complicate genetic architecture and breeding perspective of cottonseed traits by genome-wide association study. BMC Genomics, 2018; 19(1): 451.

[4] Wang Q K, Xing H X, Liu X L, Mao L L, Wei Z, Zhang H J, et al. Estimation of protein and fatty acid composition in shell - intact cottonseed by near infrared reflectance spectroscopy. Journal of the American Oil Chemists' Society, 2019; 97(4): 331–340.

[5] Dowd M K, Manandhar R, Delhom C D. Effect of seed orientation, acid delinting, moisture level, and sample type on cottonseed fracture resistance. Transactions of the ASABE, 2019; 62(4): 1045–1053.

[6] Huang W C, Taylor A G, Wang L. Air cleaning improves quality of eastern gamagrass seed with partial and complete cupule removal. International Agricultural Engineering Journal, 2018; 27(4): 95–102.

[7] Wang X, Wang C G, Wang Q X, Du J Q. Design and experiment of pre-stratified feeding system for gravity seed separator. Transactions of the CSAM, 2019; 50(12): 80–88. (in Chienese)

[8] Giyevskiy A M, Orobinsky V I, Tarasenko A P, Chernyshov A V, Kurilov D O. Substantiation of basic scheme of grain cleaning machine for preparation of agricultural crops seeds. Microelectronics Systems Education, 2018; 327(4): 042035.

[9] Holt G, Wedegaertner T, Wanjura J, Pelletier M, Delhom C, Duke S. Development and evaluation of a novel bench-top mechanical cotton seed delinter for cotton breeders. Journal of Cotton Science, 2017; 21(1): 18–28.

[10] Jin X, Zhao K X, Ji J T, Du X W, Ma H, Qiu Z M. Design and implementation of intelligent transplanting system based on photoelectric sensor and PLC. Future Generation Computer Systems, 2018; 88: 127–139.

[11] Jin X, Yuan Y W, Ji J T, Zhao K X, Li M Y, Chen K K. Design and implementation of anti-leakage planting system for transplanting machine based on fuzzy information. Computers and Electronics in Agriculture, 2020; 169: 105204.

[12] Huang D Y, Li J B, You J, Kan Z. The classification of delinted cottonseeds varieties by fusing image information based on hyperspectral image technology. Spectroscopy and spectral analysis, 2018; 38(7): 2227–2232.

[13] Zhang T T, Xiang Y Y, Yang L M, Wang, J H, Sun Q. Wavelength variable selection methods for non-destructive detection of the viability of single wheat kernel based on hyperspectral imaging. Spectroscopy and Spectral Analysis, 2019; 39(5): 1556–1562.

[14] Liu X D, Feng X P, Liu F, He Y. Identification of hybrid rice strain based on near-infrared hyperspectral imaging technology. Transactions of the CSAE, 2017; 33(22): 189–194. (in Chinese)

[15] Wang H C, Yang Q L, Yang Y. Background segmentation and parameter detection of Jatropha seeds images. Journal of Drainage and Irrigation Machinery Engineering, 2018; 36(8): 713–718. (in Chinese)

[16] Lv S Z, Du W L, Chen Z, Chen W, Surigatu. On-line measuring method of buckwheat hulling efficiency parameters based on machine vision. Transactions of the CSAM, 2019; 50(10): 35–43.

[17] Xu J Y, Xiong D H, Song S X, Chen L Z. Superconducting pulsating high gradient magnetic separation for fine weakly magnetic ores: Cases of kaolin and chalcopyrite. Results in Physics, 2018; 10: 837–840.

[18] Baawuah E, Kelsey C, Addai-Mensah J, Skinner W. A novel pneumatic planar magnetic separator for magnetite beneficiation: A focus on flowsheet configuration. Minerals, 2020; 10(9): 759.

[19] Osipova N V. Model of stabilization of the quality of iron-ore concentrate in the process of magnetic separation with the use of extreme regulation. Metallurgist, 2018; 62(3-4): 303–309.

[20] Chen L Z, Yang R Y, Guo S K. A wet belt permanent high gradient magnetic separator for purification of non-metallic ores. International Journal of Mineral Processing, 2016; 153: 66–70.

[21] Tripathy S K, Singh V, Rama Murthy Y, Banerjee P K, Suresh N. Influence of process parameters of dry high intensity magnetic separators on separation of hematite. International Journal of Mineral Processing, 2017; 160: 16–31.

[22] Tang D D, Wang F W, Dai H X, Lu M Y, Gong Z H. Influence of separation chamber shape in dry magnetic separator on the dispersion and separation of multiple magnetites. Minerals Engineering, 2021; 171: 107130.

[23] Kozlova E V, Skrypnikov A V, Kozlov V G. Air magnetic separator for the preparation of forestry seed material and its theoretical justification. International Conference on Mechanical Engineering, Automation and Control Systems, 2019; 560: 012070.

[24] Yin W Z, Wang D H, Drelich J W, Yang B, Li D, Zhu Z L, et al. Reverse flotation separation of hematite from quartz assisted with magnetic seeding aggregation. Minerals Engineering, 2019; 139: 105873.

[25] Wang L H, Yang Y, Shi J C. Measurement of harvesting width of intelligent combine harvester by improved probabilistic Hough transform algorithm. Measurement, 2020; 151: 107130.

[26] Badretdinov I, Mudarisov S, Lukmanov R, Permyakov V, Ibragimov R, Nasyrov R. Mathematical modeling and research of the work of the grain combine harvester cleaning system. Computers and Electronics in Agriculture, 2019; 165: 104966

[27] Lozovaya S Y, Lozovoy N M, Okunev A N. Theoretical validation for changing magnetic fields of systems of permanent magnets of drum separators. Materials Science and Engineering Conference Series, 2018; 327: 042065.

[28] Oleksandr S, Vitaliy S, Alla D. Development and analysis methods of transporter electric drive for electrotechnological complex of crop seed presowing by electromagnetic field. 2019 IEEE 20th International Conference on Computational Problems of Electrical Engineering (CPEE), Lviv-Slavske: IEEE, 2019; pp.201–206.

[29] Viacheslav V, Nikolay K, Yuriy. Nitrolignosulfonates as a magnetic fluid stabilizer. 17th International Multidisciplinary Scientific Geoconference, 2017; 17(63): 55–60.

[30] Zhang D, Chen H Y, Hong R Y. Preparation and conductive and electromagnetic properties of $Fe3O_4$/PANI nanocomposite via reverse in situ polymerization. Journal of Nanomaterials, 2019; 2019: 7962754.

[31] Xie X, He Y J, Shi J Z, Li X F. Design and test of the plate type plug seeder based on magnetic attraction. Journal of Henan Agricultural University, 2015; 49(2): 219–222. (in Chinese)

[32] Ji S L, Zhu E L, Qin W H, He Y J, Li X F, Wang W Z. Design of magnetic drum tray seeder for tobacco. Journal of Henan Agricultural University, 2014; 48(3): 326–329. (in Chinese)

[33] Manimehalai N, Viswanathan R. Physical properties of fuzzy cottonseeds. Biosystems Engineering, 2006; 95(2): 207–217.

[34] Zhan P X, Yang S Q, Lu C, Shi W M. Research status and advance on modification of strontium ferrites. Journal of Magnetic Materials and Devices, 2018; 49(1): 64–68, 72.

[35] Han Z Q. Problems on measuring field of *Ms* of microwave ferrites and remanence ratio. Journal of Magnetic Materials and Devices, 2013; 44(1): 73–78. (in Chinese)

[36] Zhu H, Li J L, Xu M, Jin L L, Shan Y, Wang Z S. Study on the relationship between nutrient composition and germination characteristics of crop seed. Seed, 2019; 38(8): 47–52. (in Chinese)

[37] Cui X P, Zheng J H, Hu D M. Research progress on cracks in soybean seed coat. Soybean Science, 2019; 38(4): 656–663.