STUDY ON THE IMPACT-BLOCKING EFFECT BETWEEN GRINDING MEDIA AND WHEAT BRAN POWDER DURING THE VIBRATION CRUSHING PROCESS

/

振动粉碎过程中磨介与小麦麸皮粉体间的冲击阻滞效应研究

Min CHENG*[1)], Haocong MENG[1)], Guangbo XIANG*[2)], Shihao ZHOU[1)], Mingxu WANG[1)], Baoguo LIU[1)]

[1)] School of Mechanical and Electrical Engineering, Henan University of Technology, Zhengzhou / China;

[2)] School of Mechanical Engineering, Zhengzhou University of Science and Technology, Zhengzhou / China

Corresponding author: Min Cheng, Tel: +86-18623710936; E-mail: chengminhappy2006@163.com,

Guangbo Xiang, Tel: +86-18625520309; E-mail: xianggpo@163.com

DOI: https://doi.org/10.35633/inmateh-76-34

Keywords: *wheat bran, vibration mill, impact-blocking effect, powder particle size, grinding media diameter, damping coefficient*

ABSTRACT

During the vibration crushing of wheat bran, an impact-blocking effect occurred between the grinding media and wheat bran powder. Experimental results showed that the impact depth exhibited quadratic relationship with respect to particle size, while the acceleration and damping coefficients followed the order: fine powder > coarse powder > uncrushed bran > micro powder. Increasing the diameter of the grinding media enhanced the impact depth by 81.10% for uncrushed bran and by 40.41% for coarse powder, but reduced acceleration by 45.35% and 29.56%, respectively. Damping coefficients positively correlated with grinding media diameter but negatively with cylinder diameter. Material layer thickness demonstrated threshold-dependent bidirectional regulation, peaking at 40 mm, with maximum damping difference rates of 20.40% for uncrushed bran and 17.67% for coarse powder. Drop height linearly influenced the impact depth, while showing cubic relationships with both acceleration and damping. Both parameters were minimized at 500 mm. Sensitivity analysis identified grinding media diameter as the primary factor affecting damping coefficients, revealing the sensitivity hierarchy: grinding media diameter > drop height > material layer thickness > cylinder diameter. This study provided a theoretical foundation and experimental support for optimizing the vibration superfine crushing efficiency of wheat bran.

摘要

在振动粉碎小麦麸皮时，磨介与粉体间存在冲击阻滞效应。实验表明，冲击深度与粉体粒度呈二次非线性关系，加速度、阻尼系数大小顺序为：细粉 > 粗粉 > 未粉碎麸皮 > 微粉。增加磨介直径可使未粉碎麸皮和粗粉的冲击深度分别增加 81.10% 和 40.41%，加速度降低 45.35% 和 29.56%。阻尼系数与磨介直径正相关，与圆筒直径负相关。料层厚度对各参数有双向调控作用，临界厚度为 40mm。下落高度与冲击深度线性相关，与加速度、阻尼呈三次非线性关系，500mm 时二者取极小值。灵敏度分析显示，磨介直径是影响阻尼系数的主因，灵敏度顺序为：磨介直径 > 落差高度 > 料层厚度 > 筒体直径。该研究为优化小麦麸皮振动超微粉碎效能提供依据。

INTRODUCTION

Wheat bran is rich in essential nutrients such as protein, dietary fiber, vitamins, and minerals. Its superfine powder has shown significant application potential in the development of functional foods, pharmaceutical excipients, and biochemical research (*Praveenet et al., 2023; Zheng et al., 2022; Ying et al., 2022*). However, the high lignocellulose content in its structural layers poses a major challenge for conventional grain crushing equipment, which often fails to achieve the required superfine particle size (<25 μm) (*Hemery et al., 2011*). Vibration mills, leveraging comprehensive crushing actions including impact, shearing, extrusion, and friction, have emerged as a promising solution for wheat bran superfine crushing (*He et al., 2018; Rajaonarivony et al., 2021*). During the vibration process, wheat bran particles in the grinding cylinder are subjected to continuous crushing forces from grinding media, while imposing a blocking effect that hinders media movement, reduces collision velocity, and consumes energy (*Bulgakov et al., 2018*).

[1]*Min Cheng, Lecturer Ph.D.Eng.;* [1]*Haocong Meng, M.Stud.Eng.;* [1]*Guangbo Xiang, Lecturer M.S.Eng.;* [2]*Shihao Zhou, M.Stud.Eng.;* [1]*Mingxu Wang, Prof. Ph. D. Eng;* [1]*Baoguo Liu, Prof. Ph. D. Eng.*

This bidirectional impact-blocking interaction directly influences grinding media dynamics and energy transmission, thus determining the overall crushing efficiency.

Current research on vibration mills focuses on grinding media dynamics, crushing process optimization, and media-material interaction mechanisms. High-speed cameras and the discrete element method (DEM) have been applied to analyze media dynamics. The former confirmed three motion forms of spherical media: impact, total rotation, and self-rotation, while DEM studies on non-spherical media remain limited. *Yokoyama et al. (1996)* simulated 2D media motion, analyzing collision characteristics and grinding rate. *Lee et al. (2010)* established an impact model for media-material grinding, and *Yang et al. (2015, 2016)* studied media flow dynamics under different vibration conditions.

In the optimization of vibration crushing process efficiency, DEM and experimental research methods are typically employed to investigate the effects of vibration characteristics, grinding media properties, filling rate, crushing time, and other factors on the crushing efficiency mechanism of vibration mills. *Li et al. (2015)* discovered that grinding media size correlates with power density, achieving a 42% increase in griseofulvin dissolution through process optimization. *Yang et al. (2016)* demonstrated that medium-frequency and large-amplitude operation of double-mass vibration mills optimizes super hard particle crushing, refining diamond to a median particle size (D_{50}) of 0.26 μm. *Bogdanov et al. (2019)* proposed a poly-harmonic vibration mill with adjustable multi-parameters to enhance crushing efficiency. *Qian et al. (2023)* revealed that amplitude-frequency coupling dominates particle crushing, developing a model that reduced calcium carbonate crushing energy consumption by 29.2%. *Haddad (2020)* identified rotating mass as a key factor, determining optimal conditions (1500 rpm, 16 mm media, 222 g rotating mass) for minimal grinding time. *Yildirim et al. (2025)* recently achieved the multi-objective optimization of the dry grinding of hydrated lime in a vertical vibratory mill, producing powders with a D_{50} of 6.26 μm and a specific surface area of 2.71 m²/g.

Concerning the interaction between grinding media and materials and the grinding mechanism, it primarily reveals the formation process of impact, compression, shear, friction, and other mechanisms through which grinding media in the grinding cylinder act on the crushed material, as well as their influence on the crushing effect. *Frolov et al. (2017)* found ceramic media had 30-50% lower wear than steel, with cylindrical shapes reducing contamination. *Cheng et al. (2019, 2021)* showed particle size affects crushing mechanisms (impact extrusion for large particles, impact shearing for small) and media properties (density, size, shape) influence yield by up to 70.07%. *Tomach (2024)* reported a grinding time that was 22.5% shorter with 15 mm media than with 12 mm media. Notably, research on materials' reverse influence on media dynamics remains scarce, with most studies relying on indirect evidence via particle size or moisture comparisons.

To investigate the impact-blocking effect between the grinding media and wheat bran in the vibration crushing process, this study constructed a grinding media-wheat bran powder impact test platform. Wheat bran powder with different particle sizes was used to simulate various stages of wheat bran crushing, material layer thickness simulated the bran filling amount, drop height simulated the impact velocity of the grinding media, and grinding media diameter and cylinder diameter directly represented the geometrical dimensions of the grinding media and the cylinder. Using impact depth, average acceleration, and damping coefficient as key indicators, this study systematically investigated the effects of wheat bran particle size, grinding media diameter (8–16 mm), cylinder diameter (60–180 mm), layer thickness (20–60 mm), and drop height (400–800 mm) on the impact-blocking effect. On this basis, a sensitivity analysis was conducted to rank the influence of factors on damping coefficients. The study aims to provide both theoretical foundations and practical guidance for optimizing vibration mill efficiency in wheat bran superfine crushing.

MATERIALS AND METHODS

Preparation of wheat bran powder samples

The raw material of wheat bran was Zhengmai 379, produced in 2024 and purchased from Zhengzhou Jinyuan Flour Mill. During the experiment, materials passing through a 5 mesh sieve and retained by a 20 mesh sieve were taken as wheat bran samples, with an adjusted moisture content of approximately 10.65%. To simulate the different crushing stages of wheat bran in a vibration mill, the samples were pre-crushed in a vibration mill prior to the experiment. The crushed samples were then sieved and classified, yielding four types of powder: uncrushed bran (d_A > 900 μm), coarse powder (280 μm < d_A < 900 μm), fine powder (74 μm < d_A < 280 μm) and micro powder (d_A < 74 μm). Their morphologies are shown in Fig. 1.

a. Uncrushed bran b. Coarse powder c. Fine powder d. Micro powder

Fig. 1 - Wheat bran powder samples

Experimental principle and platform

To investigate the impact-blocking effect between grinding media balls and wheat bran powder during vibration crushing, a test platform for the impact mechanical properties of wheat bran powder was constructed based on the free–fall principle, as shown in Fig. 2. This experimental platform mainly consists of a height-adjustable support, an electromagnet capable of adsorbing the grinding media balls, and a plexiglass cylinder filled with wheat bran powder (*Seguin et al., 2008*).

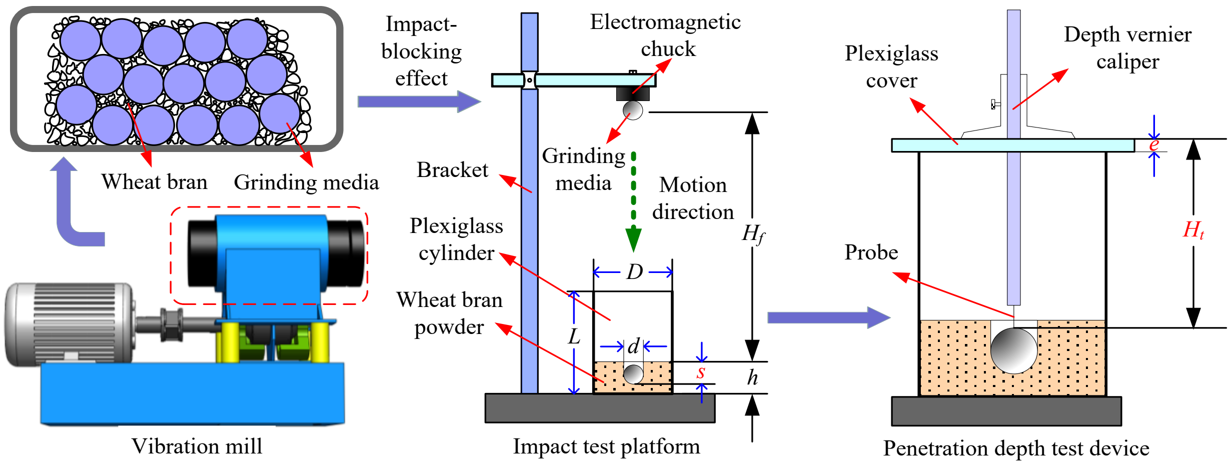


Fig. 2 - Grinding media-wheat bran powder impact test platform

d - grinding ball diameter; D - cylinder diameter; e - plexiglass cover plate thickness; h - material layer thickness; H_f - grinding ball height from material surface; H_t - distance between depth gauge base and probe; L - cylinder height; s - grinding ball impact depth in bran powder

During the experiment, the height of the grinding media is first adjusted, then the grinding media is aligned with the center of the cylinder and the power supply to the electromagnet is disconnected. At this point, the grinding media will continuously accelerate under the effect of gravity until it contacts the surface of the bran powder and starts to decelerate, and finally stops at a certain depth due to the resistance of the bran powder. To measure the impact depth of the grinding media, a probe is installed at the bottom of the depth gauge, and a glass cover plate is installed at the top, forming a gauge that allows direct read of the impact depth of the grinding media ball. After the experiment, first gently brush away the bran powder above the grinding media; then, touch the probe of the depth gauge to the upper surface of the grinding ball and read the distance H_t between the depth gauge's measuring base and the probe. Finally, the impact depth of the grinding ball s as it penetrates into the bran powder can be calculated using the mathematical relationship among the cylinder height L, grinding ball diameter d, and plexiglass cover plate thickness e.

Experimental scheme

Numerous impact test studies on powder or granular materials have shown that factors such as the particle size of the powder or granules, the size of the impacting object, the cylinder diameter, the material layer thickness, and the drop height (or impact velocity) can all affect the impact mechanical properties (*Ji et al., 2012, 2016; Wang and Ji, 2018*). To explore the impact-blocking effect between the grinding media balls and the wheat bran powder, the bran powder particle size, grinding media ball diameter, cylinder diameter, material layer thickness, and drop height were selected as experimental conditions. A series of tests were conducted to investigate the effect of grinding media balls on wheat bran powder.

The objectives were to simulate different crushing stages of wheat bran by using powders with different particle sizes, to simulate the boundary effect of the grinding cylinder by using cylinders with different diameters, to simulate the filling rate of bran by using material layers with different thicknesses, and to simulate the impact velocity of the grinding media balls by using different drop heights.

During the experiment, one experimental condition was selected as the variable, while the other four were kept constant. The specific experimental design is shown in Table 1. To improve the reliability of the results, each group of experiments was repeated at least 10 times. To reduce experimental errors, unreasonable test data such as extreme values were excluded. To eliminate the impact of the cylinder's boundary effect, the cylinder diameter was required to be more than 5 times the grinding media ball diameter (*Ji et al., 2012*). As shown in Table 1, the diameters of the media balls and cylinders meet this requirement. The masses of the grinding media balls with different diameters listed in Table 1 were 2.14 g, 4.17 g, 7.23 g, 11.45 g, and 17.06 g, respectively.

Table 1

Experimental scheme

Experimental factors	Variable experimental conditions					Constant experimental conditions			
	NO.1	NO.2	NO.3	NO.4	NO.5	Grinding media diameter [mm]	Cylinder diameter [mm]	Material layer thickness [mm]	Drop height [mm]
Powder particle size [μm]	5-20	20-60	60-200	<200	—	10	90	30	500
Grinding media diameter [mm]	8	10	12	14	16	—	90	30	500
Cylinder diameter [mm]	60	90	120	150	180	12	—	30	500
Material layer thickness [mm]	20	30	40	50	60	10	90	—	500
Drop height [mm]	400	500	600	700	800	10	90	40	—

Experimental evaluation indicators

To simulate and analyze the impact-blocking effect between the grinding media ball and the bran powder in the grinding cylinder of the vibration mill, the impact depth of the grinding media ball in the bran powder, the average acceleration of the grinding media ball after being blocked by the bran powder, and the average damping coefficient were selected as evaluation indicators.

According to Fig. 2, the impact depth of the grinding media ball can be obtained as:

$$s = H_t + h + d - e - L \tag{1}$$

Assuming that the grinding media ball undergoes uniform deceleration while impacting through the wheat bran powder, its average acceleration can be calculated from Fig. 2 as:

$$a = \frac{gH_f}{H_t + h + d - e - L} \tag{2}$$

Where: *a* is the average acceleration, m/s^2; *g* is the gravitational acceleration, 9.8 m/s^2.

By neglecting the elastic compression effect of the grinding media ball on the wheat bran powder during the impact process and the frictional energy consumption between the powder particles, the average damping coefficient of the bran powder acting on the grinding media ball is derived as:

$$c = m\sqrt{2gH_f}\left(\frac{1}{H_f} + \frac{1}{H_t + h + d - e - L}\right) \tag{3}$$

Where: *c* is the average damping coefficient, Ns/m. During the experiment, H_f, *h*, *d*, *e*, and *L* are known parameters. By measuring H_t with a depth gauge and substituting it into Eqs. (1), (2), and (3) respectively, the specific values of evaluation indicators *s*, *a*, and *c* can be determined.

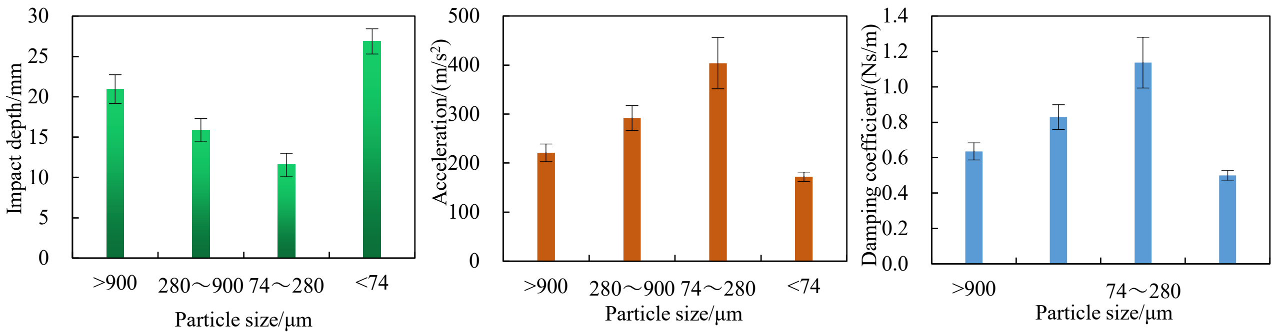
RESULTS

Influence of powder particle size on the blocking effect of wheat bran powder

Fig. 3 shows the variations in the impact depth, acceleration, and damping coefficient when grinding media balls impact four types of wheat bran powders respectively. Under the same impact conditions, as depicted in Fig. 3 (a), the impact depth exhibits a quadratic nonlinear trend of first decreasing and then increasing with decreasing powder particle size.

The average acceleration of the grinding media balls and the damping coefficient of the wheat bran powder both demonstrate a quadratic nonlinear pattern: they first increase and then decrease. This pattern is exactly opposite to the trend of the impact depth, as shown in Fig. 3 (b) and Fig. 3 (c).

When the bran powder particle size is relatively large, the inter-particle voids are large, and the powder fluidity is good. When the grinding media balls penetrate, the resistance mainly originates from the frictional force between the particles and the grinding media surface. At this point, the resistance is relatively small, leading to a large impact depth. When the powder particle size is moderate, the inter-particle voids decrease, and powder fluidity diminishes. During media ball penetration, the particle collision frequency increases, as does the resistance to particle rearrangement. Here, the resistance reaches a maximum, and the impact depth attains a minimum. When the powder particle size is relatively small, the inter-particle voids further decrease, and the powder fluidity significantly declines. During grinding media ball penetration, the inter-particle collision resistance decreases, and the particles become more flowable. The resistance instead decreases, causing the impact depth to increase. In the field of particle damping and vibration reduction, studies have shown that for a specific type of damping particles, an optimal particle size typically exists, at which the particle-generated damping is the maximized (*Shinde and Pathak, 2016*; *Kumbhar, 2021*).



a. Impact depth b. Average acceleration c. Damping coefficient

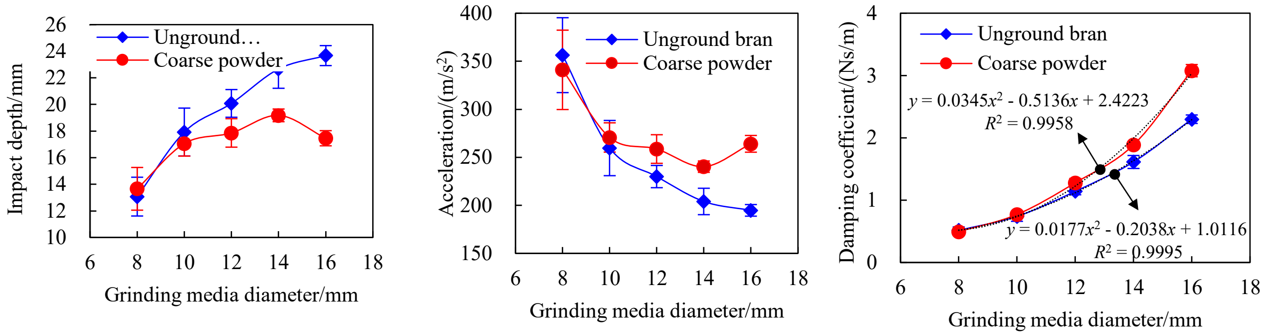
Fig. 3 - Impact mechanical property parameters of wheat bran powders with different particle sizes

As shown in Fig. 3, the impact depth of the grinding media ball in the fine powder is the smallest, measuring 11.57 mm, and that in the micro powder is the largest, reaching 26.86 mm. The difference rate between the maximum and minimum impact depths is 132.15%, while the difference rates for the acceleration and damping coefficient are 134.79% and 127.53% respectively. This indicates that the bran powder particle size significantly influences the blocking effect on the grinding media ball. Given that the impact depth in the fine powder is minimal and the damping coefficient is maximal, the grinding media ball encounters the greatest resistance when penetrating the fine powder, whereas penetration into the micro powder is the easiest. This implies that crushing the fine powder into micro powder is relatively difficult. It further reveals that during different stages of vibration crushing, the crushing difficulty of wheat bran particles varies, as do the required crushing force and energy consumption. To avoid the mutation region between fine powder and micro powder and ensure test result reliability, this study selects uncrushed bran and coarse powder as the impacted materials to further investigate the effects of grinding media diameter, drop height, material layer thickness, and cylinder diameter on their blocking effect.

Influence of grinding media diameter on the blocking effect of wheat bran powder

According to Fig. 4(a), as the impact depth of the grinding media ball generally increases as its diameter increases. This is because, at the same drop height, a larger media ball diameter corresponds to higher gravitational potential energy, thereby increasing its impact kinetic energy gradually. It is also observed that the impact depth in uncrushed bran is typically greater than that in coarse powder, consistent with the results in Section 3.1. Notably, when the grinding media ball diameter is 8 mm, its impact depth in coarse powder exceeds that in uncrushed bran. This can be explained by the better fluidity of coarse powder, which facilitates the penetration of the small grinding media ball. Conversely, when the grinding media ball diameter is 16 mm, the impact depth in coarse powder decreases. This may be due to the larger grinding media ball encountering changes in structural support or inter-particle friction within the coarse powder, leading to reduced impact depth (*Ye et al., 2015*).

As shown in Fig. 4(b), the variation trend of acceleration during the grinding media ball impacts and penetration into the two types of bran powder is completely opposite to that of the impact depth. According to Fig. 4(c), the damping coefficients for the two types of wheat bran powder increase with the grinding media ball diameter, and the damping from the coarse powder exceeds that from the uncrushed bran. This is because a larger grinding media ball diameter increases the contact area between the grinding media surface and the bran powder, thereby enhancing the frictional force between the wheat bran powder particles and the grinding media surface. As the grinding media ball diameter increases, the damping coefficient of the coarse powder rises more rapidly, widening the gap between the damping coefficients of the two types of bran powder. This can be attributed to the voids and mobility of the coarse powder particles. Based on the fitted expressions in Fig. 4(c), when the grinding media diameter exceeds 9.25 mm, the coarse powder exhibits higher sensitivity than the uncrushed bran, meaning its damping coefficient is more susceptible to changes in the grinding media diameter. Therefore, to optimize the vibration crushing efficiency of wheat bran, the grinding media diameter should be rationally selected based on the results of wheat bran vibration crushing tests (*Cheng et al., 2021*).

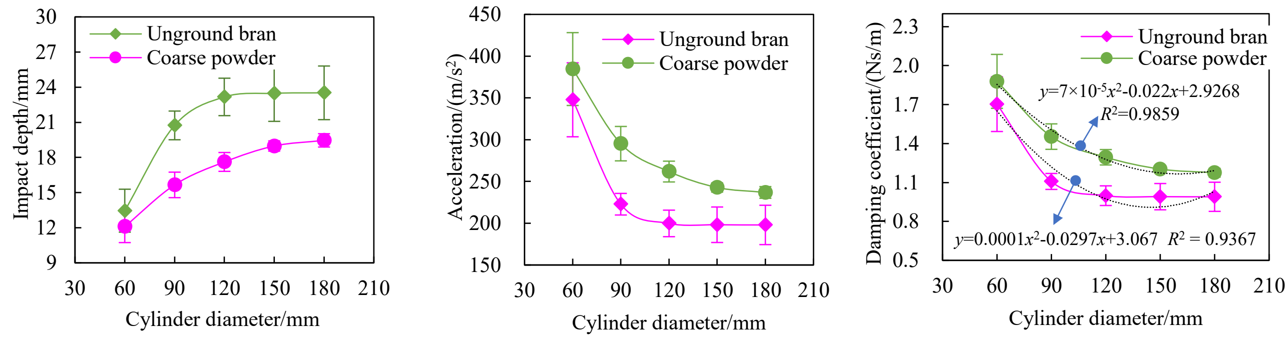


a. Impact depth b. Average acceleration c. Damping coefficient

Fig. 4 - Influence of grinding media diameter on the blocking effect of wheat bran powder

Influence of cylinder diameter on the blocking effect of wheat bran powder

As shown in Fig. 5(a), the impact depth of the grinding media in uncrushed bran is consistently greater than that in coarse powder, in line with the results in Section 3.1. As the cylinder diameter increases, the impact depth of the grinding media in the two types of bran powders increases and gradually stabilizes, following an approximate quadratic nonlinear trend. In other words, the boundary effect of the grinding cylinder on the impact depth of the grinding media diminishes as the cylinder diameter increases. This is because a small cylinder diameter imposes higher resistance to bran diffusion in all directions, leading to a larger proportion of frictional energy consumption between bran powder particles and the cylinder wall during impact (*Seguin, 2023*). Conversely, a larger cylinder diameter results in lower diffusion resistance, and the proportion of frictional energy consumption between particles and the cylinder wall is small and tends to be stabilize. As shown in Fig. 5(b) and Fig. 5(c), the average acceleration and damping coefficient exhibit identical variation trends, which are opposite to that of the impact depth of the grinding media. Both parameters decrease with increasing cylinder diameter and eventually reach a stable state.



a. Impact depth b. Average acceleration c. Damping coefficient

Fig. 5 - Influence of cylinder diameter on the blocking effect of wheat bran powder

As shown in Fig. 5(c), when the cylinder diameter exceeds 114.46 mm, the uncrushed bran exhibits higher sensitivity than the coarse powder. When the cylinder diameter surpasses 145.12 mm and 160.35 mm respectively, the slopes of the functional relationships for the damping coefficients of uncrushed bran and coarse powder become zero, and the damping coefficients stabilize, indicating the disappearance of the cylinder's boundary effect. In conclusion, the critical cylinder diameters for the two types of bran differ, with the coarse powder having a larger critical diameter than the uncrushed bran. This discrepancy may primarily arise because the coarse powder has a higher density than the uncrushed bran, enabling a more stable energy transfer path that allows the impact wave from the grinding media ball to propagate further. As demonstrated above, the ratios of cylinder diameter to grinding media diameter for the two types of bran powders are 9.54 and 12.09 respectively. This indicates that the cylinder's boundary effect is influenced by both the powder type and its particle size (*Ji et al., 2012*).

Influence of material layer thickness on the blocking effect of wheat bran powder

As depicted in Fig. 6(a), with the increase in thickness of the two types of wheat bran powder layers in the cylinder, the impact depths of the grinding media both display a trend of first increasing, then decreasing, and finally stabilizing. This can be attributed to the fact that when the material layer thickness exceeds an optimal threshold, its elastic effect intensifies, absorbing the impact energy of the grinding media. *Tomach (2024)* and *Seguin (2023)* have also pointed out that for particles with different shapes, the critical material layer thickness varies, and the damping rate exhibits a pattern of increasing first, then decreasing, and eventually stabilizing with increasing thickness—findings that align well with the results of this study. When the material layer thickness reaches a critical value of 40 mm, the impact depths of the grinding media in both bran powders attain their maxima. The ratio of material layer thickness to the grinding media diameter at this point is 4:1. Additionally, it is observed that the impact depth of the grinding media in uncrushed bran is consistently greater than that in coarse powder, in line with the results presented in Section 3.1. The difference rates between the maximum and minimum impact depths for uncrushed bran and coarse powder are 23.86% and 20.13%, respectively. This indicates that material layer thickness has a significant effect on the impact depths of the two types of wheat bran powders. The maximum difference rate in impact depth between the two types of bran powders is 33.60%, with the minimum rate at 25.79%, further highlighting the substantial influence of powder particle size on the blocking effect of wheat bran powder.

As shown in Fig. 6(b) and Fig. 6(c), the variation trends of the average acceleration and damping coefficient of the grinding media are consistent and opposite to that of the impact depth. The average acceleration and damping coefficient for the coarse powder are consistently higher than those for the uncrushed bran. When the ratio of material layer thickness to grinding media diameter is 4:1, the damping coefficient reaches its minimum. The difference rates between the maximum and minimum damping coefficients of uncrushed bran and coarse powder are 25.63% and 21.47%, respectively.

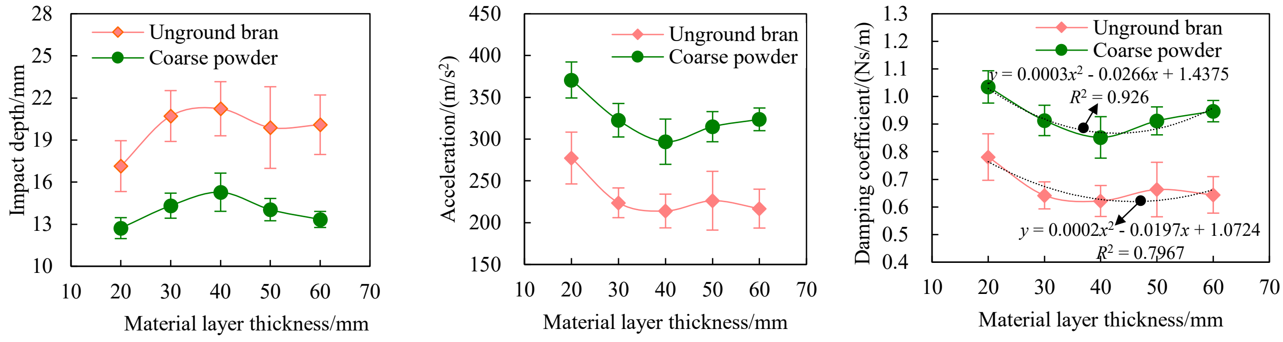


Fig. 6 - Influence of material layer thickness on the blocking effect of wheat bran powder

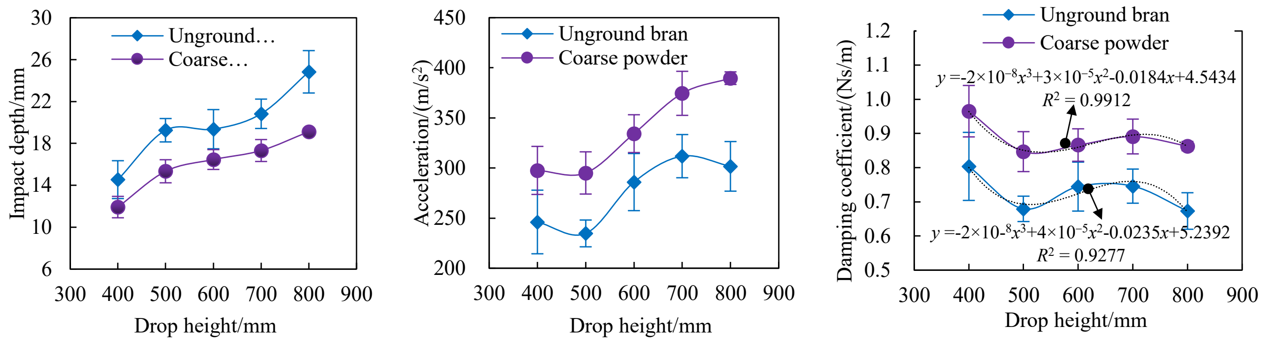
As shown in Fig. 6(c), when the material layer thickness is between 26.1 mm to 45.8 mm, the uncrushed bran demonstrates higher sensitivity than the coarse powder. During this range, variations in material layer thickness more significantly influence the damping coefficient of the uncrushed bran. For thicknesses of 20–26.1 mm and 45.8–60 mm, the coarse powder exhibits greater sensitivity, indicating it is more responsive to thickness changes. In wheat bran vibration crushing, the material layer thickness correlates positively with the bran filling amount. The higher the filling, the thicker the material layer that the grinding media need to penetrate.

When the thickness reaches the critical value, the damping coefficient of the bran powder is minimized, optimally facilitating the penetration of the grinding media. Thus, to improve wheat bran crushing efficiency, the bran powder filling amount should be rationally determined through experimental analysis.

Influence of drop height on the blocking effect of wheat bran powder

As shown in Fig. 7(a), the impact depth increases overall with the drop height of the grinding media (*Seguin et al., 2008*). Within a certain error margin, the relationship between drop height and initial impact velocity can be considered approximately linear. Thus, drop height can be regarded as equivalent to the initial impact velocity of the grinding media. This is consistent with the conclusion that "under identical conditions, the greater the initial impact velocity of an object, the deeper its impact depth"(*Ye et al., 2016*). The impact depth of the grinding media in uncrushed bran exceeds that in coarse powder, in line with the results in Section 3.1.

As shown in Fig. 7(b), owing to varying initial impact velocities, the average acceleration of the grinding media during their impact and penetration into wheat bran powder shows a cubic nonlinear trend: decreasing first, then increasing, and then decreasing again. The average acceleration of the coarse powder remains higher than that of the uncrushed bran. According to Fig. 7(c), the damping coefficient reaches a local minimum at a grinding media drop height of 500 mm. From the impact velocity perspective, it is not that the higher the impact velocity, the more favorable the penetration of grinding media into bran powder; instead, there exists a locally optimal impact velocity. The difference rates between the maximum and minimum damping coefficients of the uncrushed bran and the coarse powder are 19.41% and 13.98%, respectively; those for impact depths are 70.84% and 60.40%, respectively; and the coefficients of variation for accelerations are 32.83% and 32.04%, respectively. As shown above, the uncrushed bran exhibits higher difference rates in impact depth, acceleration, and damping coefficient than the coarse powder. The order of influence of drop height on the three parameters is: impact depth > acceleration > damping coefficient.



a. Impact depth b. Average acceleration c. Damping coefficient

Fig. 7 - Influence of drop height of the grinding media ball on the blocking effect of wheat bran powder

As shown in Fig. 7(c), when the drop height is between 429 mm and 656 mm, the uncrushed bran demonstrates higher sensitivity than the coarse powder. Within this range, variations in drop height more significantly influence the damping coefficient of the uncrushed bran. For drop heights of 400–429 mm and 656–800 mm, the coarse powder exhibits greater sensitivity, indicating it is more responsive to drop height changes. In conclusion, the performance parameters of the vibration mill, such as rotational speed and amplitude, should be rationally selected within a defined range to bring the grinding media's impact velocity close to the optimal state. This approach reduces the damping coefficient between the grinding media and bran powder, enabling more energy to be converted into crushing energy.

Sensitivity analysis of the damping coefficient of wheat bran powder

Given that the dimensions and value intervals of the experimental factors (e.g., the grinding media diameter, material layer thickness, drop height, and cylinder diameter) vary, the sensitivities of the damping coefficients for uncrushed bran and coarse powder with respect to these influencing factors are not comparable. Thus, dimensionless normalization of these factors is necessary.

Considering the non-negativity of the factors' value intervals, the following equation for dimensionless normalization can be used.

$$X_i = (x_i - \min x_i)/(\max x_i - \min x_i) \tag{4}$$

where:

X_i is the i-th dimensionless value, with $X_i \in (0, 1)$; x_i is the i-th dimensional value.

By using Eq. (4) to perform dimensionless normalization on the above influencing factors, the dimensionless fitting expressions for the damping coefficients of uncrushed bran and coarse powder with respect to these factors can be derived, as shown in Table 2.

According to Table 2, the dimensionless sensitivity distribution curves for the damping coefficients of the two types of wheat bran powders can be derived, as illustrated in Fig. 8.

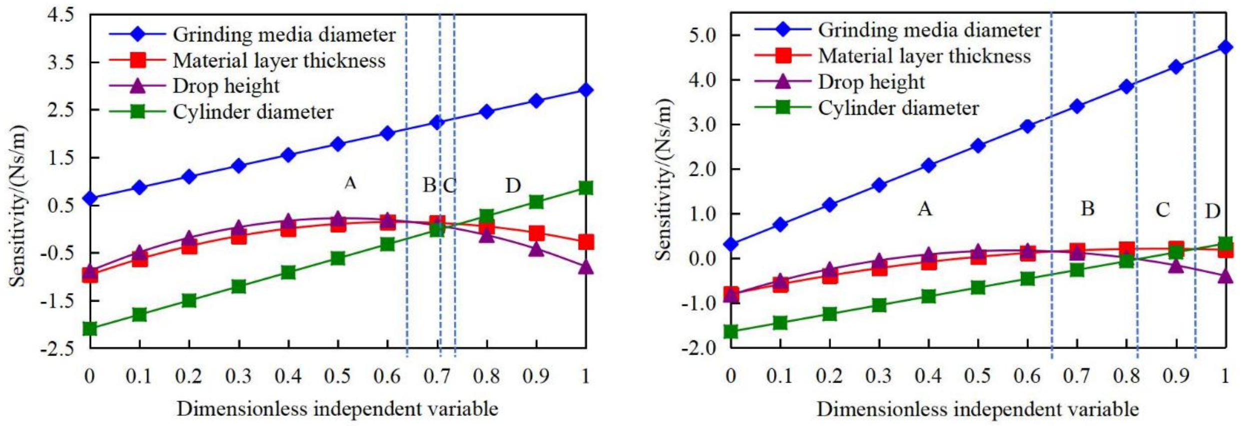
Fig. 8 shows that the sensitivity distribution laws of the damping coefficients of the two types of bran powders are very similar. This indicates that the test results have relatively high reliability. For both types of wheat bran powders, the grinding media diameter is consistently the most sensitive factor for changes in the damping coefficient, exceeding the drop height, material layer thickness, and grinding cylinder diameter.

Table 2

Dimensionless fitting expressions of damping coefficients of two types of wheat bran powders

Powder type	Uncrushed bran	Coarse powder
Grinding media diameter	Y=1.1354X^2+0.6402X+0.5164 (R^2=0.9995)	Y=2.2072X^2+0.306X+0.5211 (R^2=0.9958)
Cylinder diameter	Y=1.4754X^2-2.0933X+1.6515 (R^2=0.9367)	Y=0.986X^2-1.6491X+1.8558 (R^2=0.9859)
Drop height	Y=-1.4062X^3+2.1542X^2-0.8787X+0.8002 (R^2=0.9277)	Y=-1.0171X^3+1.7386X^2-0.8236X+0.9641 (R^2=0.9912)
Material layer thickness	Y=-0.9577X^3+1.7805X^2-0.96X+0.7818 (R^2=0.9962)	Y=-0.451X^3+1733X^2-0.8101X+1.0379 (R^2=0.9658)

For uncrushed bran and coarse powder, when 0 < X < 0.65 or 0 < X < 0.68 (Region A), the sensitivity ranking is: grinding media diameter > drop height > material layer thickness > cylinder diameter; when 0.65 < X < 0.72 or 0.68 < X < 0.82 (Region B), the sensitivity ranking is: grinding media diameter > material layer thickness > drop height > cylinder diameter; when 0.72 < X < 0.74 or 0.82 < X < 0.94 (Region C), the sensitivity ranking is: grinding media diameter > material layer thickness > cylinder diameter > drop height; when X > 0.74 or X > 0.94 (Region D), the sensitivity ranking is: grinding media diameter > cylinder diameter > material layer thickness > drop height.



a. Uncrushed bran b. Coarse powder

Fig. 8 - Dimensionless sensitivity of damping coefficient of wheat bran powder

Thus, when regulating the vibration crushing effect of wheat bran, the grinding media diameter should be adjusted preferentially. Subsequently, the performance parameters of the vibration mill and powder filling amount can be optimized. In practice, the size or capacity of the grinding cylinder is typically non-adjustable, which aligns with previous research conclusions (*Haddad, 2020; Cheng et al., 2021*).

CONCLUSIONS

This paper constructed an impact test platform for grinding media-wheat bran powder to simulate the impact-blocking effect, with impact depth, average acceleration, and damping coefficient serving as evaluation indicators. The effects of powder particle size, grinding media diameter, cylinder diameter, material layer thickness, and drop height were investigated, leading to the following conclusions:

(1) Under identical impact conditions, as wheat bran powder particle size decreases, impact depth demonstrates a quadratic nonlinear trend of decreasing first and then increasing, whereas average acceleration and damping coefficient change in the opposite direction. Particle size exerts a significant influence on the impact-blocking effect, with maximum-minimum difference rates of the three indicators reaching 132.15%, 134.79%, and 127.53%, respectively. The order of acceleration and damping coefficient is: fine powder > coarse powder > uncrushed bran > micro powder.

(2) An increase in media or cylinder diameter results in an increase in impact depth, but a decrease in acceleration. The damping coefficient exhibits a quadratic nonlinear relationship with both diameters: it increases with grinding media diameter (accompanied by growing differences) and decreases with cylinder diameter, stabilizing at critical diameters of 145.12 mm (uncrushed bran) and 160.35 mm (coarse powder). This finding helps to select the grinding media diameter and cylinder diameter based on the powder type or crushing stage.

(3) With the increase in material layer thickness, impact depth first increases then decreases, while acceleration and damping coefficients first decrease and then increase, stabilizing at a critical thickness of 40 mm (4:1 ratio to grinding media diameter). Impact depth increases monotonically with drop height, whereas acceleration and damping coefficients follow a cubic nonlinear pattern, reaching minima at 500 mm. Drop height has the most significant influence on impact depth, followed by average acceleration and damping coefficient. This finding facilitates the determination of the cylinder's material filling amount based on the critical warning value of layer thickness.

(4) Uncrushed bran and coarse powder show consistent dimensionless sensitivity distributions for damping coefficients, with grinding media diameter being the most sensitive factor, outperforming drop height, material layer thickness, and cylinder diameter. This finding contributes to the development of sensitivity weight-based control algorithms for multi-parameter coupled control of vibration crushing.

This study revealed the impact-blocking mechanism in wheat bran vibration crushing by simulating different stages and parameters of the crushing process. The results contribute to the understanding of the vibration mill's crushing mechanism and provide insights for optimizing its efficiency.

ACKNOWLEDGEMENT

This research was supported by the Joint Fund Project of Henan Province Science and Technology R&D Plan (232103810087), Scientific Research Project with R&D Special Fund Subsidy in Zhengzhou (22ZZRDZX14) and Scientific Research Fund for Senior Talents of Henan University of Technology (2020BS020).

REFERENCES

[1] Bogdanov V.S., Bogdanov N.E., Bogdanov D.V., & Samsonova P.S. (2019). Intensification of the grinding process in vibration mills. *Journal of Physics: Conference Series*, 1353(1), 012041.

[2] Bulgakov V., Pascuzzi S., Ivanovs S., Kaletnik G., & Yanovich V. (2018). Angular oscillation model to predict the performance of a vibratory ball mill for the fine grinding of grain. *Biosystems engineering*, 171, 155-164.

[3] Cheng M., Liu B.G., Cao X.Z., & Wang M.X. (2021). Effect of grinding medium characteristics of vibration mill on superfine grinding of wheat bran (振动磨机磨介特征对小麦麸皮超微粉碎效果的影响). *Transaction of the Chinese Society of Agricultural Engineering*, 37(23), 256-263.

[4] Cheng M., Liu B.G., & Liu Y.X. (2019). The influence of grinding ball on the vibration-impact crushing properties of wheat bran (磨介球对小麦麸皮振动冲击破碎性能的影响). *Journal of Vibration and Shock*, 38(24), 261-268.

[5] Frolov V., Blinichev V., Bogorodsky A., & Vetyugov A. (2017). Research of the influence of abrasive wear of grinding bodies in the rotational vibration mill. *Technical Transactions*, 10(4), 179-187.

[6] Gock E., & Kurrer K.E. (1999). Eccentric vibratory mills — theory and practice. *Powder Technology*, 105(1), 302-310.

[7] Haddad J. (2020). Experimental study of the effect of ball diameter, rotating mass and input grain size of silica sand on the efficiency of milling in vertical vibrating mill. *International Journal of Mechanical and Production Engineering Research and Development*, 10(1), 355-368.

[8] He S., Li J., He Q., Jian H.F., Zhang Y., Wang J.L., & Sun H.J. (2018) . Physicochemical and antioxidant properties of hard white winter wheat (Triticum aestivm L.) bran superfine powder produced by eccentric vibratory milling. *Powder Technology*, 325, 126-133.

[9] Hemery Y., Chaurand M., Holopainen U., Lampi A.M., Lehtinen P., Piironen V., Sadoudi A., & Rouau X. (2011). Potential of dry fractionation of wheat bran for the development of food ingredients, Part I: Influence of ultra-fine grinding. *Journal of Cereal Science*, 53(1), 1-8.

[10] Ji S.Y., Li P.F., & Chen X.D. (2012). Experiments on shock-absorbing capacity of granular matter under impact load. *Acta Physica Sinica*, 61(17), 184703.

[11] Ji S.Y., Fan L.F., & Liang S.M. (2016). Buffer capacity of granular materials and its influencing factors based on discrete element method. *Acta Physica Sinica*, 65(10), 104501.

[12] Kumbhar S.R. (2021). Effect of particle material, size and filling Percentage on particle damping phenomenon for gear transmission system. *International Journal for Research in Applied Science and Engineering Technology*, 9(6), 3740-3753.

[13] Lee H., Cho H., & Kwon J. (2010). Using the discrete element method to analyze the breakage rate in a centrifugal/vibration mill. *Powder Technology*, 198(3), 364-372.

[14] Li M., Zhang L., Dave R.N., & Bilgili E. (2015). An intensified vibratory milling process for enhancing the breakage kinetics during the preparation of drug nanosuspensions. *AAPS PharmSciTech*, 17(2), 389–399.

[15] Qian H., Dong Z.H., Zhuang H.J, Zheng M.Q., & Wang K. (2023). Numerical study on particle movement and crushing characteristics in vibromill. *Journal of Physics: Conference Series*, 2610(1), 2050.

[16] Rajaonarivony K.R., Mayer-Laigle C., Piriou B., & Rouau X. (2021). Comparative comminution efficiencies of rotary, stirred and vibrating ball-mills for the production of superfine biomass powders. *Energy*, 227(3): 120508.

[17] Saini P., Islam M., Das R., Shekhar S., Sinha A.S.K., & Prasad K. (2023). Wheat bran as potential source of dietary fiber: Prospects and challenges. *Journal of Food Composition and Analysis*, 116, 105030.

[18] Seguin A., Bertho Y., & Gondret P. (2008). Influence of confinement on granular penetration by impact. *Physical Review E*, 78(1), 010301.

[19] Seguin A. (2023). Force model in the penetration by impact into confined granular media. *Europhysics Letters*, 144(6), 670001.

[20] Shinde V.L., & Pathak A.K. (2016). Review on particle damping technique for vibration suppression. *International Journal of Innovative Research in Science, Engineering and Technology*, 5(3), 2890-2895.

[21] Tomach P. (2024). The Influence of the grinding media diameter on grinding efficiency in a vibratory ball mill. *Materials*, 17(12), 2924.

[22] Wang S.Q., & Ji S.Y. (2018). Discrete element analysis of buffering capacity of non-spherical granular materials based on super-quadric method. *Acta Physica Sinica*, 67(9): 094501.

[23] Yang X.L., Liu J.F., Zhang X., & Cheng S.W. (2015). Dynamic numerical simulation on grinding medium flow field for vibration mill under various vibrating amplitude–frequency combination conditions. *International Journal of Modeling, Simulation, and Scientific Computing*, 6(01), 1550004.

[24] Yang X.L., Zhang N., Liu J.F., Wang Z.J., & Zhou Y.J. (2016). Simulation analysis and experimental demonstration of velocity vector field of medium flow in double mass vibration mill. *International Journal of Modelling and Simulation*, 36(1-2), 34-43.

[25] Yang X.L., Wang Y.T., Xia Z.Q., Zhang T., & Liu J.F. (2018). Numerical simulation and experiment of medium flow energy field in vibrating mill. *International Journal of Modeling, Simulation, and Scientific Computing*,9(2), 1850011.

[26] Ye X.Y., Wang D.M., & Zheng X.J. (2015). Effects of density ratio and diameter ratio on penetration of rotation projectile obliquely impacting a granular medium. *Engineering Computations*, 32 (4), 1025 -1040.

[27] Ye X.Y., Wang D.M., & Zheng X.J. (2016). Criticality of post-impact motions of a projectile obliquely impacting a granular medium. *Powder Technology*, 301, 1044-1053.

[28] Yildirım O., Ariol H., & Sabah E. (2025). Multiobjective optimization of dry batch micronized grinding of slaked lime in a vibrating mill via TOPSIS and ANOVA. *Separation Science and Technology*,60(7), 873-886.
[29] Ying W., Li X., Lian Z., Xu Y., & Zhang J.H. (2022). An integrated process using acetic acid hydrolysis and deep eutectic solvent pretreatment for Xylo oligosaccharides and monosaccharides production from wheat bran. *Bioresource Technology*, 363, 127966.
[30] Yokoyama T., Tamura K., Usui H., & Jimbo G. (1993). Numerical analysis of movement of balls in a vibration mill in relation with its grinding rate. *KONA Powder and Particle*, 11, 179-190.
[31] Yokoyama T., Tamura K., Usui H., & Jimbo G. (1996). Simulation of ball behavior in a vibration mill in relation with its grinding rate: effects of fractional ball filling and liquid viscosity. *International Journal of Mineral Processing*, 44: 413-424.
[32] Zheng Y, Wang X, Sun Y, Cheng C.X., Li J.R., Ding P., & Xu B.F. (2022). Effects of ultrafine grinding and cellulase hydrolysis separately combined with hydroxypropylation, carboxymethylation and phosphate crosslinking on the in vitro hypoglycaemic and hypolipidaemic properties of millet bran dietary fibres. *LWT-Food Science and Technology*, 172, 114210.