QUANTITATIVE ANALYSIS OF THE MIXING CHARACTERISTICS OF SIMULATED BROWN RICE PARTICLES BASED ON THE DISCRETE ELEMENT METHOD
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基于离散元模拟的糙米颗粒混合特性定量分析

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ABSTRACT
The mixing characteristics and movement principles of brown rice particles in two different types of sprouted brown rice machine tanks were investigated based on the discrete element method. Through numerical simulation, the effects of different mixing process parameters on the mixing uniformity and energy consumption of brown rice particles were quantitatively analyzed. The optimal mixing parameters for blade-type sprouted brown rice machine were 40.16% filling degree and 20 r/min rotational speed and for drum-type sprouted brown rice machine were 37.9% filling degree and 20 r/min rotational speed. In addition, a drum-type sprouted brown rice machine mixing test platform was designed and constructed. Physical tests validated the accuracy of the discrete element simulation outcomes, confirming their consistency with physical test environments in terms of the change rule of the movement state and mixing uniformity of brown rice particles. This paper provides a significant theoretical basis and experimental support for the refinement of the design and the enhancement of the manufacturing process for the sprouted brown rice machine.

摘要
本文基于离散元法研究了糙米颗粒在两种不同类型的发芽糙米机罐体内的混合特性和运动规律。通过数值模拟，定量分析了不同混合工艺参数对糙米颗粒混合均匀度和能耗的影响，确定了最优混合工艺参数：叶片式发芽糙米机填充度 40.16%、转速 20r/min，滚筒式发芽糙米机填充度 37.9%、转速 20r/min。此外，还设计并搭建了一套滚筒式发芽糙米机混合试验平台，通过物理试验验证了离散元模拟仿真结果的准确性，表明仿真环境与物理试验环境下糙米颗粒的运动状态及混合均匀度的变化规律一致。这一研究为发芽糙米机的设计优化和生产工艺优化提供了重要的理论依据和实验支持。

INTRODUCTION
China is a large producer and consumer of rice. Brown rice obtained after coarse dehulling retains all the nutrients of rice, but its taste is poor and indigestible which is not easily accepted by the public. To address this issue, some scholars have developed sprouted brown rice, a whole grain variant. This product is derived from brown rice that has been cultivated to a specific bud length under optimal temperature and humidity conditions. Sprouted brown rice boasts an array of bioactive compounds, offering higher nutritional value and an enhanced flavor profile compared to traditional brown rice (*Zhang et al., 2021*). Research on the production process of sprouted grains has been a hot and difficult issue in the deep processing of grains (*Chen et al., 2021*).

Scholars at home and abroad have tried to improve the method of grain water absorption to improve the quality of sprouted grains. For example, *Jia et al, (2012),* introduced a new technique to produce sprouted brown rice by circulating humidification and conditioning treatment. The process used atomized humidification and supplemented with mixing to make the brown rice tumble and flow to achieve the required moisture content for germination (*Yaraghi et al., 2018*). The uniformity of its mixing has a direct impact on the quality of sprouted brown rice. At present, the research and development of sprouted grains primarily remains confined to laboratory-based theoretical studies, centering on fundamental investigations into their nutritional makeup.

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The humidification and conditioning processes involved in sprouted grain production face challenges, including a lack of clear methods for quantitatively describing the mixing mechanism of stratified particles. Difficulties in achieving uniform conditioning control significantly hinder widespread and high-quality application of this technology in the grain processing industry. Therefore, it is essential to examine the mixing and movement principles of brown rice within the sprouted brown rice machine.

Recently, discrete element numerical simulation has been widely used in the study of particle mixing laws in mixers (*Zuo et al., 2021*). This method can intuitively reflect the motion and mixing law of particle population and help to obtain the optimal mixing parameters and energy consumption data. The discrete element method is a numerical simulation method based on the assumption of discontinuity, which has become an important means to study particle mixing (*Bao et al., 2018; Zhang et al., 2020*). The discrete element method enables the acquisition of detailed information on individual particles, such as velocity and direction, which illuminates the underlying principles and characteristics of the particle population (*Chandratilleke et al., 2021*). By employing this method, the energy consumption of brown rice particles when they are mixed uniformly can be understood. Information such as the motion trajectory, position, velocity, direction and force of individual particles can be localized (*Tang et al., 2017*). The discrete element method can also be used to analyze the particle mixing behavior in a mixer (*Yu et al., 2022*). For example, *Zhao et al, (2019),* used the discrete element method to analyze the motion trajectory of particles in the soil-fertilizer mixing process to obtain the mixing uniformity of fertilizer particles in the soil. *Chen et al, (2015),* distinguished the radial mixing motion of particles in the drum into active zone, stable zone and mixing dead zone based on the discrete element method. *Wang et al, (2020),* used the coefficient of variation and net power consumption as evaluation indexes to optimize the parameters such as rotational speed and filling degree through discrete element simulation. This optimization process aimed to identify the optimal combination of mixing parameters. Y*ang et al (2021*) constructed a mathematical model of the correlation between the rotational speed of the screw mixer blades, the filling volume and the degree of particle mixing, and optimized the mixing process parameters based on this model.

Most scholars used discrete element numerical simulation to study the mixing kinematic properties of binary spherical particles in the drum. This revealed a link between drum rotational speed and particle states. As drum rotational speed rose, six kinematic states would appear successively: sliding, stepping, rolling, small waterfall, large waterfall and centrifugal (*Tsunazawa et al., 2022*). And there are three mixing mechanisms of convection, diffusion and shear in the mixing process (*Tanabe et al., 2019; Ebrahimi et al., 2021*). The degree of influence of each mixing stage on the mixing effect is different, and the mixing performance of particles with complex shapes is lower. Meanwhile, most scholars often apply similarity theory approach to obtain the relationship between the prototype mixer and model parameters. Similarity theory fused with discrete element numerical simulation studies favors the model scaling aspect.

In summary, the current research mostly uses spherical particles to validate the discrete element simulation, and there are fewer studies on real brown rice particles. Therefore, this paper primarily investigated the mixing characteristics of real brown rice grains in the tank. The two comparative test programs of reducing the tank and particle amplification were proposed based on the similarity theory. The two typical sprouted brown rice machine tanks of brown rice particles in the optimal mixing process parameters and the law of change of energy consumption were quantitatively analyzed. A physical test platform specifically designed for drum-type sprouted brown rice machine mixing was built. The accuracy and reliability of discrete element numerical simulation were validated by comparing the outcomes of the physical tests conducted on this platform with the simulation results.

MATERIALS AND METHODS

Discrete element numerical simulation system

Due to the large prototype of sprouted brown rice machine, computer hardware and EDEM software limitations, the simulation was based on similar theoretical principles to shrink the tank or enlarge the brown rice particles. In this paper, the mixing movement principles of brown rice particles under the two conditions of enlarged particles and reduced tank were compared and analyzed.

EDEM software was applied to simulate the particle mixing characteristics in the tank of a non-soaked sprouted brown rice machine with ellipsoidal particles with low water content and without considering the effect of adhesion. The Hertz-Mindlin (no slip) contact mechanics model was used. Table 1 lists the initial boundary and physico-mechanical parameters of the simulated tank and brown rice particles.

Table 1

Parameters required for simulation

Parameters	value
Particle density/ (kg·m^{-3})	1538
Particle Poisson's ratio	0.4
Interparticle coefficient of recovery	0.6
Coefficient of static friction between particles	0.43
Coefficient of interparticle kinetic friction	0.01
Coefficient of static friction between particles and inner wall	0.3
Coefficient of kinetic friction between particles and inner wall	0.01
Coefficient of recovery of particles from the inner wall	0.6
Mixer tank density/ (steel, kg·m^{-3})	7800
Tank Poisson's ratio	0.3
Mixer tank shear modulus/ Pa	7×10^{10}
Particle shear modulus/ Pa	1.1×10^{7}

Numerical simulation conditions and test program for the tank of the blade-type sprouted brown rice machine

Blade type sprouted brown rice machine tank ensures uniform mixing and precise control during brown rice germination, improving germination quality, but can be costly due to the complexity of the technology and relatively complicated maintenance. Roller type sprouted brown rice machine has high production efficiency, simple operation and wide practicality, but with low loading factor, inconvenient drainage and high power consumption.

Blade type sprouted brown rice machine tank was mainly composed of three parts: tank shell, center shaft and drum bottom plate. The structure was simple and the processing cost was low. The three-dimensional model was shown in Fig.1.

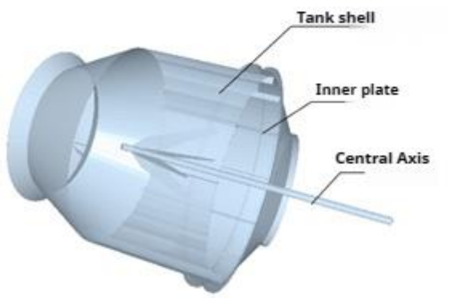
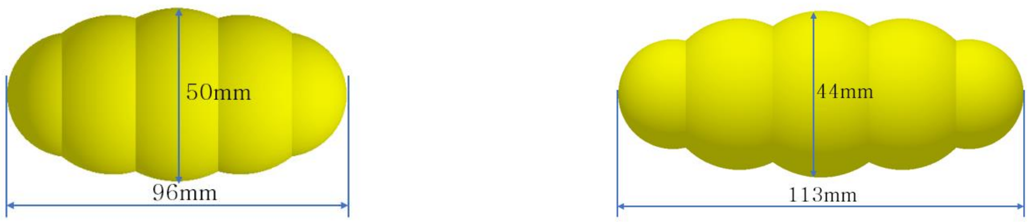


Fig. 1 - 3D model of the blade type sprouted brown rice machine tank

The diameter of the tank was 1600 mm, and the mixing area was 1000 mm long. There were 12 straight plates and 4 inclined plates in the drum, which were evenly distributed. There were four identical and evenly distributed mixing blades on the center shaft to match the mixing, with a blade angle of 42°, thickness of 2 mm, width of 210 mm and vertical distance of 220 mm. The brown rice grains simulated in the test were Dongnong 429, which were oval in shape. One hundred grains were randomly selected for measurement, with the long axis ranging from 5.5 mm to 6.8 mm, and the short axis ranging from 2.6 mm to 3.1 mm. Considering the effect of brown rice particle size, two particle models, long and short, were selected for the test.

Unchanged tank, enlarged grain, bladed sprouted brown rice machine tanks

In order to meet the simulation conditions, the size of the tank of the sprouted brown rice machine was kept unchanged and the brown rice particle model was enlarged. Five round balls with different radii were used to fill in, and the approximate short and long particle models were obtained, as shown in Fig. 2.



(a) Modeling of short particles in the tank of a blade-type sprouted brown rice machine

(b) Modeling of long particles in the tank of a blade-type sprouted brown rice machine

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Fig. 2 - Two models of filled particles in the blade sprouted brown rice machine tank (particle amplification)

To ascertain the parameter range for rotational speed in the simulation test, different rotational speeds were employed in the simulation and the range of rotational speeds was determined based on the end-of-mix status. The method used to determine the range of the simulation test filling degree is consistent with the determination of the rotational speed. The particles were separated into upper and lower layers with different colors but the same number. The simulated mixing time was about 35 s, and the exact time was determined based on the final mixing status.

According to the relationship among rotational speed, number of particles and filling degree, the mixing parameters under particle amplification were determined, as shown in Table 2.

Table 2

The blade sprouted brown rice machine mixing parameters test program

Sprouted Brown Rice Machine Type	Particle type	Filling degree	Number of particles	Number of revolutions per minute
Blade Sprouted Brown Rice Machine	long grain	33.83%	4700	10r/min 20r/min 30r/min 40r/min
		44.59%	6400	
		55.23%	7600	
	short grain	40.16%	4800	
		50.5%	6000	
		60.83%	7600	

Reduced tank, no change in grain condition, blade type sprouted brown rice machine

According to the grain magnification, the tank was reduced by the same amount and the brown rice grain size was kept constant. The Blade Sprouted Brown Rice Machine tank was reduced by a factor of 16 and the diameter is reduced to 100 *mm*. The short and long grain models were shown in Fig. 3.

(a) Modeling of short particles in the tank of a blade-type sprouted brown rice machine

(b) Modeling of long particles in the tank of a blade-type sprouted brown rice machine

Fig. 3 - Two models of filled particles in the blade sprouted brown rice machine tank (tank reduction)

In order to comparatively analyze the particle mixing process under the two scaling modes of tank reduction and particle enlargement, the mixing parameters such as rotational speed and particle filling degree are consistent with Table 2.

Numerical simulation conditions and test program for drum type sprouted brown rice machine tanks

The whole tank of roller type sprouted brown rice machine consisted of two parts: tank shell and inner baffle, with relatively simple structure and no central axis. Its three-dimensional model is shown in Fig. 4.

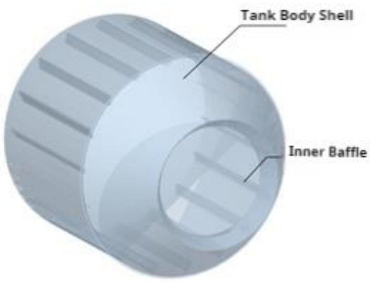


Fig. 4 - 3D model of the drum-type sprouted brown rice machine tank

Roller type sprouted brown rice machine had a diameter of 2000 mm and mixing area length of 1490 mm. Eighteen inner baffles were uniformly distributed, each 20 mm thick and 1400 mm long with 45° angle to tangent line. In this paper, long and short particle models were selected to investigate the effect of particle size on mixing characteristics.

Unchanged tanks, grain enlargement conditions, drum type sprouted brown rice machine tanks

In order to meet the simulation conditions, the size of the tank of the sprouted brown rice machine was kept constant and the brown rice particle model was enlarged. Five round balls with different radius were used to fill in, and the approximate short and long particle models were obtained as shown in Fig. 5.

(a) Modeling of short particles in the tank of a drum-type sprouted brown rice machine

(b) Modeling of long particles in the tank of a drum-type sprouted brown rice machine

Fig. 5- Two models of filled particles in the drum-type sprouted brown rice machine tank (particle amplification)

The rotational speeds of the tank were 10 r/min, 20 r/min, 30 r/min and 35 r/min. The particles were divided into upper and lower layers in the initial state, with the upper layer being blue and the lower layer being red, and with the same number of particles in both colors. The mixing parameter settings under particle amplification conditions are shown in Table 3.

Table 3

Test program of the drum-type sprouted brown rice machine mixing parameters

Mixer Type	Particle type	Filling degree	Number of particles	Number of revolutions per minute
Cylindrical Sprouted Brown Rice Machine	long grain	37.9%	4800	10 r/min 20 r/min 30 r/min 35 r/min
		44.2%	6000	
		53.7%	7200	
	short grain	38.5%	4800	
		45.8%	6000	
		55.8%	7200	

Reduced tanks, unchanged grain conditions, drum-type sprouted brown rice machine tanks

Based on grain magnification above, reduce the tank by the same number of times and keep the brown rice grain size the same. Roller-type sprouted brown rice machine was reduced by a factor of 20 and the diameter was reduced to 100 mm. Its short and long grain models are shown in Fig. 6.

(a) Modeling of short particles in the tank of a drum-type sprouted brown rice machine

(b) Modeling of long particles in the tank of a drum-type sprouted brown rice machine

Fig. 6- Two models of filled particles in the drum-type sprouted brown rice machine tank (tank reduction)

To comparatively analyze the mixing process of particles under two scaling modes of tank reduction and particle enlargement, the mixing parameters such as rotational speed and particle filling degree of the drum-type sprouted brown rice machine were designed to be consistent with Table 2.

Simulation test parameter

Quantitative analysis of particle mixing systems

In this study, the separation index was used to characterize the degree of mixing homogeneity of brown rice particles in the mixing process (*Cho et al., 2017; Kamesh et al., 2022*). To obtain the separation index, the tank was divided into 6x6x8 operational domains. Since the difference or absence of the number of particles in the operational domains would affect the results, only the operational domains with the number of brown rice greater than 20 were calculated, and a weighting scheme was used to make the weights of the operational domains with a large number of particles larger (*Zuo et al., 2021*). On this principle, the formula for the separation index of the two types of particles is as follows:

$$S = \sqrt{\frac{1}{k}\sum_{i=1}^{N_s} k_i (a_i - \bar{a})^2} \quad (1)$$

Where:

N_s - The total sample size;

a_i - The volume fraction of one type of brown rice grain within the sample;

$\bar{a}$ - The volume fraction of a brown rice particle within the tank of the sprouted brown rice.

k can be expressed by the following equation:

$$k = \sum_{i=1}^{N_s} k_i \quad (2)$$

Here k_I is the sample weight which can be expressed as:

$$k_i = \frac{N_i}{N_t} \quad (3)$$

where:

N_I - the sample$i$ is the total number of particles within the sample;

N_t - the total number of particles within all samples.

Effect of rotational speed on energy consumption

The EDEM software can only export the average output torque data when the mixer is rotating, so the following formula was usually used to calculate the energy consumption (*Wang et al., 2020*):

$$W = 2\pi nTt \quad (5)$$

where:

n - the tank rotational speed (r/min);

T - the average output torque ($N \cdot m$);

t - the time for the granular system to reach homogeneous mixing.

Physical test equipment and program design

The physical test platform was mainly composed of switching power supply, stepping motor, motor driver, controller and hybrid roller, as shown in Fig. 14.

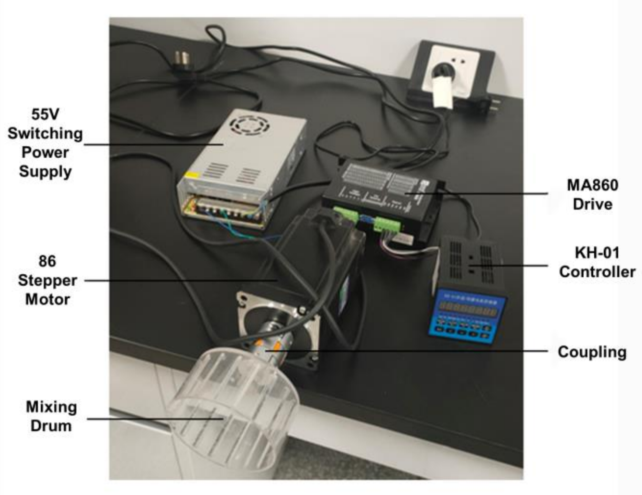


Fig. 14 – The mixing test platform of the drum-type sprouted brown rice machine

The drum-type sprouted brown rice machine tank rotated horizontally and its diameter, length, rotational speed and filling degree were the main parameters. The diameter of the drum was100 *mm*, the angle of the inner bottom plate was 45° and there were 18 bottom plates. In order to investigate the effect of different transverse planes on the mixing of brown rice, three different lengths of tanks were used in the experiment: 75 mm, 50 mm and 25 mm, which were consistent with the simulation test conditions. The tank of its drum type sprouted brown rice machine was shown in Fig. 15.

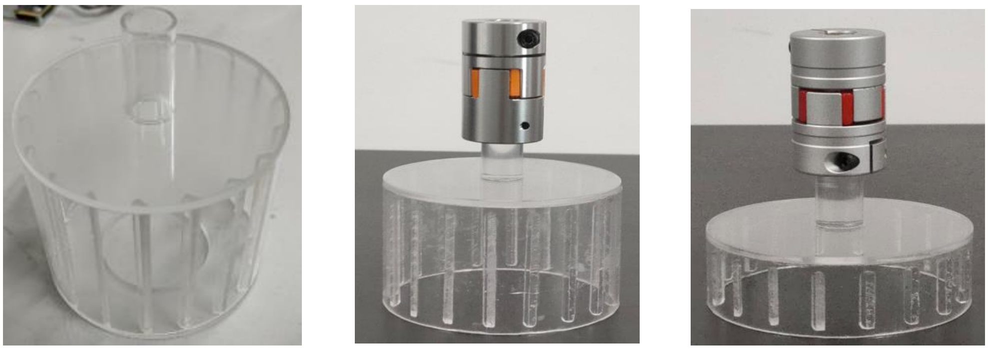


Fig. 15 - Three different lengths of the drum-type sprouted brown rice machine tank
(left: 75 mm mid: 50 mm right: 25 mm)

The experimental research object was Japonica brown rice, dyed with vegetable dyes into red and blue, respectively, the lower layer was filled with blue, the upper layer was filled with red, and the number of brown rice particles of both colors was the same when they were filled. The dyed brown rice particles are shown in Fig. 16.

Fig. 16 - Brown rice particles after dyeing
(left: blue, right: red)

The mixing drum material was acrylic plate, which can clearly observe the mixing motion state of brown rice particles during the test. A high-speed video camera was used to photograph and videotape the mixing process of brown rice particles. Its physical test program design was shown in Table 3.

Table 3

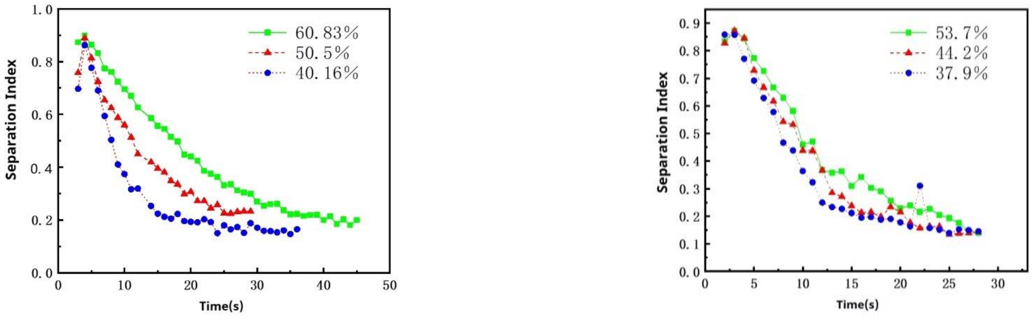
Validation test scheme design

Mixer Type	Number of revolutions per minute	Filling degree
Cylindrical Sprouted Brown Rice Machine	10 r/min	32% 45% 55%
	20 r/min	
	30 r/min	
	35 r/min	

RESULTS

Effect on separation index at the same rotational speed

According to the results of mixing uniformity calculations, the relationship curve between mixing time and separation index of particles in the tank of two typical sprouted brown rice machines under the conditions of particle amplification and rotation speed of 20 r/min was drawn, as shown in Fig. 7.



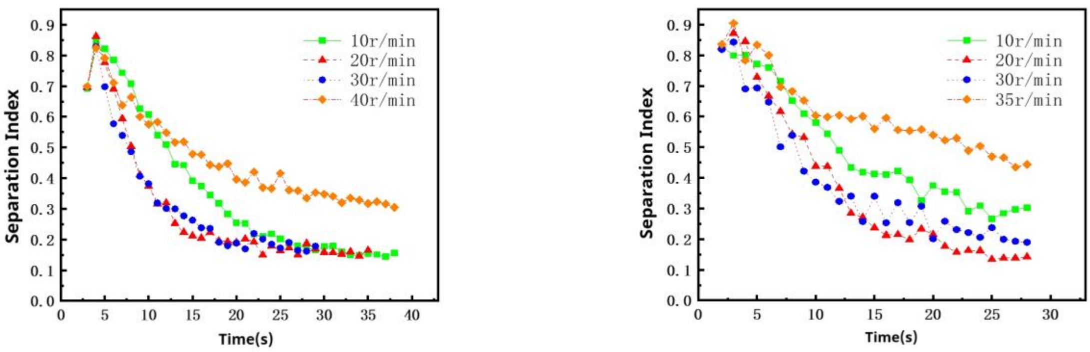
(a) Blade-type sprouted brown rice machine, 20 r/min, short grain *(b) Drum type sprouted brown rice machine, 20 r/min, long grain*

Fig. 7- Variation curves of separation index with time at different filling degrees (particle amplification)

The separation index represents the uniformity of mixing, the lower the value, the better the mixing. Fig. 7. showed that the separation index first rises and then decreases rapidly at different filling degrees, and finally stabilizes, the lower the filling degree the faster the stabilization. The final mixing degree of the three filler degrees was similar at 20 r/min. The mixing speed was fast in the first 10 seconds of mixing, then the convection effect weakened, and the mixing effect was no longer obvious. Finally, the particles were uniformly distributed and tended to stabilize. The mixing speed was the fastest at the lowest filling degree, and the mixing degree was slightly better.

Effect on separation index at the same filling degree

At a fixed degree of filling (40.16% for the blade type and 44.2% for the drum type), Fig. 8 demonstrated the relationship between mixing time and separation index for different tank rotation speeds.

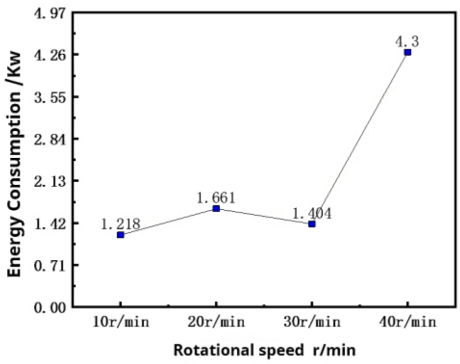


(a) Blade-type sprouted brown rice machine, 40.16%, short grain *(b) Drum-type sprouted brown rice machine, 44.2%, long grain*

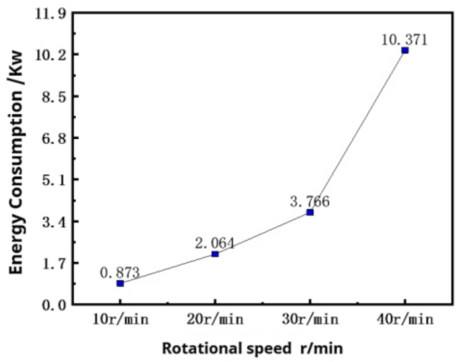
Fig. 8 - Variation curves of separation index with time at different rotational speeds (particle amplification)

Fig. 8 demonstrated the effect of different rotational speeds on the separation index. The separation index started with a small increase and then decreased rapidly and finally stabilized. Blade tanks showed a slower decrease in separation index at 10 r/min and 40 r/min, while 20 r/min and 30 r/min showed a faster decrease and better mixing. Roller tanks had the fastest initial decline at 30 r/min, but the 20 r/min group ended up with a higher degree of mixing. Excessive rotational speed can lead to particles being affected by centrifugal force and rotating with the tank without mixing, e.g. poor mixing in the 40 r/min and 35 r/min groups.

Effect of rotational speed on energy consumption



(a) Blade-type sprouted brown rice machine, 40.16%, short grain

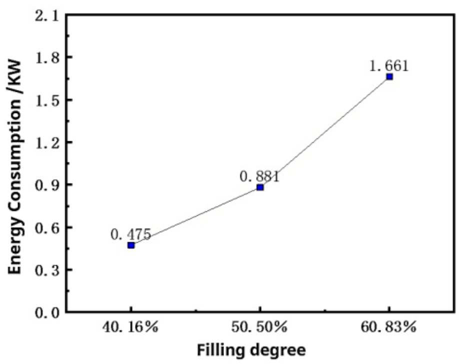


(b) Drum-type sprouted brown rice machine, 44.2%, long grain

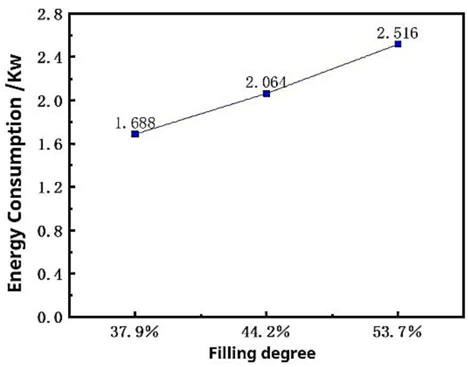
Fig. 9 - The effect of rotational speed on energy consumption (particle amplification)

Fig. 9 demonstrated the variation of energy consumption with rotational speed when the particles were uniformly mixed. The energy consumption was calculated based only on the work done by the tank on the motion of the particles; other factors were not considered. And it also showed that energy consumption increased with increasing rotational speed. At 40.16% filling degree, the stabilized mixing time was similar, so faster rotational speed resulted in higher energy consumption, especially when the rotational speed exceeded 30 r/min, the energy consumption increased sharply.

Effect of filling degree on energy consumption



(a) Blade-type sprouted brown rice machine, 20 r/min, short grain



(b) Drum-type sprouted brown rice machine, 20 r/min, long grain

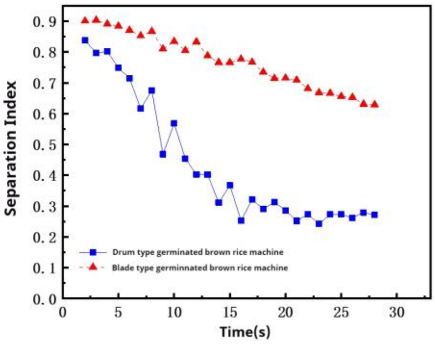
Fig. 10 - Effect of filling degree on energy consumption (particle amplification)

Fig. 10 showed that the energy consumption for particle movement increased gradually with increasing filling degree. Taking into account the filling degree, rotational speed and energy consumption, the optimum mixing parameters were: blade type sprouted brown rice machine was mixed at 40.16% filling degree and 20 r/min rotational speed, while the drum type was best at 37.9% filling degree and 20 r/min rotational speed.

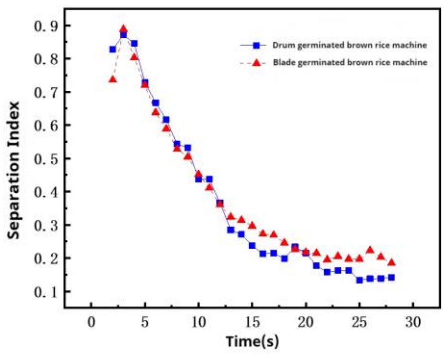
Comparison of the mixing process of two types of sprouted brown rice machine tanks

Both mixers went through three phases of rapid, slow mixing and mixing fluctuations in particle mixing involving convection, shear and diffusion mechanisms. The centrifugal motion appeared at 35 r/min in the drum-type sprouted brown rice machine, while it appeared at 40 r/min in the blade-type sprouted brown rice machine, indicating that the rotational speed had a great influence on the particle mixing state in the drum-type tank. Both types of tank particle movement path were gradually narrowed elliptical helix and the degree of narrowing reflects the mixing effect, the superior the mixing effect, the more obvious changes in the movement path.

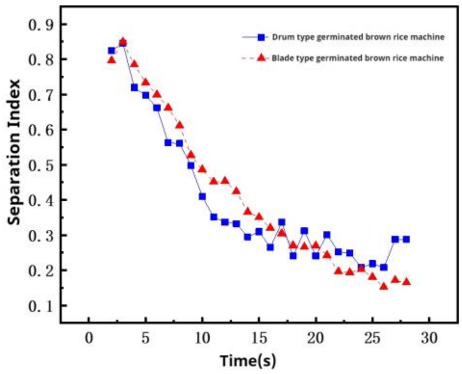
Comparison of two sprouted brown rice machine tank mixing ration analysis



(a) Long particles at 10 r/min, 55%



(b) Long particles at 20 r/min, 44%



(c) Long particles at 30 r/min, 55%

Fig. 11 - Changes of mixing degree of two kinds of machines with mixing time (particle amplification)

In this paper, the degree of particles mixing in the two kinds of germinated brown rice machines was compared and analyzed under the condition of particle amplification. As can be seen from Fig. 11, when the rotational speed was low, the mixing effect of the particles in the tank of the drum-type sprouted brown rice machine was generally better than the blade-type sprouted brown rice machine. When the rotational speed was higher than 30 r/min, the particles in the tank of drum-type sprouted brown rice machine were hindered from mixing due to centrifugal effect, so the mixing effect of blade-type sprouted brown rice machine was better.

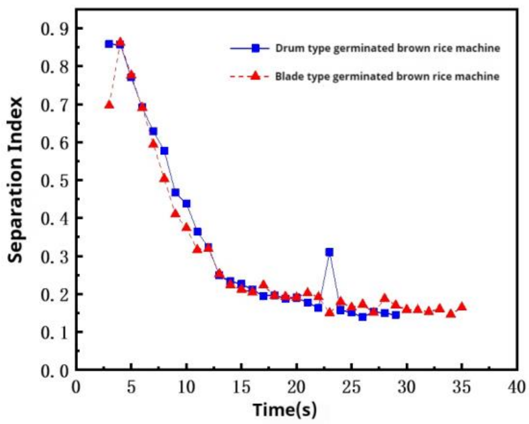
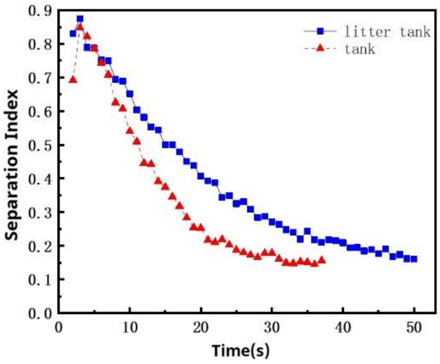


Fig. 12 - Changes of mixing degree with time under the optimal mixing parameters of two sprouted brown rice machines (particle amplification)

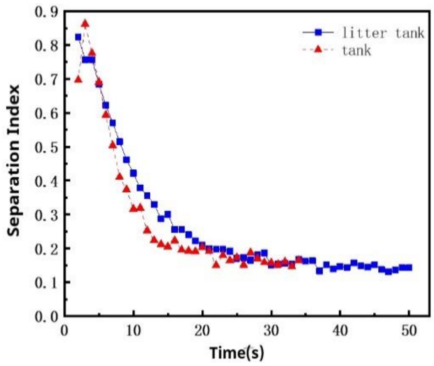
Fig. 12 showed the curves of the degree of mixing with time for the two sprouted brown rice machines under the conditions of optimal mixing parameters. The two curves had similar trends and reached the optimal mixing state after 25 s, indicating that the mixing effect of the two types of sprouted brown rice machine was consistent. Fig. 10 showed that the blade type sprouted brown rice machine had the filling degree of 40.16%, rotational speed of 20 r/min, energy consumption of 0.476 kw, while the drum type sprouted brown rice machine had the filling degree of 37.9%, rotational speed of 20 r/min, energy consumption of 1.687 kW. Considering the mixing effect and energy consumption, the blade type sprouted brown rice machine mixing performance was better.

Comparative analysis of mixing processes under particle enlargement and tank reduction conditions

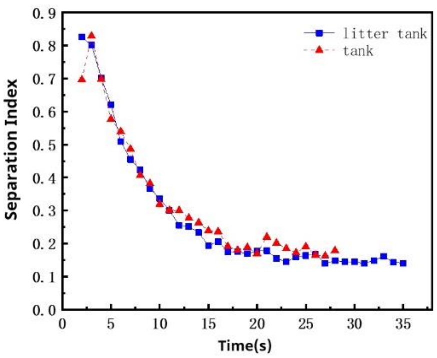
In order to clarify the difference between the numerical results under the two conditions of particle enlargement and tank shrinkage, taking the blade type sprouted brown rice machine as an example, a comparison graph of the change of separation index with time under different rotational speeds was drawn, as shown in Fig. 13.



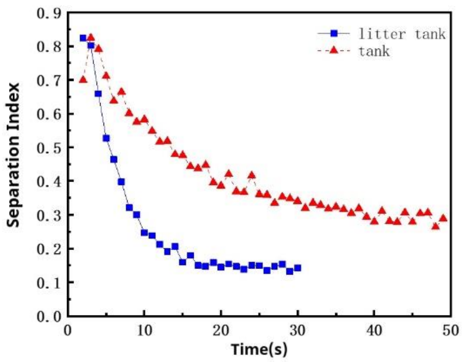
(a) Short grain 40.16% 10 r/min



(b) Short grain 40.16% 20 r/min



(c) Short grain 40.16% 30 r/min



(d) Short grain 40.16% 40 r/min

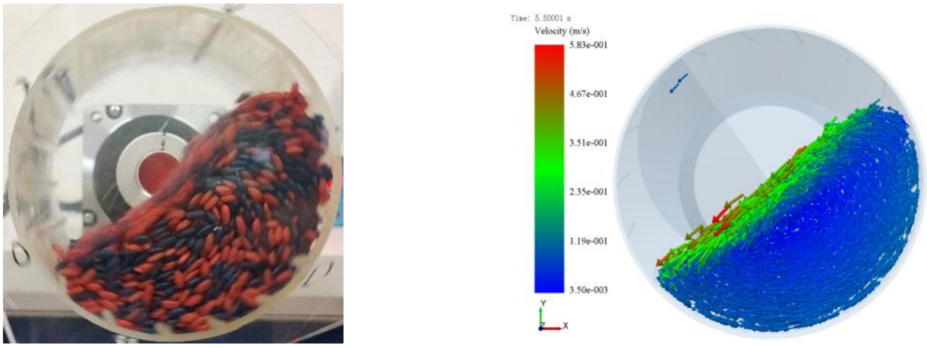
Fig. 13 - Comparison of mixing degrees at different rotational speeds under two scaling conditions

Fig. 13 illustrated the mixing of short particles at 40.16% filling at different rotational speeds for tank downsizing versus particle upsizing. Mixing uniformity was similar at 20 r/min versus 30 r/min, with little difference in the separation index values. At 10 r/min, tank downsizing was less efficient but the end of the mixing was similar. At 40 r/min, particle upsizing was reduced due to centrifugal force mixing efficiency. And the tank shrinkage test conditions were not affected.

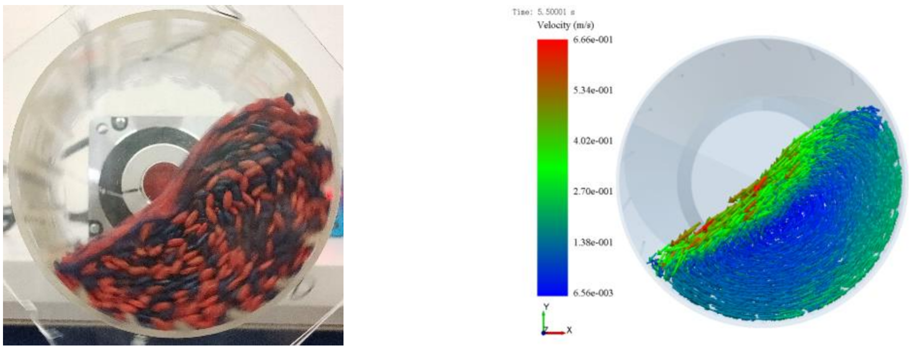
Comparison of particle mixing patterns between physical and simulation tests of mixing drums

The physical test was conducted by using the full-factor test method to mix the brown rice particles in the drum with drum rotational speed and filling degree as variables, and a high-speed video camera was used to record the mixing process. Taking 75 mm tank, 45% filling degree, and rotational speeds of 10 r/min, 20 r/min, and 30 r/min as examples, the motion images of the physical test and the simulation test at different rotational speeds were compared, as shown in Fig. 17.

(a)Rotational speed: 10 r/min   Filling degree: 45%



(b)Rotational speed: 20 r/min   Filling degree: 45%



(c)   Rotational Speed: 30 r/min   Filling degree: 45%

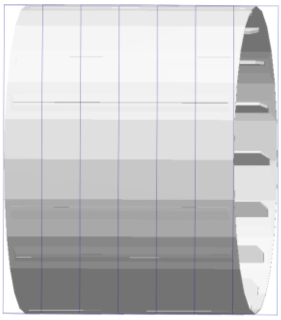
Fig. 17 - Comparison of particle mixing morphology between verification test and simulation test

From the physical test images, it can be seen that the brown rice particles move in a circular motion with the tank and the number of falling particles increases when the rotational speed increases, indicating faster mixing and higher efficiency. The comparative images in Fig. 17 showed that the brown rice particles were mainly in a rolling state with similar morphology during mixing. Under the same conditions, the falling height and flow range of the brown rice particles in the physical and simulation tests were the same, with no significant difference.

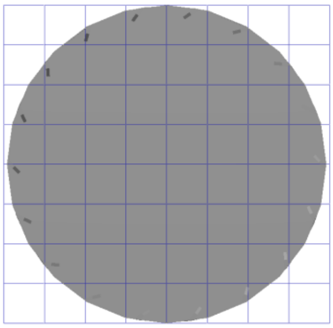
Quantitative analysis of particle mixing for physical tests

Comparison of 2D discrete element simulation and 3D discrete element simulation results

Transverse mixing has been the focus of particle mixing research due to its high efficiency and speed, compared to axial mixing of particles which is slower and occurs in smaller numbers. The 2D DEM simulation uses a small number of particles, as *WU et al., (2022)* to reduce the computational effort of the computer in the simulation process. The 2D model was considered as a cheap alternative model to the 3D model. Therefore, in this paper, the mixing uniformity is considered in a particular plane of the drum-type sprouted brown rice machine to represent the overall mixing uniformity.



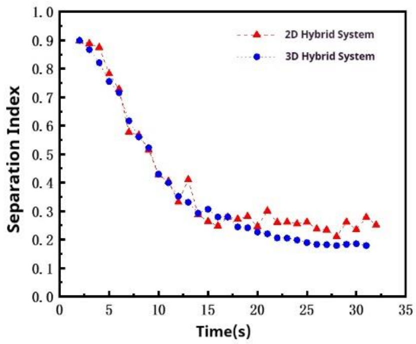
(a) Axial direction



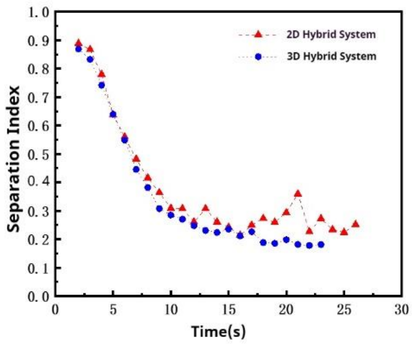
(b) Transverse direction

Fig. 18 - The grid division method of the drum-type sprouted brown rice machine

Fig. 18 divided the entire 3D mixing system of the drum-type sprouted brown rice machine into 384 subdomains, axially divided into 6 layers, each with a thickness of 8 mm (approximately equal to the length of the grain). The horizontal direction was divided into an 8 × 8 square grid. And the 64 subdomains of the first layer were used as the 2D mixing system.



(a) Short particles, rotational speed 30 r/min, 55%



(b) Short particles, rotational speed 35 r/min, 45%

Fig. 19 - Comparison of separation index between 2D hybrid system and 3D hybrid system (tank reduction)

Fig. 19 showed that the separation indices of the two mixing systems were similar in the steady state with the same decreasing trend. However, the 2D system had large fluctuations in the separation index due to the small number of particles. The 2D mixing system uniformity can characterize the overall mixing uniformity of the 3D system. Therefore, the overall mixing uniformity of the particles in the sprouted brown rice machine can be replaced by the lateral mixing on the 3D thin layer.

Brown Rice Grain Mixing Image Processing

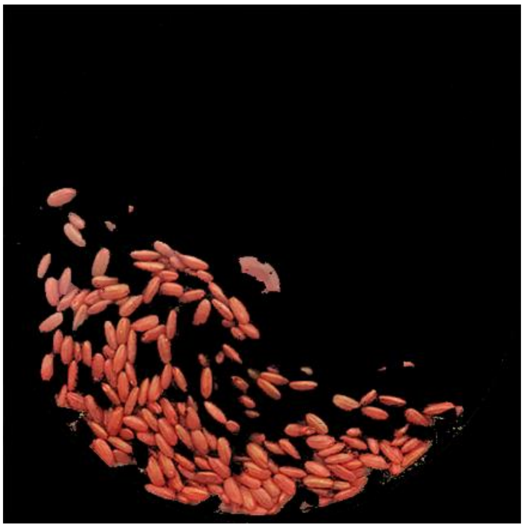
The physical test of brown rice layered particle mixing was carried out at 45% filling degree and 30 r/min rotational speed conditions, and the lateral particle mixing motion was filmed with a high-definition video camera for 40 s. The mixing status was recorded every 5 s.

(a) Original image

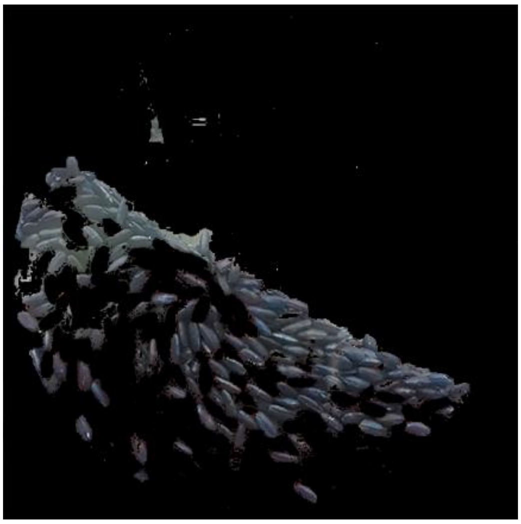
(b) Cropped image

Fig. 20 - Image of particle blending at a mixing time of 5 s

Fig. 20(a) showed the original particle mixing image with a mixing time of 5 s. After cropping process, the middle circular mixing region was retained, as in Fig. 20(b), with a pixel interval of 630*630. To calculate the mixing uniformity, two colors of brown rice needed to be distinguished. The target image was segmented by comparing each pixel point in the image based on the gray level difference using the threshold editor in OpenCV. The distribution map of red and blue pixel points was finally obtained, as shown in Fig. 21.



(a) Distribution of red pixels



(b) Distribution of blue pixels

Fig. 21 - Pixel distribution map of two colors

Then the pixel distribution maps of two colors were divided into 5x5 grids using PS software. The regions of the pixel point distribution maps of the two colors corresponded to each other after segmentation. The grid division image was shown in Fig. 22.

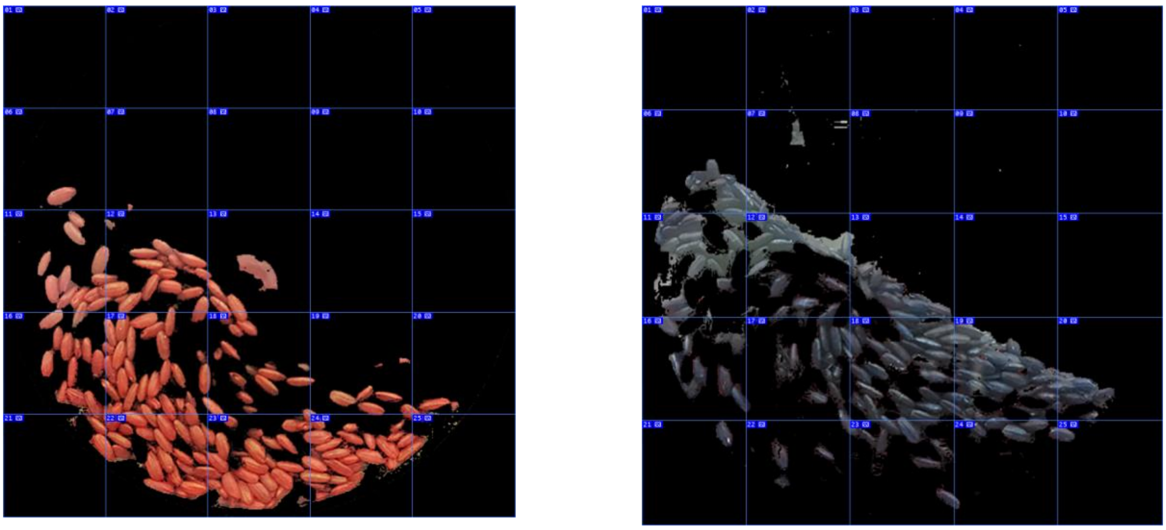


Fig. 22 - Meshing images

(left: red, right: blue)

OpenCV functions analyzed and processed image pixels. The processed image had only two colors, black and red (or blue). Using Python-OpenCV function to extract the number of red (or blue) pixel points in each image, after statistical analysis, it was known that the more pixel points, the greater the proportion of the corresponding color brown rice. After data processing, the separation index value of the mixing moment could be obtained. The whole image processing process was shown in Fig. 23.

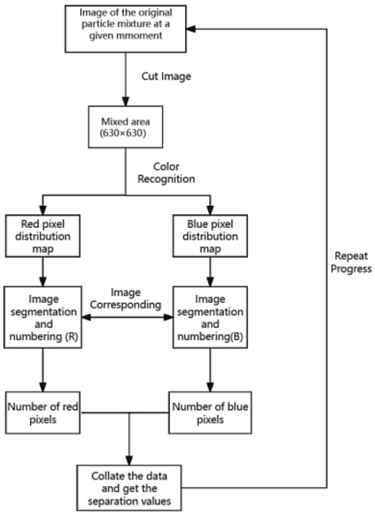
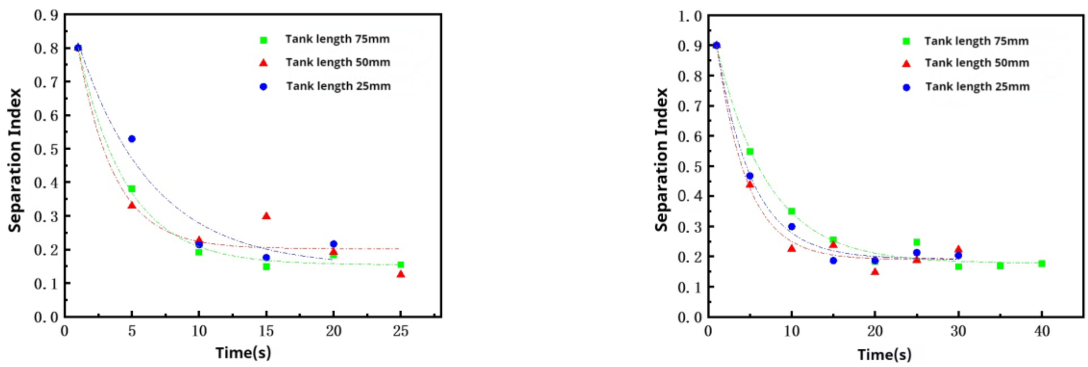


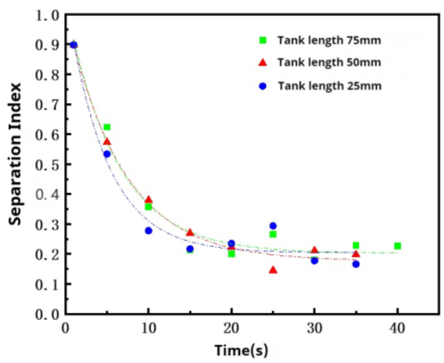
Fig. 23 - Image processing flowchart

Results of mixing uniformity of brown rice grains under physical test conditions

In order to clarify the effect of different transverse planes on the mixing process of brown rice particles, this study compares the change curves of separation index with mixing time for different tank lengths under different filling degree and drum rotational speed, as shown in Fig. 24.



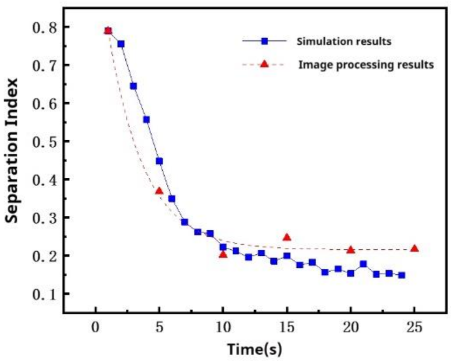
(a) Filling degree: 32% Drum rotational speed: 20 r/min *(b) Filling degree: 45% Drum rotational speed: 30 r/min*



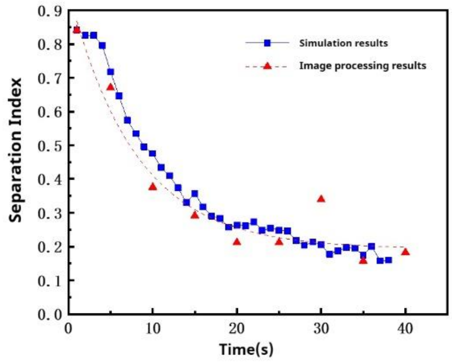
(c) Filling degree: 55% Drum rotational speed: 30 r/min

Fig. 24 - Comparison of separation index of different tank lengths

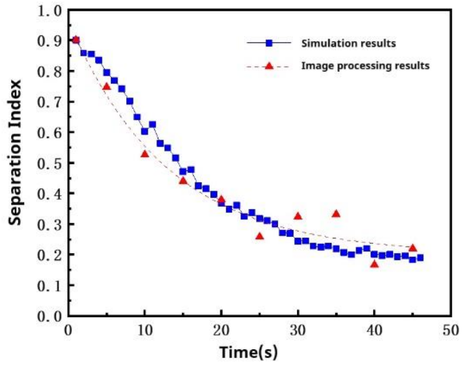
Fig. 24 showed that the trend of particle mixing uniformity with time was the same for different tank mixing depths, and the values of separation index were similar from 0 to 15 s. It indicates that the mixing depth has a small effect on the mixing uniformity of brown rice. This study takes the 75 mm tank as an example to explore the variation rule of separation index with mixing time under physical test and simulation, as shown in Fig. 25.



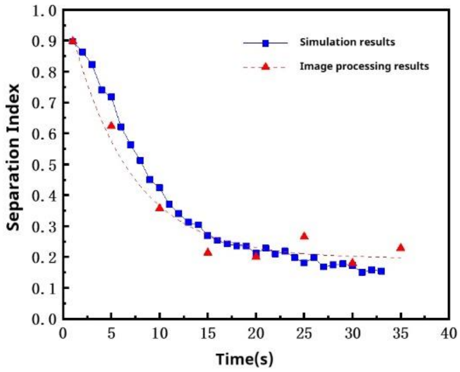
(a) 32% 30 r/min (long particles)



(b) 45% 20 r/min (long particles)



(c) 55% 20 r/min (long particles)



(d) 55% 30 r/min (long particles)

Fig. 25 - Comparison of separation indices of simulation environment and test environment

Fig. 25 showed that the separation index gradually decreased with increasing mixing time, i.e., the particles were mixed more uniformly. The trend of the separation index curves under the simulation and test environments is consistent, with a rapid decline at the initial stage, followed by a slower rate and eventual stabilization. Under the same mixing time, the two separation index values are similar, indicating that the change rule of mixing uniformity is consistent, which verifies the accuracy of the discrete element simulation.

CONCLUSIONS

In this paper, the discrete unit method was used to study the mixing process and movement law of brown rice particles in the tank of two kinds of sprouted brown rice machine. The mixing mechanism of brown rice particles under different mixing process parameters was quantitatively analyzed. And based on the results of the above research, a set of drum type sprouted brown rice machine mixing test platform was built. The accuracy of the discrete element simulation results was verified by physical test based on real brown rice particles. The main conclusions of the whole study are as follows:

(1) Appropriate mixing process parameters can significantly improve the working efficiency and mixing performance of sprouted brown rice machine. When the rotational speed is higher than 20 r/min, the mixing efficiency of the particle system decreases; the lower the filling degree, the higher the mixing efficiency of the particle system.

(2) There was comprehensive consideration of mixing uniformity and energy consumption to determine the optimal mixing process parameters of two kinds of sprouted brown rice machine. Blade type sprouted brown rice machine: filling degree was 40.16%, rotational speed was 20 r/min; Drum type sprouted brown rice machine: filling degree was 37.9%, rotational speed was 20 r/min. Under the optimal conditions for both sprouted brown rice machine tank mixing process parameters, the mixing performance of the blade type sprouted brown rice machine was better than that of drum type sprouted brown rice machine.

(3) A set of drum type sprouted brown rice machine mixing test platform was designed and built. The results showed that the simulation environment and physical test environment of brown rice particles motion state and mixing uniformity change rule is consistent. The accuracy of the discrete element simulation results is verified via the actual brown rice particle physical test.

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