Effects of Support Stiffness and Grinding Media Shape on Vibration Superfine Grinding Performance of Wheat Bran

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To explore the effects of support stiffness and grinding media shape on the superfine grinding performance of wheat bran, a vibration grinding platform with adjustable support stiffness (25 to 55 kN/m) was used for tests with stainless steel spherical grinding media (SGM) and cylindrical grinding media (CGM), respectively. The results showed that both factors significantly affected the grinding effect. When stiffness exceeded 35 kN/m, micro powder quality and yield improved for both media. Below 35 kN/m, SGM's micro powder quality deteriorated, while CGM's micro powder quality peaked at 30 kN/m. At 30 kN/m, fine powder, micro powder, and superfine powder yields reached their maximum for both media. The mass fraction of superfine powder was 52.9% for CGM, and that of SGM was 29.3% higher than at 35 kN/m. SGM consistently produced better particle size distribution than CGM, with the smallest median particle size (D_{50}) difference (21.5%) at 30 kN/m. The superfine yield of CGM was not always higher than that of SGM. Their mass fraction difference showed a quadratic nonlinear relationship. A coupling effect between media shape and stiffness was found to determine grinding performance. Overall, this work provides a basis for optimizing the superfine grinding performance of wheat bran in vibration mills.

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Keywords: Support stiffness; Vibration mill; Superfine grinding; Wheat bran; Grinding media shape

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INTRODUCTION

Wheat bran, as an important source of dietary fiber, has good application prospects in food processing, biochemistry, functional materials, and other fields (Onipe *et al.* 2021; Ying *et al.* 2022; Praveen *et al.* 2023). The use of superfine grinding equipment to grind wheat bran at the cell level has become an important technical means for the in-depth development and comprehensive utilization of wheat bran (Jin *et al.* 2020; Kong *et al.* 2020; Zheng *et al.* 2022). However, due to its high fiber content (Hemery *et al.* 2011), conventional grain grinding equipment struggles to achieve superfine grinding of wheat bran. In contrast, vibration mills—medium grinding equipment with coupled grinding effects (*e.g.*, impact, shearing, extrusion, and friction)—are more suitable for superfine grinding of wheat bran (Rajaonarivony *et al.* 2021; Luo *et al.* 2012). Even so, they still have shortcomings such as low yield, high energy consumption, and unstable quality, which hinder the comprehensive utilization of wheat bran.

To improve the vibration superfine grinding performance of wheat bran, scholars in China and abroad have carried out relevant research from the aspects of grinding temperature, vibration mass, grinding media characteristics, vibration strength, and so on. In terms of grinding temperature, Hemery *et al.* (2010) studied the effect of low temperature on the mechanical properties of wheat bran and its structural layers. Cheng *et al.* (2019, 2025) explored the effect of low temperature on the tensile mechanical properties and the superfine grinding performance of wheat bran, respectively. Huang *et al.* (2009) compared the effects of normal temperature and low temperature freezing grinding on the physical and chemical properties of wheat bran dietary fiber by using vibration grinding method. They found that under the premise of obtaining the same micro powder particle size, the freezing superfine grinding efficiency was higher and the grinding effect was better. Cheng *et al.* (2022) established a vibration and impact numerical calculation model of three components named “grinding media - bran - grinding media” according to the vibration grinding mechanism of vibration mill, and compared and analyzed the vibration and impact grinding performance of wheat bran at room temperature and low temperature.

In terms of vibration parameters, the filling rate of grinding media, the filling rate of materials or the pellet ratio is usually used to characterize the vibration parameters of grinding media or materials (Piekaj and Cieplok 2021). Cheng *et al.* (2023) studied the effect of vibration parameters on the superfine grinding performance of wheat bran by regulating the mass ratio of wheat bran and grinding media. They found that it was easier to improve the superfine grinding performance of a vibrating mill by regulating the quality of wheat bran than the quality of grinding media. In addition, Li *et al.* (2008), Qin *et al.* (2010), and Huang *et al.* (2011), respectively, studied the effect of grinding media filling rate of vibrating mill on the superfine grinding effect of black fungus, *Coptis chinensis*, leech and notoginseng. They found that the greater the filling rate of grinding media, the better the grinding effect of vibrating mill.

In terms of grinding media characteristics, there are currently few relevant reports on using wheat bran as the grinding object to study the influence of grinding media characteristics of vibration mill on its superfine grinding effect (Cheng *et al.* 2021), while there are more studies on mineral materials. Tang *et al.* (2011) studied the influence of the size and ratio of grinding balls on the vibration grinding effect of coal gangue. Simba *et al.* (2014) investigated the influence of mixtures of grinding media with three different shapes (spheres, semi-ellipsoids, and cubes) on the grinding kinetics of a laboratory-scale ball mill through quartz grinding tests. Yang *et al.* (2018) and Lin *et al.* (2018) used discrete element method to study the influence of multiple density combination conditions of the same size grinding balls on the grinding effect of the vibration mill, respectively.

In terms of vibration strength, Li *et al.* (2015) improved the superfine grinding effect of drugs by increasing the vibration intensity of the vibration mill. Liu *et al.* (2013) studied the two-dimensional grinding force model of the powder particles in the grinding cylinder and obtained the relationship between the particle size of the material and the vibration strength. Yang *et al.* (2016) and Zhang *et al.* (2017) used the discrete element method to study the influence of different amplitudes and frequencies combinations of vibration intensity on the internal grinding media flow of the vibration mill, respectively. In addition, Dong *et al.* (2023) studied the effects of material characteristics, shape characteristics, filling rate, and vibration frequency and amplitude of the mill on the grinding effect. As a vibration-damping and supporting element of a vibration mill, the supporting stiffness of the spring is one of the key parameters affecting the dynamic mechanical characteristics of the equipment (Xu *et al.* 2013; Ding *et al.* 2019;). However, nowadays, very few studies have been conducted on the influence of supporting stiffness and grinding media shape on the vibration superfine grinding performance of wheat bran.

In this paper, different support stiffnesses were obtained by replacing rubber springs of different sizes, and a test scheme was designed based on the principle of consistent vibration characteristics of the vibration mill. Spherical grinding media (SGM) and cylindrical grinding media (CGM) were selected to carry out the vibration superfine grinding test of wheat bran, respectively. The mass fraction of wheat bran powder was selected as the yield index, and the particle size distribution characteristic parameter of micro powder was adopted as the quality index. Through variance analysis and similarity analysis, the influence law of support stiffness on the superfine grinding effect of wheat bran under different grinding media shapes was explored. This study provides a practical and scientific basis for regulating the support stiffness and grinding media shape of the vibration mill to control the superfine grinding effect of wheat bran.

EXPERIMENTAL

Materials

The wheat bran used in this study was Zhengmai 379 (2022 harvest), which was purchased from Jinyuan Flour Mill in Zhengzhou. To eliminate the effect of residual endosperm on the superfine grinding of wheat bran, the wheat bran was first washed, then dried and screened. Finally, the bran passing through the 5-mesh screen but retained on the 20-mesh screen was used as the test samples. The moisture content of the wheat bran was approximately 10.4%.

Instruments and Equipment

The instruments and equipment included a small experimental vibrating mill, rubber springs, a powder particle size analyzer, a texture analyzer, an electronic balance, a moisture tester, standard test sieves (5-mesh, 20-mesh, 60-mesh, 200-mesh), and SGM and CGM for the vibrating mill. To ensure the stable operation of the vibrating mill, a laser displacement sensor was used to measure the Y-direction displacement of the grinding cylinder with different rubber spring supports, preventing the vibration body from jumping due to excessive amplitude. To simulate the changes in support stiffness of the vibration mill, 5 sets of cylindrical rubber springs were prepared (4 springs per group). Their inner diameter was 15 mm, height was 56 mm, and outer diameters were 27, 30, 32, 35, and 37 mm, respectively. The vibration grinding test platform with different support stiffnesses, constructed using the above equipment, is shown in Fig. 1.

Before the test, based on the compressive mechanical properties of the rubber springs, a texture analyzer was used to determine their support stiffness parameters, and the results are shown in Table 1. According to Table 1, there was also a certain deviation in the support stiffness of rubber springs with the same geometric size. Compared with the mean values, the maximum deviations of the five groups of springs were 1.70%, 1.96%, 4.98%, 1.95%, and 1.86%, respectively, which were all less than 5%. Thus, it can be approximated that the support stiffness of each group of springs is the same. The nominal values of their support stiffnesses were 25, 30, 35, 40, and 55 kN/m, respectively. Among these, 35 kN/m is the support stiffness of the rubber spring provided by the vibration mill manufacturer.

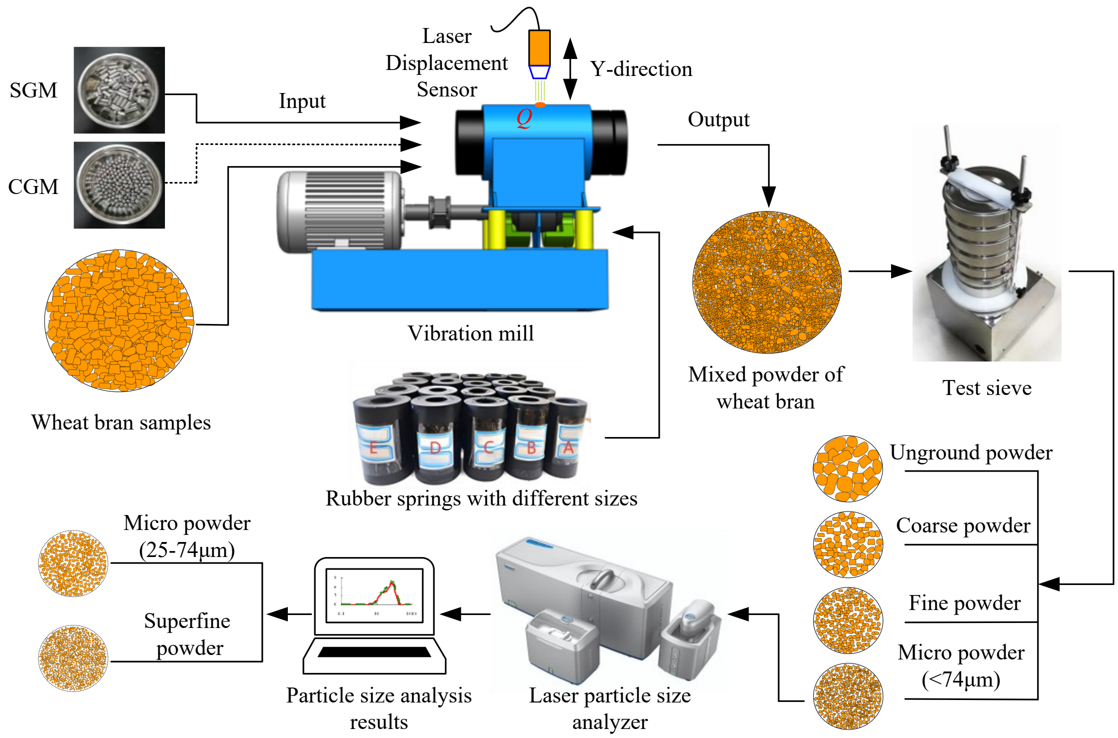


Fig. 1. Vibration grinding test platform with different support stiffness

Table 1. Identification Results of Support Stiffness of Rubber Springs

No.	Outer diameter (mm)	No.1 (N/m)	No.2 (N/m)	No.3 (N/m)	No.4 (N/m)	Mean value (N/m)	Nominal value (kN/m)
A	27	24873	24251	24928	24630	24671	25
B	30	28578	29663	29124	29236	29150	30
C	32	36208	35184	33005	34538	34734	35
D	35	40096	40572	41263	41635	40892	40
E	37	55713	54571	55656	53948	54972	55

Experiment Scheme

The grinding media shape has been found to have a significant effect on the superfine grinding effect of wheat bran (Cheng *et al.* 2021). This study selected two types of grinding media, namely SGM and CGM, to carry out vibration grinding tests on wheat bran under different support stiffnesses. While exploring the influence law of support stiffness on the superfine grinding performance of wheat bran, the test results of the two types of grinding media can also be used to compare and analyze the effect of grinding media shape on the superfine grinding performance of wheat bran. To ensure consistent vibration conditions of the vibration mill, 300 g of wheat bran samples were used for each test. A total of 4 kg of grinding media were used, and the motor speed was 1440 rpm. The rated power was 3 kW, and the grinding time was 1 h. To minimize the influence of grinding media size on wheat bran grinding performance, the diameter of both SGM and CGM was 14 mm, and the height of CGM was 25 mm. To further ensure the stable operation of the vibration mill, a laser displacement sensor was used to measure the Y-direction displacement (amplitude) at Point Q of the grinding cylinder under different support stiffnesses during the experiment. This not only helps discuss the vibration grinding mechanism of wheat bran from the perspective of vibration intensity, but also enables timely shutdown when the amplitude is excessively large, thereby ensuring the safety of the coupling and bearings. The experiment scheme is shown in Fig. 2.

To save research time and costs while eliminating cumulative errors in test data, each grinding test was repeated 3 times. The ground bran powders were mixed, and the mixture was screened using standard test sieves with different mesh sizes to obtain unground bran, coarse powder, fine powder, and micro powder respectively. The particle size of the bran micro powder obtained by screening was analyzed by a laser particle size analyzer to determine the volume fraction of superfine powder in the bran micro powder, thereby determining the yield of superfine powder.

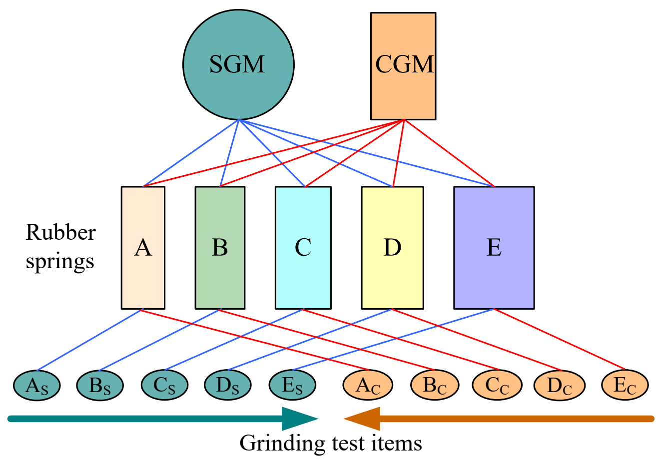


Fig. 2. Diagram of the experiment scheme

Test Results Analysis Method

Calculation method of powder mass fraction

On completion of the grinding test, the grinding media and the powder were separated using a standard 5-mesh test sieve. The powder was then graded using standard 20-mesh, 60-mesh, and 200-mesh test sieves. In the powder classification process, the powder that does not pass the 20-mesh sieve is defined as unground powder (particle size $d_A > 900\mu m$); the powder that passes the 20-mesh sieve but does not pass the 60-mesh sieve is defined as coarse powder ($280\mu m < d_A < 900\mu m$); the powder that passes the 60-mesh sieve but does not pass the 200-mesh sieve is defined as fine powder ($74\mu m < d_A < 280\mu m$); the powder that passes the 200-mesh sieve is defined as micro powder ($25\mu m < d_A < 74\mu m$); and the powder with a particle size $d_A < 25\mu m$ is defined as superfine powder (Zhang *et al.* 2010). In practice, it is difficult to sieve superfine powder using standard test sieves.

In this paper, a laser particle size analyzer was used to determine the volume percentage of superfine powder. The masses of unground bran, coarse powder, fine powder, micro powder, and superfine powder were designated as m_{nc}, m_{cp}, m_{fp}, m_{mp}, and m_{sp}, respectively. Taking into account the loss of powder during the sieving process, the total mass m_{tp} of the wheat bran powder after sieving was calculated as the sum of the above individual masses.

$$m_{tp} = m_{nc} + m_{cp} + m_{fp} + m_{mp} + m_{sp} \tag{1}$$

The mass fractions of all types of wheat bran powder are

$$\begin{cases} M_{cp} = m_{cp} / m_{tp} \times 100\% \\ M_{fp} = m_{fp} / m_{tp} \times 100\% \\ M_{mp} = m_{mp} / m_{tp} \times 100\% \\ M_{sp} = m_{sp} / m_{tp} \times 100\% \end{cases} \tag{2}$$

where M_{cp}, M_{fp}, M_{mp}, and M_{sp} are the mass fractions of coarse powder, fine powder, micro powder, and superfine powder, respectively (%), and m_{tp} is the total mass of the powder (g). The above mass fractions were used to quantify the yield index of various powders in this paper.

Similarity analysis

The Euclidean distance method was used to calculate the similarity of the particle size distribution curves of bran micro powder under different test conditions. The specific calculation method was carried out as follows (Li *et al.* 2021): Select any two points *A* and *B* in the n-dimensional space. The coordinate vector of point *A* is X = (x_1, x_2, …, x_n), and the coordinate vector of point *B* is Y = (y_1, y_2, …, y_n). The Euclidean distance between *A* and *B* was calculated by Eq. 3.

$$d(X,Y) = \sqrt{\sum_{i=1}^{n} (x_i - y_i)^2} \tag{3}$$

The similarity was calculated by Eq. 4.

$$W_{AB} = 1/[1 + d(X,Y)] \tag{4}$$

Greater similarity indicated a smaller difference between them; conversely, a smaller similarity indicated a greater difference. This indicates that the test conditions have a significant effect on the particle size distribution of wheat bran micro powder.

Difference analysis

The mass fractions of various bran powders were selected as the yield index, and the yield difference rate of various powders was calculated as follows,

$$DR_{C-R} = (C_V - R_V)/R_V \times 100\% \tag{5}$$

where DR_{C-R} is the yield difference rate of different types of bran powder (%), C_V is the current value of the mass fraction of different types of bran powder (%), and R_V is the reference value of the mass fraction of bran powder (%). If DR_{C-R}<5%, it indicates that the yield difference is not significant. If DR_{C-R}>5%, it indicates that the yield difference is significant.

Sensitivity analysis

Assuming the relationship between the mass fraction of wheat bran powder and support stiffness can be expressed as $y_M = f(x_k)$, the sensitivity is defined as follows:

$$S = \mathrm{d}y_M / \mathrm{d}x_k \tag{6}$$

where *S* is the sensitivity (%/(kN/m)), and both positive and negative values are possible. y_M is the bran powder mass fraction (%); x_k is the support stiffness (kN/m).

RESULTS AND DISCUSSION

Experimental Results

The wheat bran was subjected to vibration superfine grinding, sieving treatment, and particle size analysis, and the test results are shown in Table 3. As the support stiffness increased, the masses of unground bran for SGM and CGM first decreased, then increased, and then decreased, with an overall decreasing trend. When the support stiffness was 30 kN/m, the mass of unground bran reached an extremely small value, indicating that the support stiffness at this time was conducive to the grinding of wheat bran. When the maximum support stiffness was 55 kN/m, the mass of unground bran corresponding to the two types of grinding media reached the minimum value. These results show that increasing the support stiffness improved the grinding effect of wheat bran.

Table 2. Experimental Results of Vibration Superfine Grinding of Wheat Bran

Type	Test item	Support stiffness (kN/m)	Mass of unground bran (g)	Mass of coarse powder (g)	Mass of fines powder (g)	Mass of micro powder (g)	Mass of superfine powder (g)	Total mass of powder (g)
SGM	A_S	25	46.95	202.40	38.66	7.19	3.58	298.78
	B_S	30	29.71	191.18	50.25	16.27	8.63	296.04
	C_S	35	32.75	206.97	43.37	11.64	5.75	300.48
	D_S	40	20.44	189.48	55.09	19.02	12.30	296.33
	E_S	55	14.55	172.36	72.54	20.81	14.03	294.29
CGM	A_C	25	61.79	176.82	37.95	15.59	5.18	297.33
	B_C	30	41.44	185.57	47.10	18.26	7.04	299.41
	C_C	35	50.17	184.58	41.72	16.24	5.40	298.11
	D_C	40	53.31	179.90	42.28	17.40	6.33	299.22
	E_C	55	9.85	163.47	70.84	30.68	18.97	293.81

Effects of Support Stiffness on Grinding Performance of Wheat Bran

Effect on particle size distribution of wheat bran micro powder

As shown in Fig. 3, the particle size distribution curves of wheat bran micro powder for the two types of grinding media were highly similar under different support stiffnesses, both exhibiting a single particle size peak. This suggests that the wheat bran micro powder samples were pure and free of residual endosperm (Nyombaire and Ng 2022). For both SGM and CGM, an increase in support stiffness caused the particle size distribution characteristic curve of wheat bran micro powder to tilt to the left and the particle size to gradually decrease. This suggests that increasing support stiffness can improve the quality of wheat bran micro powder to some extent.

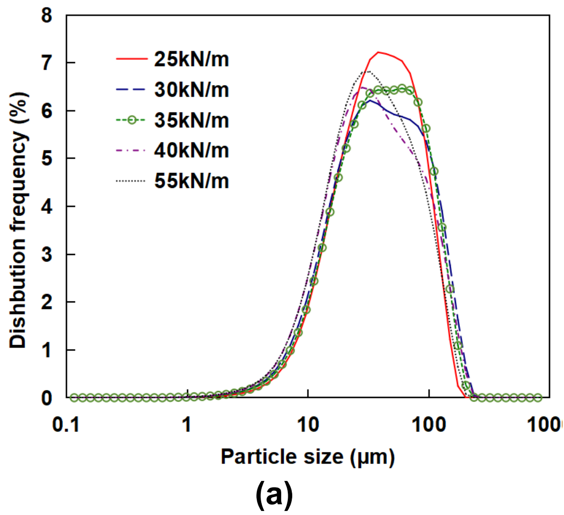


Fig. 3. Particle distributions of wheat bran micro powder under different support stiffness: (a) SGM; (b) CGM

Next, the particle size distribution characteristics of wheat bran micro powder will be analyzed in detail. Columns 3 to 6 of Table 3 present the characteristic parameters of the particle size distribution for wheat bran micro powder ground by the two types of grinding media under different support stiffnesses. When the support stiffness was less than 35 kN/m, the particle size of the main peak of wheat bran micro powder for the two types of grinding media first decreased and then increased. The distribution frequency of the main peak exhibited the same trend. When the support stiffness exceeded 35 kN/m, the particle size of the main peak of wheat bran micro powder corresponding to SGM first decreased and then increased, while the distribution frequency of the main peak showed a continuous upward trend. For CGM, the particle size of the main peak of wheat bran micro powder remained unchanged and then decreased. The distribution frequency of the main peak showed a continuous downward trend. When the support stiffness was 30 kN/m, the main peak particle size and distribution frequency of the wheat bran micro powder particle size distribution curves (corresponding to the two types of grinding media) reached their local minimum values. When the support stiffness was less than 35 kN/m, the median particle size (D_{50}) of wheat bran micro powder for SGM increased, while that for CGM first decreased and then increased. When the support stiffness was greater than 35 kN/m, the median particle size (D_{50}) of wheat bran micro powder for both types of grinding media showed a decreasing trend. In general, when a vibration mill uses grinding media of different shapes for grinding, the influence of support stiffness on the quality of wheat bran micro powder is consistent.

Table 3. Characteristic Parameters of Particle Size Distribution of Wheat Bran Micro Powder with Different Support Stiffness

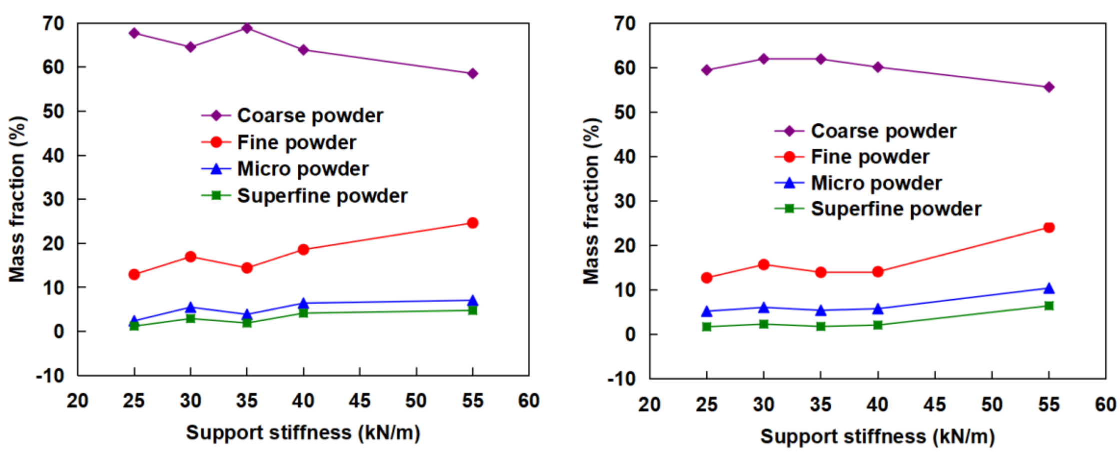
Grinding Media	Support stiffness	Test Item	Main Peak		D_{50} (μm)	Similarity (%)
			Particle Size (μm)	Distribution Frequency (%)		
SGM	*25*	A_S	38	7.22	36.10	27.60
	30	B_S	32.6	6.21	36.58	38.32
	35	C_S	60	6.47	37.57	—
	40	D_S	28	6.48	32.17	23.55

	55	E_S	32.6	6.81	30.08	21.23
CGM	*25*	A_C	94.8	6.67	50.01	69.84
	30	B_C	81.4	6.35	44.46	32.22
	35	C_C	94.8	6.78	49.92	—
	40	D_C	94.8	6.43	47.20	51.30
	55	E_C	32.6	6.21	33.69	13.13

Taking test items C_S and C_C as the respective control groups, Column 7 of Table 3 shows the similarity of the particle size characteristic curves of wheat bran micro powder to those of the two types of grinding media. As support stiffness increased, the similarity between each test item (ground with SGM) and C_S showed a quadratic non-linear trend of first increasing and then decreasing. When the support stiffness was 30 kN/m, the similarity reached a maximum of 38.3%. When the support stiffness was 55 kN/m, the similarity reached a minimum of 21.2%. The percentage of difference between the maximum and minimum similarities was 44.6%. The similarity between each test item (ground with CGM) and C_C showed a cubic non-linear trend: first decreasing, then increasing, and then decreasing. Similarly, the difference rate between the maximum and minimum similarities for the test items ground with CGM was 81.2%. The results indicate that the influence of support stiffness on the quality of wheat bran micro powder was significant and non-uniform.

Effect on mass fractions of wheat bran powder

As shown in Fig. 4, the mass fraction of coarse powder for the two types of grinding media generally exhibited a downward trend with the increase of support stiffness. The mass fractions of fine powder, micro powder, and superfine powder showed an upward trend. When the support stiffness was less than 35 kN/m, the mass fractions of the three types of wheat bran powder (*i.e.*, fine powder, micro powder, and superfine powder) reached their maximum values at 30 kN/m. When the support stiffness exceeded 35 kN/m, the mass fractions of the three types of wheat bran powders increased monotonically. When the support stiffness of the vibration mill was 30 kN/m, the mass fraction of wheat bran superfine powder reached a local maximum.



(a) (b)

Fig. 4. Relationship between mass fraction of wheat bran micro powder and support stiffness: (a) SGM; (b) CGM

To further analyze the effect of support stiffness on the mass fraction of wheat bran powder, the test items A_S and A_C with a support stiffness of 25 kN/m were also selected as the control groups. Table 4 shows the difference rates in the mass fraction of wheat bran powder between the remaining four test items and the control groups. A positive difference rate indicates an increase in the mass fraction of bran powder, while a negative difference rate indicates a decrease in the mass fraction of bran powder.

Table 4. Differences in Mass Fractions of Wheat Bran Powder with Different Support Stiffness

Type of Grinding Media	Powder Type	DR_{B-A} (%)	DR_{C-A} (%)	DR_{D-A} (%)	DR_{E-A} (%)	DR_{max} (%)
SGM	Coarse powder	-4.66	1.68	-5.61	-13.54	-13.54
	Fine powder	31.14	11.51	43.66	90.49	90.49
	Micro powder	128.22	60.58	166.39	193.36	193.36
	Superfine powder	143.33	59.17	245.83	297.5	297.50
CGM	Coarse powder	4.22	4.12	1.09	-6.44	-6.44
	Fine powder	23.28	9.64	10.74	88.95	88.95
	Micro powder	16.41	4.01	10.88	99.24	99.24
	Superfine powder	34.48	4.02	21.84	271.26	271.26

Note: DR_{B-A} is the difference rate of wheat bran powder mass fraction between item B and item A, the same below. DR_{max} is the maximum difference rate of wheat bran powder mass fraction.

As shown in Table 4, with the increase of support stiffness, the percent differences of mass fractions for various powders with SGM showed an increasing trend, all reaching the maximum value at 55 kN/m. The differences of mass fractions for various wheat bran powders with CGM also reached the maximum value at 55 kN/m. The maximum differences of mass fractions for wheat bran superfine powders for the two types of grinding media were 150% and 257%, respectively. This result indicates that the rational selection of support stiffness improved the superfine grinding performance of wheat bran. When the support stiffness was 30 kN/m, the percent differences of mass fractions for wheat bran superfine powders for the two types of grinding media were 52.9% and 29.3%, respectively, which are both far greater than 5%. Therefore, the superfine grinding effect of wheat bran can be optimized without significantly changing the support stiffness of the vibration mill.

Discussion

Increasing the support stiffness can improve the quality and yield of wheat bran superfine powder. However, during the test, it was found that with the increase of support stiffness, the vibrating body of the vibration mill gradually deviated from the preset motion trajectory, resulting in unstable jumping of the vibrations (Yang *et al.* 2015). When the vibration jumping phenomenon is severe, it will cause damage to the coupling and rotor support system of the vibration mill. Therefore, in order to ensure the service life of the vibration mill, the support stiffness cannot be increased infinitely. At the same time, when the support stiffness is too small, the spring deformation increases (Ding *et al.* 2019). This means that a large part of the vibrational energy of the vibration mill is converted into spring deformation energy, thereby further reducing the proportion of energy available for wheat bran grinding. Therefore, the support stiffness should not be too small.

As shown in Fig. 1, taking a vibration mill filled with SGM as the test object, the support stiffness was simulated by changing rubber springs of different sizes. The average displacements of the measuring point *Q* above the vibrating body within one test cycle were measured by a laser displacement sensor, which were -0.4541 mm (25 kN/m), 0.9614 mm (30 kN/m), 1.3353 mm (35 kN/m), 2.8530 mm (40 kN/m), and 3.4724 mm (55 kN/m), respectively (Sun 2024). This indicates that with the increase of support stiffness, the amplitude of the vibration mill also increases, which in turn improves its vibration intensity index. A large number of studies have shown that increasing the vibration intensity of the vibration mill is conducive to improving the superfine grinding performance of the vibration mill (Yang *et al.* 2016; 2018). This is because as the support stiffness (or amplitude) increases, the velocity, contact force, total energy, and collision frequency of the grinding media inside the grinding cylinder all show an increasing trend (Sun 2024). The research results of this paper are completely consistent with this. As shown in Table 3, when the support stiffness was 30 kN/m, the median particle size (D_{50}) of wheat bran micro powder for the two types of grinding media was smaller than that when the support stiffness was 35 kN/m. According to Fig. 4, when the support stiffness was 30 kN/m, the yield of wheat bran superfine powder for the two types of grinding media was greater than that when the support stiffness was 35 kN/m. At the same time, the amplitude of the vibration mill at a support stiffness of 30 kN/m was also smaller than that at 35 kN/m. Therefore, considering the quality and yield of superfine powder and the stable operation of the vibration mill comprehensively, the rubber spring with a support stiffness of 30 kN/m should be preferentially selected for the vibration mills.

Effect of Grinding Media Shape on Grinding Performance of Wheat Bran

Effect on particle size distribution of wheat bran micro powders

Figure 5 presents the particle size distribution curves of wheat bran micro powder ground by SGM and CGM under different support stiffnesses. Obviously, the particle size distribution curves of wheat bran micro powder for the two types of grinding media were different. With the increase of support stiffness, the particle size distribution curve of wheat bran micro powder for SGM was always located on the left side of that for CGM. This indicates that the quality of wheat bran micro powder for SGM was generally better than that for CGM. This is consistent with the research results of Cheng *et al.* (2021).

The similarities of the particle size distribution curves of wheat bran micro powder for the two types of grinding media at support stiffnesses of 25, 30, 35, and 40 kN/m were 11.09%, 22.93%, 15.00%, and 13.23% respectively. This indicates that with the increase of support stiffness, the similarity of the particle size distribution curves of wheat bran micro powder for the two types of grinding media showed a change characteristic of first increasing and then decreasing. When the support stiffness was 30 kN/m, the similarity of the particle size distribution curves of wheat bran micro powder for the two types of grinding media was the largest. According to Table 3 and Fig. 5, the difference rates of the median particle size (D50) of bran micro powder corresponding to the two types of grinding media at support stiffness of 25, 30, 35, and 40 kN/m were 38.53%, 21.54%, 32.87%, and 46.72% respectively, which were far greater than 5%. This indicates that the shape of grinding media had a significant influence on the quality of wheat bran micro powder, but its influence degree under different support stiffness was not completely the same, presenting a variation characteristic of first decreasing and then increasing. When the support stiffness was 30 kN/m, the similarity of the particle size distribution curves of wheat bran micro powder for the two types of grinding media was the largest and the difference was the smallest. At this time, the influence of grinding media shape on the quality of wheat bran micro powder was the smallest.

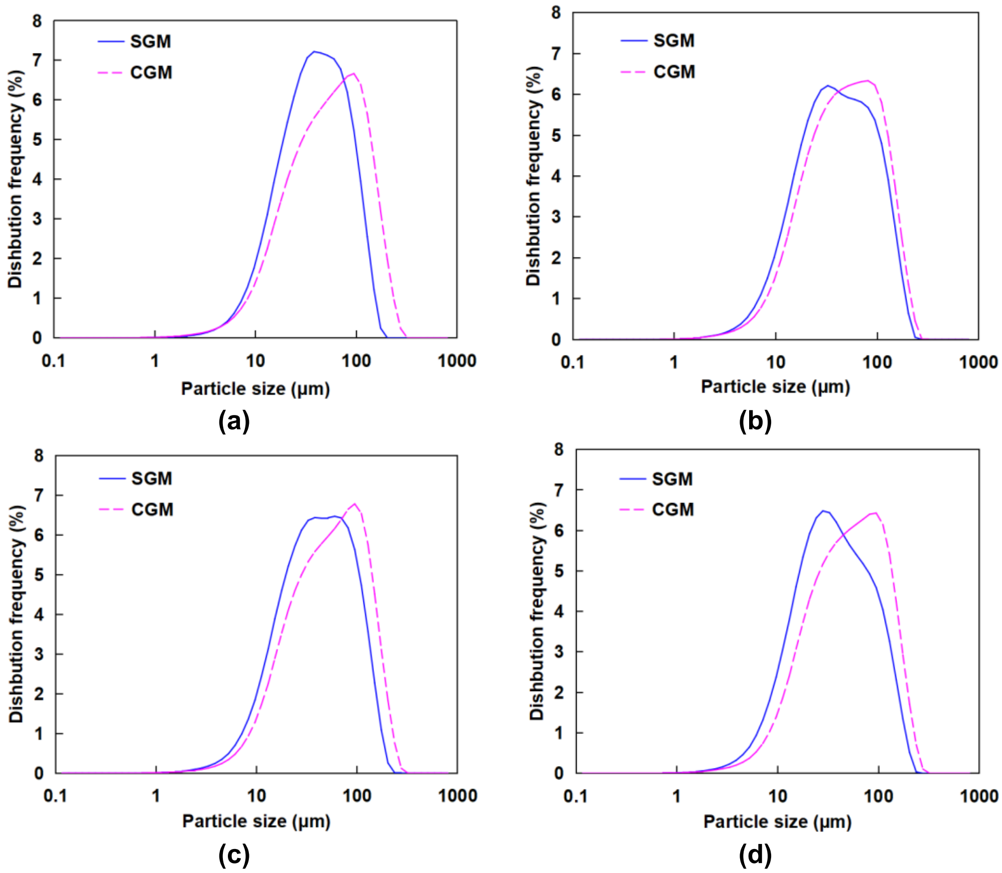


Fig. 5. Comparison of particle size distribution of micro powders when filling SGM and CGM at different support stiffness: (a) 25KN/m; (b) 30KN/m; (c) 35KN/m; (d) 40kN/m

Effect on mass fractions of wheat bran powders

As shown in Fig. 6, with the increase in support stiffness, the variation patterns of the mass fraction of various bran powders for SGM and CGM exhibited a certain degree of similarity. With the increase in support stiffness, the yield of coarse bran powder for the two types of grinding media showed a downward trend, while the yields of fine powder, micro powder, and superfine powder generally showed an upward trend. This indicates that the increase in support stiffness was conducive to the vibration grinding of wheat bran. According to the fitting results, the mass fraction of wheat bran powder under SGM varied linearly with support stiffness, whereas that under CGM follows a quadratic nonlinear variation pattern with support stiffness.

The similarities of the mass fraction curves of coarse powder, fine powder, micro powder, and superfine powder obtained by the Euclidean distance method were 0.68%, 4.36%, 4.24% and 11.61%, respectively. The similarity of the mass fraction curve of superfine powder was the highest, and that of coarse powder was the lowest, indicating that the grinding media shape had a relatively small influence on the yield change of superfine powder, but it had a great influence on the yield change of coarse powder. However, under different support stiffnesses, the influence degree of grinding media shape on the yield of various wheat bran powders was different. The main reason lies in the fact that the SGM and CGM exhibit different contact mechanical properties on the surface of wheat bran. Under the same vibration conditions, the total energy possessed by the SGM is generally lower than that of the CGM (Sun 2024).

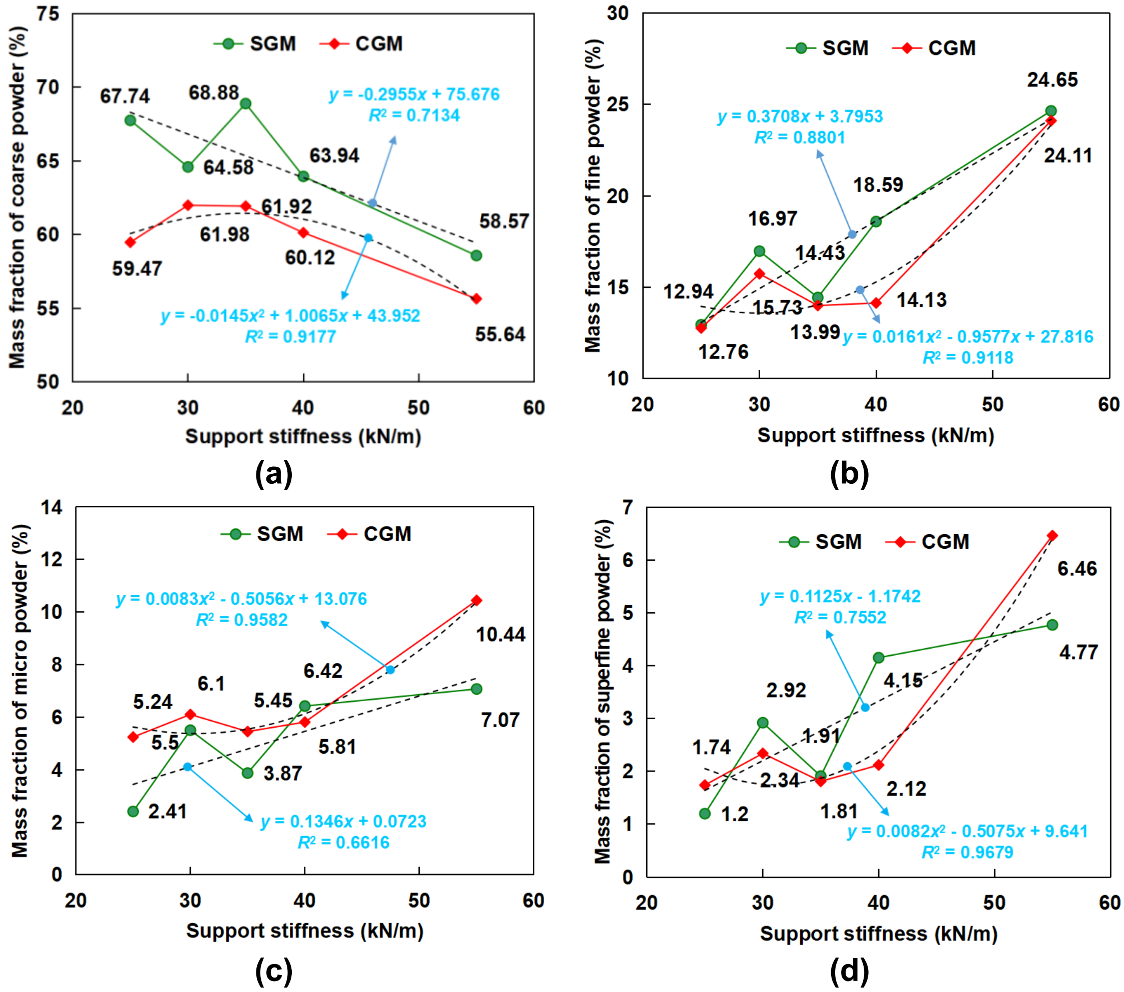


Fig. 6. Comparison of mass fractions of wheat bran powders when filling SGM and CGM at different support stiffness: (a) Coarse powder; (b) fine powder; (c) micro powder; (d) superfine powder

According to Table 5, the difference in the mass fraction of wheat bran powder under the two types of grinding media was not the same at different support stiffnesses. The difference rates of coarse powder, fine powder, micro powder, and superfine powder reached minimum values at support stiffnesses of 30, 25, 40, and 35 kN/m, which were -4.03%, -1.39%, -9.50%, and -5.24%, respectively. At this time, the influence of grinding media shape on the yield of these four types of bran powder was small and could be ignored within a certain range. The difference rates of coarse powder, fine powder, micro powder, and superfine powder reached maximum values at support stiffnesses of 25, 40, 25, and 40 kN/m, which were -12.21%, -23.99%, 117.43%, and -48.92%, respectively. Therefore, when the support stiffness is near its maximum value, the influence of the grinding media shape on the yield of wheat bran powders cannot be ignored.

Table 5. Difference Rates of Powder Mass Fractions of Wheat Bran Powder between SGM and CGM

Type of powder	Type of grinding media	Support stiffness/(kN/m)				
		25	30	35	40	55
Coarse powder	SGM/%	67.74	64.58	68.88	63.94	58.57
	CGM/%	59.47	61.98	61.92	60.12	55.64
	Difference rate/%	-12.21	-4.03	-10.10	-5.97	-5.00
Fine powder	SGM/%	12.94	16.97	14.43	18.59	24.65
	CGM/%	12.76	15.73	13.99	14.13	24.11
	Difference rate/%	-1.39	-7.31	-3.05	-23.99	-2.19
Micro powder	SGM/%	2.41	5.5	3.87	6.42	7.07
	CGM/%	5.24	6.1	5.45	5.81	10.44
	Difference rate/%	117.43	10.91	40.83	-9.50	47.67
Superfine powder	SGM/%	1.2	2.92	1.91	4.15	4.77
	CGM/%	1.74	2.34	1.81	2.12	6.46
	Difference rate/%	45.00	-19.86	-5.24	-48.92	35.43

Note: Difference rate = (CGM-SGM) / SGM×100%

Discussion

According to Fig. 6 and Table 5, the functional relationships between the mass fraction of wheat bran superfine powder corresponding to the two types of grinding media (i.e., SGM and CGM) and the support stiffness can be obtained as follows,

$$\begin{cases} y_{SGM} = 0.1125x - 1.1742 & (R^2 = 0.7552) \\ y_{CGM} = 0.0082x^2 - 0.5075x + 9.641 & (R^2 = 0.9679) \end{cases} \tag{7}$$

where y_{SGM} and y_{CGM} represent the mass fractions (%) of wheat bran superfine powder corresponding to SGM and CGM, respectively, and x denotes the support stiffness with 25 kN/m $\leq x \leq$ 55 kN/m. The sensitivity of the mass fraction of wheat bran superfine powder to the support stiffness is shown in Fig. 7. The coordinate of intersection point A in the figure is (37.80, 0.1125). When the support stiffness was less than 37.8 kN/m, the sensitivity of the superfine powder mass fraction for SGM was greater than that for CGM, indicating that changes in support stiffness more readily affect the yield of superfine powder for SGM. When the support stiffness exceeded 37.8 kN/m, the sensitivity of SGM was lower than that of CGM, meaning support stiffness changes more significantly impact the yield of superfine powder for CGM. According to Fig. 6(d), the conclusion that "the yield of bran superfine powder with cylindrical grinding media (CGM) is always higher than that with spherical grinding media (SGM)" does not hold under different support stiffnesses (Cheng *et al.* 2021). This indicates that the influences of support stiffness and grinding media size on the yield of wheat bran superfine powder are different. According to Table 5, the difference in the mass fraction of wheat bran superfine powders for the two types of grinding media is shown in Fig. 8.

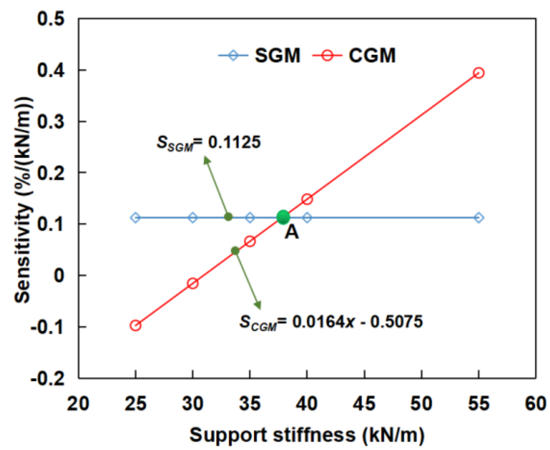


Fig. 7. Influence of grinding media shape on sensitivity of mass fraction of wheat bran superfine powder

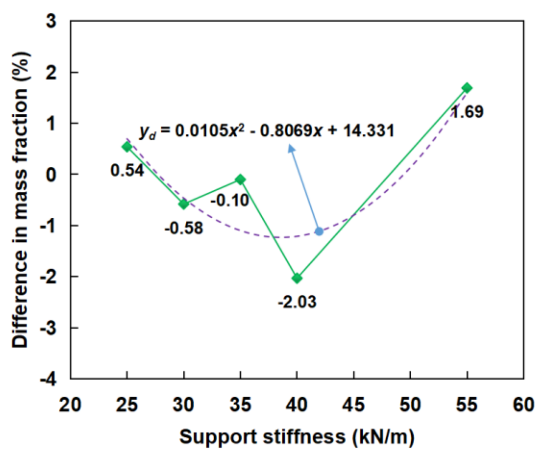


Fig. 8. Influence of grinding media shape on yield of wheat bran superfine powder

With the increase of support stiffness, the difference in the mass fraction of superfine powders between the two types of grinding media exhibited a quadratic nonlinear variation characteristic of first decreasing and then increasing. When the support stiffness was 38.4 kN/m, the grinding media shape had no effect on the yield of wheat bran superfine powders. According to Eq. (7), the support stiffness at which the mass fractions of superfine powder corresponding to the two types of grinding media are equal was calculated to be 37.8 kN/m, with a difference rate of 1.61% between the two. This indicates that the linear fitting for wheat bran powder corresponding to spherical grinding media and the quadratic nonlinear fitting for that corresponding to cylindrical grinding media are reasonable. Meanwhile, it is also found that there exists a certain coupling effect between the influence of grinding media shape on the yield of wheat bran superfine powder and the change in support stiffness.

CONCLUSIONS

1. The quality of wheat bran micro powder for the two types of grinding media showed quadratic and cubic nonlinear changes with the increase of support stiffness, respectively. When the support stiffness was less than 35 kN/m, the median particle size of the micro powder for spherical grinding media (SGM) showed an increasing trend, while that for cylindrical grinding media (CGM) first decreased and then increased, reaching a minimum value at 30 kN/m. When the support stiffness exceeded 35 kN/m, the median particle size of the bran micro powder for both grinding media showed a decreasing trend. It should be noted, however, that excessive support stiffness may cause instability of the vibration mill.
2. The variation patterns of the yields of fine powder, micro powder, and superfine powder of wheat bran for the two types of grinding media were generally consistent, all increasing with the increase in support stiffness. When the support stiffness was below 35 kN/m, the superfine powder yields for both grinding media reached a local maximum at 30 kN/m. At this stiffness, the percentages of difference between the mass fraction of superfine powder and that at 35 kN/m were 52.9% and 29.3%, respectively. This indicates that while ensuring the stable operation of the vibration mill, minor adjustments to the support stiffness can optimize the superfine grinding performance of wheat bran.
3. Under different support stiffnesses, the quality of wheat bran micro powder for SGM was generally better than that for CGM. The differences in the median particle size of micro powder reached 38.5%, 21.5%, 32.9%, and 46.7%, respectively, all of which were far greater than 5%. However, the yield of bran superfine powder for CGM was not always higher than that for SGM. With the increase in support stiffness, the difference between the mass fractions of superfine powder for the two types of grinding media exhibited a quadratic variation pattern: first decreasing and then increasing.
4. The superfine grinding performance of wheat bran was generally improved with the increase of support stiffness, which is consistent with the principle that the greater the vibration intensity of the vibration mill, the better the grinding effect. However, the coupling effect between support stiffness, grinding media shapes, and the operating state of the vibration mill should also be considered.

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