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Research article

Discrete element simulation of brown rice and paddy rice on shaking separator machine

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Abstract

Importance of the work: The operational performance of the tray of a rice separator point is critical to the productivity of a system.

Objectives: To determine the angle effects and the influence of the mixing ratio on the separation efficiency of materials.

Materials & Methods: Rice seed movement was described based on Newton's law and the Hertz-Mindlin contact model. In the simulation, the paddy rice was mixed in the range 5–50%, the tray was angled 3.5–5.0°, the average particle diameter was 2.13 mm and length was 8.38 mm, with 14% wet basis moisture content. The shaking separator machine for brown and paddy rice was evaluated using discrete element simulation and experiments at the same scale.

Results: The simulations predicted the motion of particles very well. The simulation showed that 4.30° was the most appropriate tilt angle of the tray for separating the paddy, with a maximum rejection efficiency of 0.89

Main finding: Several tests or one test with several results are necessary to better select all parameters. The simulation result was confirmed by the experiment in terms of the efficiency of separation and movement on the tray.

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Introduction

The production process of brown rice begins with the paddy rice being cracked by rubber balls that rotate at different speeds (Sawasdee, 2004). Then, the cracked rice is sent to a sieve that separates the brown rice (seed) from the paddy rice (seed). The resulting brown rice is usually mixed with about 5-20% of paddy rice (Sawasdee, 2004). Before packaging the brown rice for sale as a product excluding paddy rice, it is necessary to use a mechanical separator to remove the paddy rice. At present, there are 3 types of seed separators: 1) the compartment-type rice separator, which uses gravity and differences in skin friction of brown rice and paddy rice seeds to separate them; 2) the tray-type paddy rice separator, which uses gravity and differences in the lengths of brown rice and paddy rice seeds to separate them; and 3) the screen-type paddy rice separator, which uses differences in the thicknesses and widths of brown rice and paddy rice seeds to separate them. The tray-type paddy rice separator and screen-type paddy rice separator are less common, with the most popular type being the compartment-type paddy rice separator with a Z-shaped separation channel (Mendis and Jayaratne, 1982).

The most relevant research on the performance of seed separators was conducted by Das (1986), who assembled a machine that separated the paddy rice from the brown rice in a 48 cm × 88 cm tray-type paddy rice separator. Paddy rice, IR 8 and Patnai 23 varieties were tested with the separating tray set at inclination angles of 16.1°, 18.4° and 19.4°, respectively. The crank rod speed was set at 230 revolutions per minute (rpm) with a constant feeding rate of 500 kg/h and the system could mix 80% of paddy and 20% of brown rice. It was found that the inclination angle of 16.1° was the most suitable for separating the paddy rice, with a maximum overall effectiveness of 0.94. Kojima et al. (1993) investigated the separation performance of rice movement and the distribution of brown rice and paddy rice on a shaking tray at various mixing ratios to determine the optimal operating conditions. In addition, Fouda (2009) examined the most suitable conditions for separating brown rice and paddy rice using a screen-type paddy rice separator (model: SATAKE Ps 120E). It was found that the optimal inclination angle of the sieve for minimizing the cracking of the rice was 15° at a speed of 200 rpm, with seed moisture of 14 % on a wet basis (w.b.), with a maximum feeding rate ratio of the machine of 0.8 (the actual feeding rate divided by the maximum feeding rate). Discrete element simulation (DEM) is a numerical computational technique for predicting particle motion developed by Cundal and Strack (1979) that calculates the particle translational and rotational motion as well as the behavior of individual particles within a system. In addition, it can predict collisions between particles and between particles and boundaries (Yang et al., 2008).

Nowadays, it could be argued that with more advanced and less expensive computers, the use of software to simulate the work of rice separators is an alternative to facilitate faster separation, reduce the cost of trial and error and save the time spent on assembly. Seed is a type of bulk material and DEM is a common method used to simulate the particle-particle and particle-metal surface interactions. DEM software has been used to model the Hertz-Mindlin no-slip contact model (Cundal and Strack, 1979) with a spring-dashpot and friction slider in the tangential direction (Tsuji et al., 1992) for particle-particle and particle-wall contacts. According to related research, the DEM model has been applied to accurately predict the behavior of seeds in food engineering, such as simulating the separation of rice from straw using horizontal shaking (Ma et al., 2019), finding the right parameters for a centrifugal seed spreader in an unmanned aerial vehicle (Wu et al., 2020), performing seed modeling to determine the accuracy of flow in a tank (Zhang et al., 2020), separating white rice based on size in a cylinder separator (Meng et al., 2019), separating rice impurities massaged with a cylindrical sieve (Yuan et al., 2018) and conveying rice in the screws of a vertical rice mill (Han et al., 2017).

Sakaguchi et al. (2001) developed the DEM model for the separation of paddy rice from brown rice. They simulated a 2-dimensional DEM model by assuming the seed had a circular shape to predict the separation of paddy rice from brown rice by shaking it in a tray-type paddy rice separator. The shaking frequency was 3.5 Hz with a fixed tray inclination angle of 20°, and an amplitude of the horizontal at 4.0 cm and of the vertical at 4.5 cm. The results showed that the seed movement predicted by the model conformed to the experimental result at moisture contents of 12.8–13.2% w.b. Kannan et al. (2016) applied a CFD-DEM model to predict the separation of gravel from seeds by a screen-type separator. They studied the effects of the shaking speed and the speed of air that was blown through the sieve from the bottom to keep the particles buoyant. It was found that the model showed good prediction compared to the laboratory experiment. The optimal conditions for separating gravel from seeds was with table tilting at 4° and an airspeed of 1.75-2 m/s.

However, the DEM model has not been widely applied to investigate the compartment-type separator. Therefore, the purpose of the current research was to apply the DEM model to study the influence of the inclination of the separating tray and the rate of paddy rice mixture on the effectiveness of the separation of the paddy rice from brown rice in a compartment-type paddy rice separator.

Materials and Methods

Physical properties of materials and parameters

The size and shape of the rice seeds used in the DEM simulation were based on material dimensional measurements randomly selected from all materials (Wangchai et al., 2013). A sample of 200 seed measurements of each particle in the three key particle dimensions were related to the particle length, particle width, and particle thickness (two perpendiculars), respectively, and the materials were measured using a digital Vernier caliper. The mean of the particle diameter was considered as the mean of the rice seed dimensions for all records. The particle shapes and sizes of the rice seeds used were 2.13 mm wide and 8.38 mm long for brown rice, and 2.62 mm wide and 11.33 mm long for paddy rice, giving aspect ratios of 3.93 and 4.32, respectively, as shown in Table 1.

The particle density (ρ_s) of the seed material is the ratio between the material weight and the seed volume and was measured using a stereo pycnometer machine. The bulk density (ρ_b) is the ratio of the mass of the packets of rice per unit volume of the brown rice or paddy rice seeds including the voids between the grains of rice seeds. For the current study, the mass and volume of the brown rice and paddy rice were determined by weighing a cylindrical vessel of known volume (1,000 mL) without either material (brown rice and paddy rice) and then slowly pouring the rice seeds into the cylindrical vessel. The rice seeds were poured and allowed to fall through the conical hopper at a fixed height of 50 mm approximately to the rim of the cylindrical vessel (Figs. 1A and 1B). Any excess rice seeds were removed using a ruler slowly scraped off across the top of the cylindrical vessel, without disturbing the rice seeds that had settled loosely in the cylindrical vessel. This was repeated 15 times and the average was recorded.

Porosity (ε) was calculated from the relationship between the actual material density and the grain density, using the relationship in Equation 1:

$$\varepsilon = (1 - \rho_b) / \rho_s \quad (1)$$

Table 1 Physical and numerical parameters

Type	Parameter	Value
Brown rice (paddy rice)	Density (kg/m^3)	1,522±21(1,481±30)
* Value in parentheses is property of the paddy rice.	Poisson ratio	0.25 (0.25)
	Mass (kg)	0.023813±0.0012 (0.031089±0.0013)
	Shear modulus, G_p (Pa)	1×10^6 (2.6×10^6)
	Dimension L×W×T (mm)	Brown rice (8.38×2.13×2.13)±0.01
		Paddy rice (11.33×2.62×2.62)±0.01
Separating tray	Density (kg/m^3)	7,750
	Poisson ratio	0.32
	Shear modulus, G_p (Pa)	1×10^{11}
Brown rice-Brown rice	Restitution coefficient, e	0.61
Paddy rice-Paddy rice	Coefficient of static friction, μ_s	0.51
Brown rice-Paddy rice	Coefficient of rolling friction, μ_r	0.012
Brown rice-Wall machine	Restitution coefficient, e	0.61 (0.69)
(Paddy rice-Wall machine)	Coefficient of static friction, μ_s	0.51 (0.36)
	Coefficient of rolling friction, μ_r	0.010 (0.011)
Simulation conditions	Frequency of vibration (Hz)	1.86 (fixed)
	Displacement (mm)	78 (fixed)
	Tilt angle of tray, α (°)	3.5-5.0 (0.1 increments)
	Number of particles	20,000
	DEM time step (s)	1.1×10^{-6}
	Simulation duration (s)	150

L = length, W = width, T = thickness of the materials

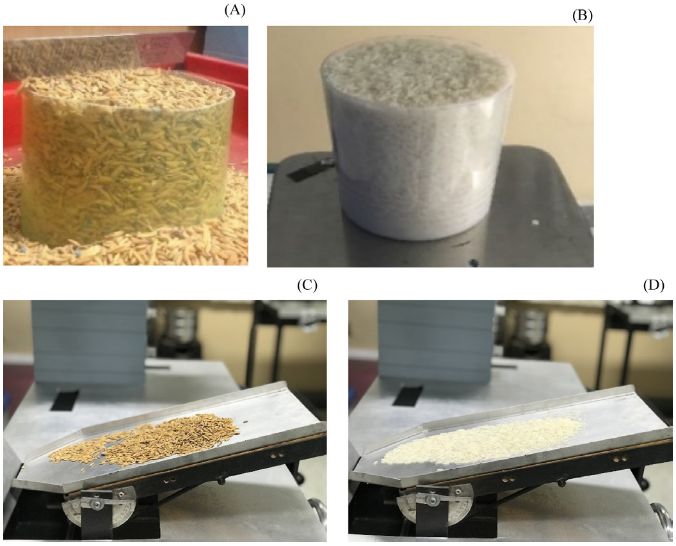

Fig. 1 Experimental apparatus: (A) bulk material of paddy rice; (B) bulk material of brown rice; (C) measuring static friction coefficient of paddy rice; (D) measuring static friction coefficient of brown rice

The coefficient of restitution (*e*) is the ratio of the relative velocity after collision / relative velocity before the collision of the two test materials used for the collision test. However, this velocity can be obtained from the equation of work and energy of motion and ultimately, the velocity is determined by the change in potential energy to kinetic energy. Therefore, the written equation *e* can be written as Equation 2, similar to that described by Batista et al. (2021). The *e* value was calculated as the ratio of the square root of the height of the material after it falls to impact upon the ground and rebounds in the vertical direction (rice seed not rotating) (h_r) and the initial height of the material before it falls and impacts the ground. For this purpose, 25 rice seeds were dropped from an initial height of 250 mm onto the flat surface of the wall.

$$e = (h_r/h_i)^{0.5} \quad (2)$$

There are two coefficients of friction: particle-wall ($\mu_{s(p.w)}$) and particle-particle ($\mu_{s(p.p)}$). The $\mu_{s(p.w)}$ value depends on the rice seeds starting to roll or slide on the inclined steel surface. At this point, the experiment was stopped and the angle of inclination of the steel surface was measured to calculate the value of the coefficient of friction for particle-wall ($\mu_{s(p.w)}$). Similar to other researchers (Hastie, 2010), the coefficient of friction $\mu_{s(p.p)}$ was approximated by the DEM modelling to match the experimental data from the inclination tester and data from the angle of repose. The material on the surface of the sheet was used as the separating tray as shown in Fig. 1C and 1D. The coefficient of static friction (μ_{ss}) was found by adjusting the inclination angle (θ) to raise the sheet up slowly until the material began to move downwards, taking note of the angle, to calculate the coefficient of static friction using Equation 3:

$$\mu_s = \tan(\theta) \quad (3)$$

The coefficient of rolling friction (μ_r) is the relationship between the rolling of materials which occurs for particle-particle ($\mu_{r(p.p)}$) and particle-wall ($\mu_{r(p.w)}$) and was approximated in DEM modelling to match the experimental data (Grima and Wypych, 2011). Rolling resistance between particles was measured indirectly using the translating tube slump tester.

Experimental setup separator machine

The main experiments were carried out at the Faculty of Engineering, Kasetsart University, Kamphaeng Sean campus, Nakhon Pathom, Thailand to study the effects of various engineering and operating parameters on the separation performance of paddy rice and brown rice by a rice separator machine. The mechanical separator to sort the paddy rice used in the current study was a compartment-type paddy rice separator. This machine was used for laboratory work and requires further improvement for pilot-scale manufacture. The physical characteristics of the particle movement behavior experiments developed in the laboratory to verify the DEM simulation results were described in the current study. The physical experiment used in the laboratory for the separation efficiency of the materials (brown rice and paddy rice) involved a rate of 250 kg/h. Further improvement would be required for large-scale industrial production. The shaking frequency and constant displacement can be adjusted by the tilt angle of the separation tray to suit the moisture and physical characteristics of each type of rice. Suphan Buri rice was selected for testing in the current study and the moisture content was controlled at 14% w.b. (moisture not exceeding 14% w.b. is suitable for rice storage). In this experiment, brown rice and paddy rice were mixed in equal proportions by weight, randomly checking the rice to ensure that the mixing ratio was in the correct proportions. Then, the rice was placed into the feed trough and the machine left on until the rice seeds flowed out through the vent within 150 s.

The designed machine imparted a force on the hard wall and through to the seeds as movement on the tray surface. Both brown rice and paddy rice were separated using a vibrating screener due to the difference in rice properties, size, shape, specific gravity, surface friction and the characteristics of brown rice and paddy rice, while the high-speed vibration and inclination of the machine operated at a predetermined separation angle. The differential properties (physical and mechanical) of the brown rice and paddy rice aided the desired separation of rice seeds by the separator machine. This work was carried out based on a designed and validated particle flow on the shaking separator machine whose dimensions (width × length × height) were 620 mm × 820 mm × 750 mm, respectively (see Fig. 2), including a hopper and two chute outlets for brown rice and paddy rice measuring 60 mm × 800 mm. All experiments were carried out at normal room temperature and relative humidity conditions. The percentage separation achieved with this method was in the range 80–90%; the distance travelled by the brown rice and paddy rice was determined.

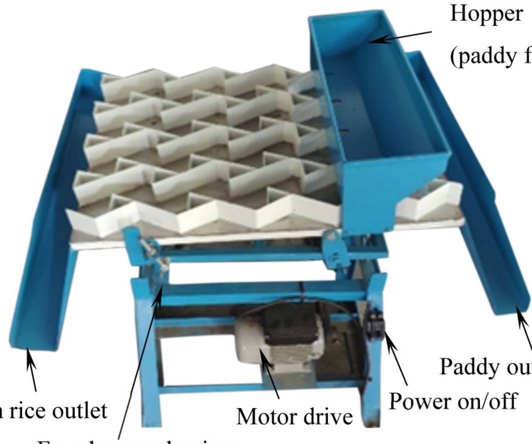

Fig. 2 Compartment-type paddy rice separator machine

An experiment was performed to study the effect of each parameter on the efficiency of the brown rice and paddy rice separator: 1) in total, 16 sixteen different tray surface angles with the horizontal (3.5–5.0°) were tested and the repose angle meter was used to measure the angle between the base and slope of the seeds with an accuracy of 0.01°; 2) Four different percentages of paddy rice mixed with brown rice (5%, 15%, 20% and 50%) were tested; 3) the feeding rate was the ratio of the actual and maximum feeding rates; 4) the yield of the separator productivity was the ratio of the mass of the brown rice seeds (in kilograms) and the time consumed in the separating operation (in hours), with an electric digital balance used to measure the mass of seed samples with an accuracy of 0.1 mg.

The vibrating tray wall was used to sperate the paddy rice from the brown rice. The oscillation of the separation tray affected the movement of the brown rice and paddy on the tray surface; thus the brown rice and paddy rice were vibrated until they had separated. The brown rice and paddy rice were spread on the vibrating tray surface and as they separated, they moved toward the exit end of the tray. Tray vibration was achieved using the multi-link kinematic characteristics of the linear motion of the drive joint and the crank rod mechanism. The behavior of the separation of brown rice and paddy rice on the surface of the vibration tray was influenced by: 1) the weight of the brown rice and paddy rice while moving; 2) the friction force between the brown rice, paddy rice and the tray surface reacting opposite to the direction of movement; and 3) the tray surface was set horizontal or tilted to the horizontal plane, where the inclination angle was selected from the conditions and the angle of the tray surface to the horizontal was less than the friction angle between the materials and the tray surface.

Based on the above conditions, the material did not slide or move on the tray surface when it was stationary. When the tray surface vibrated with a set frequency and amplitude, the movement of the tray surface was transmitted to the material in contact with the tray surface. The material moved by sliding on the tray surface to the exit end of the tray, with some materials losing all contact with the tray surface, which was moving in the reverse direction. Material movement on the tray surface separated the brown rice and paddy rice. Notably: 1) the angle of the tray surface with the horizontal level was determined to be less than the friction angle between the rice seeds and tray surface; 2) the tray surface need to be smooth, slippery and strong (generally, tray floors are made from stainless steel); and 3) at the optimum tray wall speed, the movement of the materials produced the right angle of impact on the vertical wall. The movement of the tray was designed to have an upward collision angle of approximately 60°; at this angle, it impacted the seed material and caused the paddy rice to move upward at the perpendicular angle of impact on the vertical wall. The brown rice had a forward slope and lower friction than the paddy rice, causing slippage during impact. As a result, the movement of brown rice was downward, resulting in separation between the brown rice and the paddy rice.

Mathematical models

The properties of the materials used as input to the DEM simulations was divided into two groups: material and the interactions of the particles and their geometry. The material properties were Poisson's ratio, density and shear modulus, and the interaction properties were the coefficient of static friction, coefficient of rolling friction and the coefficient of restitution. The interactions occurred as particle-particle and particle-environment; the particle shape and particle size distribution were also modelled appropriately. Table 1 summarizes the values of the material properties and the interaction materials.

The current research simulated seed as a soft-sphere model. The soft-sphere model is determined by changing the actual shape from a collision between two particles, assuming displacement instead of actual deformation (Fig. 3). The elastic contact force model causes the particles to lose kinetic energy based on a spring, retardant and slider. A collision between particles (Fig. 3A) or between particles and the wall (Fig. 3B) determines the overlapping distance (δ) and causes displacement and contact force. The movement of each particle allows calculation of the contact force and displacement. The DEM method applies Newton's second law and Hooke's law when there is contact force between particles or between particles and the wall. The size of the overlapping distance at the contact point is directly related to the contact force and the size is minimal compared to the particle size, as explained by the Hertz-Mindlin model (Mindlin and Deresiewicz, 1953) and shown in Table 2. The current study used the EDEM™ commercial software (DEM Solutions Ltd., Edinburgh, UK)

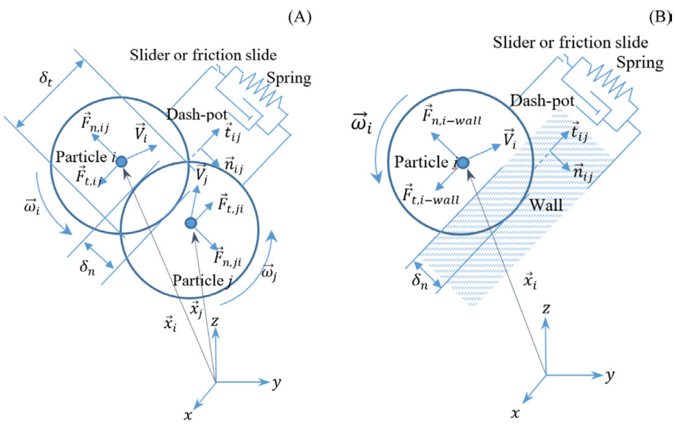

Fig. 3 Illustration of the colliding spheres showing normal overlap and interaction contact forces (Norouzi et al., 2016): (A) particle-particle and; (B) particle-wall, where $\vec{\omega}_i$ and $\vec{\omega}_j$ are rotational velocity of two particles i and j with position vector $\vec{x}_i$ and $\vec{x}_j$, δ_n and δ_t are normal and tangential overlaps, $\vec{F}_{n.ij}$ and $\vec{F}_{t.ij}$ are normal and tangential collision forces, $\vec{F}_{n.i\text{-}wall}$ and $\vec{F}_{t.i\text{-}wall}$ are the normal and tangential collision forces between the particle and the wall, $\vec{V}_i$ and $\vec{V}_j$ are the translational velocity of particles i and j ,respectively.

to simulate the influence of the inclination of the separating tray on the effectiveness of the rice separation. The governing equations for the translational and rotational motion of each particle can be written as

$$m\frac{d\vec{V}}{dt} = \vec{F}_c - m\vec{g} \quad (4)$$

$$I_p\frac{d\vec{\omega}}{dt} = \vec{T}_p \quad (5)$$

where m and Ip are the mass moment of inertia of each particle, V and ω are the translational and rotational velocities of each particle, F_c and T_p are the resultant contact force and couple applied to each particle, respectively. g is the acceleration of gravity.

The differences in the physical characteristics of brown rice and paddy rice are shown in Table 1, which covers the scope of the seven spherical pieces filled (see Fig. 4) based on the multi-sphere method (Norouzi et al., 2016). This method assumes that the particles will not be subject to breakage or invariance in the simulation (Yang et al., 2020; Mirzaei et al., 2013)

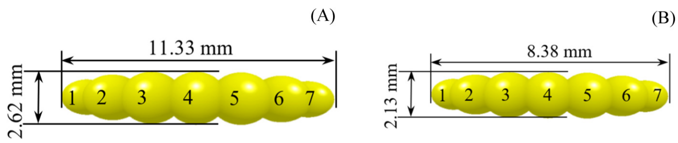

Fig. 4 Constructed multi-sphere model of rice particles used in discrete element simulation: (A) paddy rice; (B) brown rice

Table 2 Hertz-Mindlin contact model (Mindlin and Deresiewicz, 1953)

Parameter	Equation
Normal forces	
- Normal spring force	$F_n^s = -k_n\delta_n^{3/2}, k_n = \frac{4}{3}Y^{eq}\sqrt{R^{eq}}$
- Normal damping force	$F_n^d = -2\beta\sqrt{\frac{5}{4}k_n m^{eq}}\delta_n^{\frac{1}{4}}V_n^{rel}$,By $\beta = \frac{lne}{\sqrt{ln^2e+\pi^2}}$
Tangential forces	$F_t = \begin{cases} F_t^s + F_t^d, if\ \lvert F_t\rvert \le \mu_s\lvert F_n\rvert \\ -\mu_s F_n, if\ \lvert F_t\rvert \le \mu_s\lvert F_n\rvert \end{cases}$
- Tangential spring forces	$F_t^s = -S_t\delta_t, S_t = 8G^{eq}\sqrt{R^{eq}\delta_n}$
- Tangential damping forces	$F_t^d = -2\sqrt{\frac{5}{6}}\beta\sqrt{S_t m^{eq}}V_t^{rel}$,By $\beta = \frac{lne}{\sqrt{ln^2e+\pi^2}}$
Rolling friction torque	$T_r = -\mu_r F_n R_i \omega_i$

Y^{eq}, R^{eq}, m^{eq}, δ, k_n, S_t, μ_s and μ_r = Young's modulus, equivalent radius, equivalent mass, particle overlap, normal spring stiffness, tangential spring stiffness, coefficient of sliding friction, and coefficient of rolling friction; β = damping factor which is a function of the restitution coefficient (e).

For accurate DEM simulation, the particle properties of the brown rice and paddy rice were determined, coupled with compatibility with the stainless-steel plates and vertical plates (Z shape), as shown in Table 1. Based on previous observations of several materials, the assumption was that mono-sized materials have the same characteristics as brown rice and paddy rice (Wangchai et al., 2016).

Fig. 4 indicates that the spheres were partially overlapped to simulate the oval shape of the rice seed. Increasing the spheres formed shapes, similar to rice seeds. However, this required a high-performance computer and more time to simulate the problem.

The rice separator experiment is shown in Fig. 2, while Fig. 5 presents a schematic diagram of the rice separator machine used in EDEM™.

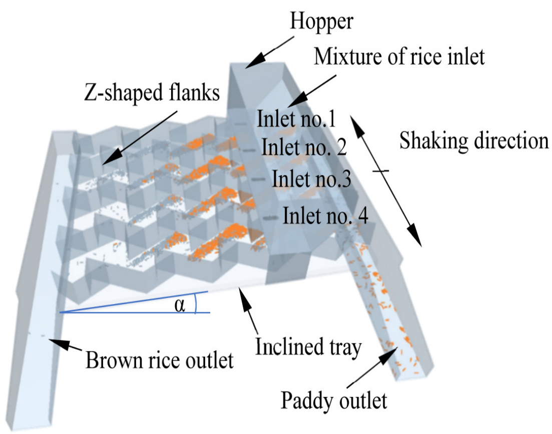

Fig. 5 CAD model of compartment-type paddy rice separator

This study used a computer to simulate brown rice and paddy rice on the shaking separator machine, with 16 GB of random access memory and four processor cores on an HP z240 workstation with GPU (Nvidia Quadro K2200). The total simulation run time was 150 s and the processing time was in the range 80–110 h, depending on the particle size and spherical combination to achieve the particle size required for the simulation. The material movements on the shaking separator machine were investigated using DEM simulations, with 16 differently angled tray surfaces. The material flow for the simulation was randomly generated, allowing the particles to fall by gravity without an initial velocity from the material discharge plane. They fell from above the loading start of the hopper. The rice seeds (brown rice and paddy rice) were in a homogeneous mixture at the beginning of the simulation and were randomized at a specified rate and continuously discharged onto the shaking separator machine through the injection plane. After that, the brown rice and paddy rice on the shaking separator machine ran for a total of 150 s in all simulated cases.

Effectiveness of separation

Fouda (2009) and Modi and Parkar (1979) applied Equation 6 to find the effectiveness of the separation to be used as an index for separating the paddy rice from the brown rice. The separation effectiveness between brown rice and paddy rice was assigned a value from 0 to 1. An efficacy of separation equal to 1 indicates that 100% of the paddy rice was separated from the brown rice.

$$E = \frac{X_b(X_s - X_p)(X_b - X_s)(1 - X_p)}{X_s(1 - X_s)(X_b - X_p)^2} \qquad (6)$$

where E is the fraction of the effectiveness of separation, X_b is the weight fraction of brown rice in the collection from the brown rice outlet of the separator machine, X_p is the weight fraction of brown rice in the collection from the paddy rice outlet of the separator machine and X_s is the weight fraction of brown rice for the sum of the collections from the brown rice and paddy rice outlets of the separator machine.

Results and Discussion

Movement trajectory of seeds

In this model, 10,000 seeds of brown rice and paddy rice were randomly located and thoroughly mixed to make a total of 20,000 seeds in the system. Then, the mixture of brown rice and paddy rice was released into the hopper. The seeds moved by gravity through four open, splitting channels to limit the mass flow rate into a tray with 4 Z-shaped splitting channels, as shown in Fig. 6. The machine tray vibrated at 1.86 Hz with 78 mm displacement and a tray inclination of 4.0°. The parameters are presented in Table 1 and Fig. 6, showing two seeds randomly selected and analyzed for their motion trajectory. The seeds moved on the tray, collided with the Z-shaped zigzag wall and then collided with other seeds. The paddy rice had less friction and a more buoyant force than the brown rice, so the paddy rice seeds moved up and out through the top outlet. The brown rice had greater friction and density, so the brown rice seeds moved along the Z-shaped channel to the outlet at the bottom.

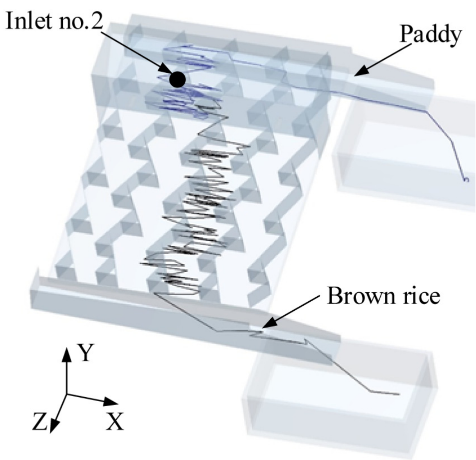

Fig. 6 Moving trajectory for selected brown rice and paddy rice seeds at t = 30 s of simulation

Fig. 7 shows the average velocity of the selected brown rice and paddy rice seeds along the x-axis direction as a function of the simulation time. The average velocity of the seeds fluctuated between -0.85 m/s and 0.89 m/s. The paddy rice seed had an oscillating speed of only 22 s as it moved from the separating tray and fell to the bottom box until it reached zero movement speed. The brown rice seed kept its zigzag movement speed until 30 s of simulation and then fell into the bottom box.

Fig. 8 shows the distance from the reference position (Inlet no. 2). It was found that the paddy rice kernels had a shorter moving distance than the brown rice seeds because the brown rice seeds travelled a longer distance along the zigzag slit, which took more time than for the paddy rice.

Influence of inclination on effectiveness of separation

An essential parameter of the vibration technique is the inclination angle of the tray, as the frictions between the two seed surfaces and the tray base are different. When the tray moved in a back-to-back horizontal line, the force acted on the seed until its force was greater than the friction. The brown rice and paddy rice movement occurred at different velocities, depending on the rice size, rice shape, the specific gravity of the rice seed, the shape of the rice and the contact area between the rice and tray surface, the smoothness of the sloping surface and the coefficient of sliding and rolling friction. The seed slid against the zigzag wall and collided with other seeds along the way. As the shaking continued, the seed became slightly buoyant, causing it to move along the slope of the tray.

In this simulation, the angle of the separating tray was adjusted from 3.5° to 5.0° by adding an inclination angle of 0.1° to simulate the material separation of 20,000 seeds in the range 0–150 s. For the measuring weight in the simulation, one weight sensor was used with a bin group in the EDEM™ software. The mass sensor was attached to measure the weight of the rice that flowed to the rice outlet. Next, the weight of that rice was used to calculate the E value using Equation 6. The E value was selected to consider a suitable inclination angle.

From Fig. 9, it was evident that in the range 0–5 s, the E value was equal to zero because, in the beginning, the seed moved within the zigzag channel, so it was impossible to calculate the E value. The brown rice seeds are smaller,

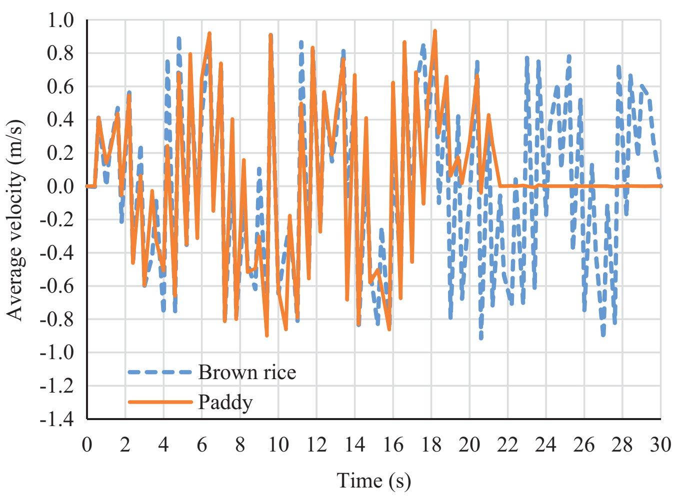

Fig. 7 Average velocity of selected brown rice and paddy rice seeds along x-axis direction

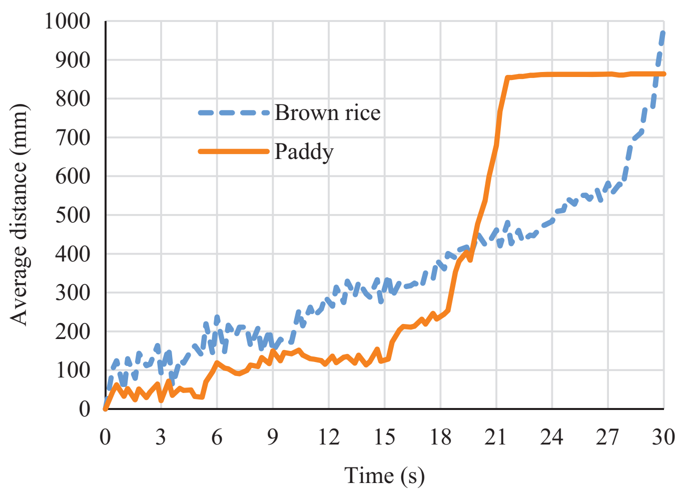

Fig. 8 Average moving distance of selected brown rice and paddy rice kernels (refer to Fig. 6)

heavier, rounder, and smoother and so slide faster than paddy rice seeds. After the two types of seed began to separate, the paddy rice seeds moved into the paddy rice outlet, while the brown rice seeds moved into the brown rice outlet.

As shown in Fig. 9, the inclination angle of the tray α = 4.3° had a maximum E value of 0.86. This angle was suitable for separating paddy rice from brown rice in this research. The E value increased from 20 s onwards and decreased after 45–150 s. As shown in Fig. 9, the low E value of the separator at a higher inclination angle was possibly due to the low conveying velocity of the paddy rice. The seed moved continuously after 90 s of simulation. Decreased efficiency of the machine was observed with no material flow in the outlet.

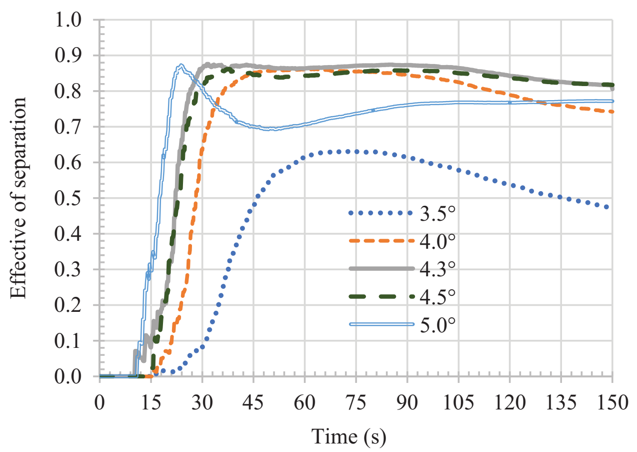

Fig. 9 Effect of inclination angle on separation efficiency at rate of 50% paddy rice mixture over different periods

Fig. 10 shows the seed weight at the brown rice and paddy rice outlets during separation, when the inclination angle of the tray was increased from 4.3° to 5.0°. As illustrated in Figs. 10A and 10B, when the inclination angle increased, the paddy rice could not pass through the top outlet because of friction. Therefore, it flowed and mixed with the brown rice and passed through the brown rice outlet. This resulted in a decrease in the effectiveness of the separation (see Fig. 9). Setting the inclination angle at less than 4.3° resulted in more brown rice seeds being passed through the paddy rice outlet, causing a reduction in the separation effectiveness.

Influence of paddy rice mixture ratio on effectiveness of separation

From the previous topic, the most effective inclination angle of the tray for separation was 4.3°. This inclination angle was applied as the condition to simulate the E values from different paddy rice ratios of 5%, 15%, 20% and 50% of the mixture. Fig. 11 illustrates the effectiveness of separation for these various paddy rice mixtures at different times during the simulation. The calculated E values were not significantly ($p < 0.05$) different. The results showed that greater percentages of paddy rice in the mixture resulted in higher effectiveness in separating the brown rice. The maximum effectiveness of separation was 0.89 at 50% of the paddy rice mixture rejection effectiveness. There was no significant difference in the effectiveness of separation between paddy rice ratios of 15% and 20%. However, the effectiveness of brown rice separation between 50% and 5% paddy rice ratios were significant ly ($p < 0.05$) different.

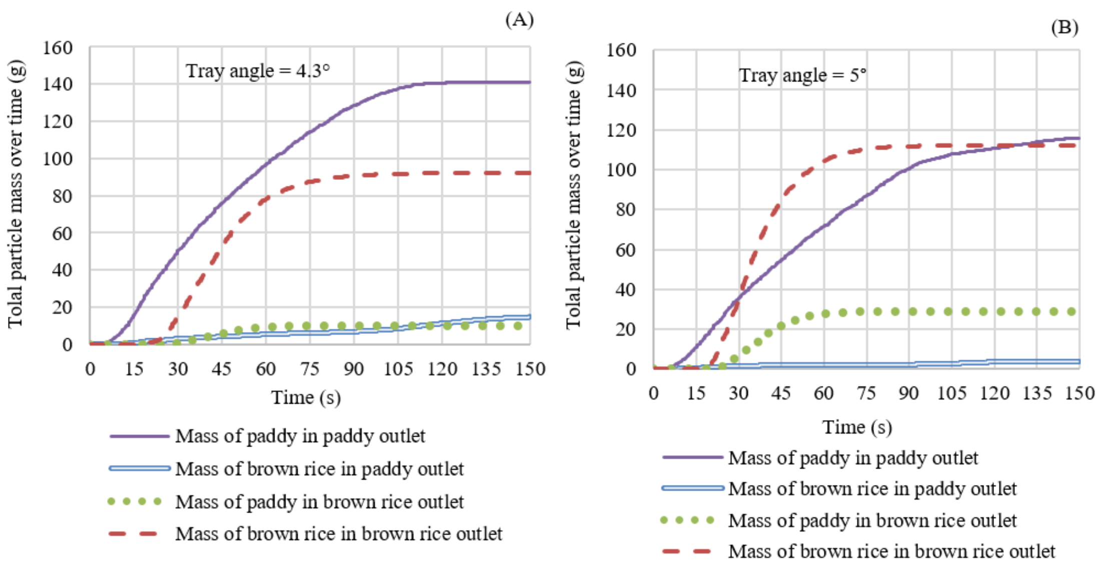

Fig. 10 Mass of rice flowing out of machine during separation according to different periods at rate of 50% paddy rice mixture at tray angle of: (A) 4.3°; (B) 5.0°

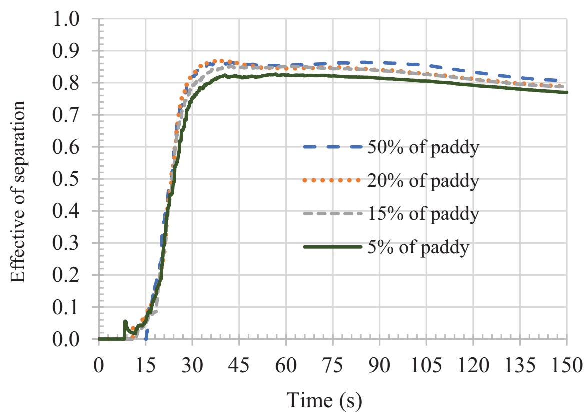

Fig. 11 Influence of paddy rice ingredients on separation efficiency at 4.3° for different times

Verifying test results analysis

Comparing the results of the test with the simulation, the appropriate angle (4.3°) was used to determine the tilt of the separating tray using a digital inclinometer (accuracy ±0.1; GemRed 82412, China), as shown in Fig. 12. In the experiment, the seeds that were sorted in each outlet were counted and the E value was calculated according to Equation 6.

Fig. 13 compares the experimental and simulation results for the material separation with the inclined angle of the tray set at 4.3° (an appropriate value for this research). Motion was imparted to the material in contact with the tray surface when the tray was agitated at a specific frequency and amplitude. As shown in Fig. 13, the acceleration of the rice mass had a force in the opposite direction to the inertia force. Furthermore, the weight of the brown rice and paddy rice directed a downward force and the friction force between the brown rice, paddy rice and the tray surface acted in the opposite direction to the motion. The movement of the materials in this case was affected by differences in the coefficient of static friction and the size and density of each material. In this case, the coefficient of static friction for tray-brown rice was higher than that of tray-paddy rice (the contact surface of the paddy was lower than for the brown rice), so the brown rice moved forward (bouncing) less than the paddy movement on the machine; thus, the two materials move separately with multiple layers. Only a sliding motion over the tray towards the delivery end, in the reverse direction, or loss of all contact between the material and the tray surface were the possible types of brown rice and paddy rice motion. As depicted in Fig. 13,

Fig. 12 Digital inclinometer used to measure tray tilt in degrees

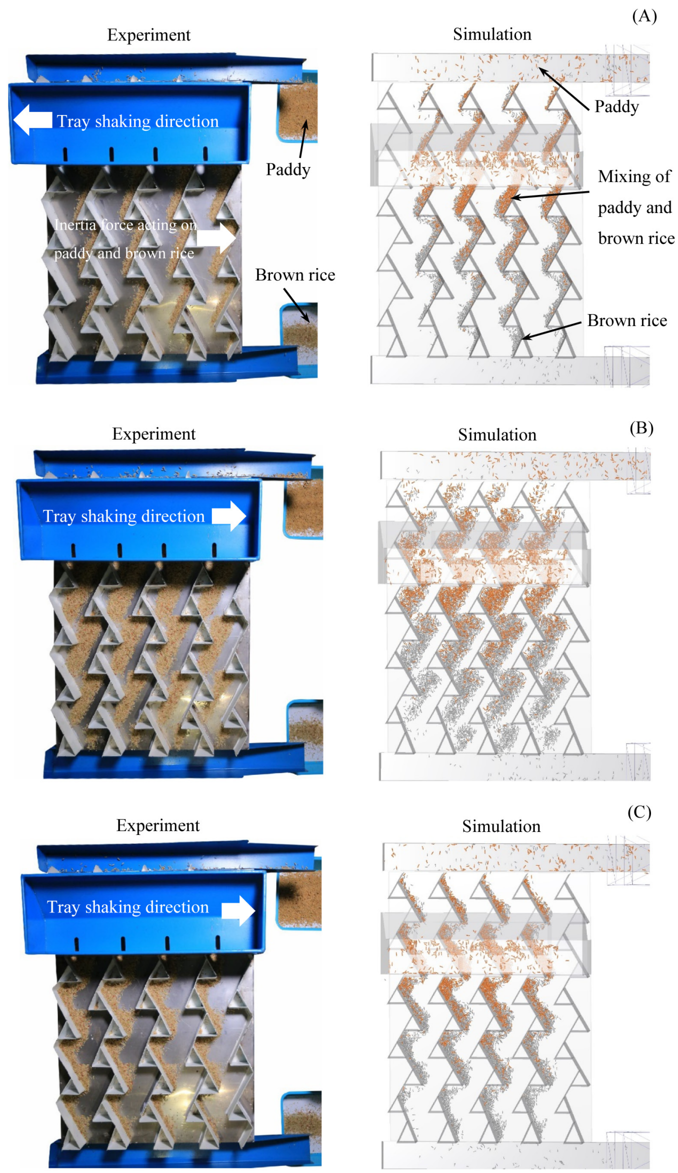

Fig. 13 Movement of paddy rice and brown rice for different tray displacements: (A) -39 mm; (B) 0 mm; (C) +39 mm, for rate of 50% paddy rice mixture and 4.3° tray angle

the paddy rice seeds (orange) moved out via the top outlet, while the brown rice seeds formed a separate layer from the paddy rice and slowly flowed down to the bottom outlet. The simulation results were consistent with the experimental value (E value from this study was 0.91). In addition, the experimental results compared favorably with the effectiveness of separation (E) with a tray-type paddy rice separator, which had E values in the range 0.90–0.94 (Das, 1986) and with a screen-type paddy rice separator, which had an E value of 0.95 (Fouda, 2009).

Although the compartment-type separator had a lower E value, it was distinctively different in terms of complexity, maintenance and pricing. Taking the rice that comes out of the separator back into the hopper also increases the E value. If the appropriate angle value in this research were applied in the same compartment-type separator, it might be highly effective for paddy rice separation without further experimentation. However, in practice, the material used to make the surface of each tray separator machine may not be the same and may have a different static friction coefficient. Finally, the simulation results for other metal separator trays and experiments with other species of rice at different moisture content levels are also needed to confirm the effectiveness of this model. Further research is needed to study the influence of the frequency of vibration and displacement of trays on the effectiveness of separation.

Conclusions

A numerical model of the machine used to separate paddy rice from brown rice by shaking using a discrete element method predicted the experimental results with a high degree of accuracy. The inclination angle and rice mixture ratio affected the effectiveness of separation (E). When the paddy rice ratio in the mixture increased, the effectiveness of separation increased. The most suitable inclination angle of the tray was 4.3^{o} for the separation of paddy rice from brown rice, with a maximum effectiveness of separation of 0.89 (14% w.b. moisture content). The developed mechanism of separation could be utilized in separating particles of similar size and shape but with differing friction characteristics.

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