# Effects of low temperature and washing on the vibration superfine grinding performance of wheat bran

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**Abstract:** To explore the effects of low temperature and washing on the superfine grinding performance of wheat bran, two types of wheat bran samples were prepared: unwashed wheat bran (UWB) and washed wheat bran (WWB). The vibration grinding experiments of UWB and WWB were carried out at different grinding temperatures by using the low-temperature vibration grinding experimental platform. The results showed that the powder quality of UWB was greatly affected by low temperature, and the effect of low temperature on the WWB was less obvious. The results also showed that the particle size distribution curve of the UWB micro powder changed from a double peak curve to a single peak curve as the grinding temperature decreased. The similarity of the particle size distribution curves of the two types of wheat bran micro powder decreased with the decrease in grinding temperature, and the maximum decrease was about 60%. Compared with the results obtained at ambient temperature, the maximum difference rates of the mass fractions of the two types of wheat bran superfine powder within the grinding temperature range were 29.91% and 50.16%, respectively. At the same grinding temperature, the difference in mass fraction between the two types of wheat bran superfine powder was about 50%. The sensitivity of the yield of UWB superfine powder to grinding temperature was greater than that of WWB. The difficulty of superfine grinding of WWB was greater than that of UWB. According to the laminate theory of composite materials, the essence of the changes in the particle size of UWB superfine powder was revealed, and the relationship between the mass fraction of residual endosperm superfine powder and the grinding temperature was obtained. The results can be applied to improve the yield and quality of the further processing of wheat bran.

**Keywords:** wheat bran, low temperature, washing, superfine powder, vibration mill, grinding effect
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## 1 Introduction

Wheat bran is a kind of by-product of flour processing, and it is rich in protein, dietary fiber, vitamins, amylase system, minerals, and other nutrients. Therefore, it has good application prospects in the medical care industry, food processing industry, biochemical industry, and so on[1-4]. At present, the cell-level grinding of wheat bran performed by using superfine grinding equipment has become an important technical method for the in-depth development and comprehensive utilization of wheat bran[5-7]. Due to the high fiber content in each structural layer of wheat bran[8], its toughness and brittleness are high. As a result, it is difficult to carry out superfine grinding processing on conventional grain grinding equipment[9]. Vibration mills have coupled grinding effects such as impact, shear, extrusion, and friction[10,11] which are more suitable for the superfine grinding of high-fiber materials[12]. Thus, vibration mills have been used for the superfine grinding of wheat bran[13]. However, there are still problems that need to be solved in the grinding performance of the vibration mill, such as low output, high energy consumption, and poor quality.

In recent years, low-temperature grinding technology has been studied by some scholars around the world and has been applied to the vibration superfine grinding of wheat bran to improve its superfine grinding performance. Bondt et al.[14] obtained wheat bran powder with a median particle size ($D_{50}$) of 6 $\mu$m, which had a high surface area and strong water-holding capacity, by low-temperature grinding on a laboratory scale. Hemery et al.[15] found that low-temperature grinding was more conducive to the dissociation of different structural layers of wheat bran, it was easier to obtain superfine particles, and the particle size curve was narrower. Huang et al.[16] reported that the freeze grinding efficiency was higher and the grinding effect was better under the premise of obtaining the same particle size. When superfine grinding wheat bran to produce whole wheat flour, Chen et al.[17] found that the grinding effect of wheat bran was optimal at –10°C. Cheng et al.[18] used LS-DYNA to simulate and analyze the impact dynamics of wheat bran at different temperatures, and found that low-temperature grinding was more beneficial than ambient-temperature grinding. At the same time, in order to reveal the reasons for the advantages of low-temperature grinding of wheat bran, Hemery et al.[19] conducted low-temperature tensile tests on wheat bran using DMA, and found that wheat bran and its structural layers gradually changed from elastic-plastic material to brittle and hard material with the decrease of

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temperature, so that their fracture energies at the glass transition temperature decreased greatly. Cheng et al.[20,21] investigated the effect of low temperature on the mechanical properties of the whole bran, outer pericarp, and intermediate aleurone layer and found that the results were consistent with those of Hemery et al.[19] In fact, when we performed the low-temperature tensile test on wheat bran, the tensile sample was generally pure wheat bran with no residual endosperm[8]. This is quite different from the bran sample in the grinding experiments. The bran sample usually has residual endosperm on one side of the aleurone layer. George et al.[22] found that there were significant differences between WWB and UWB in terms of thermal properties, components, dietary fiber content, and water binding capacity. Thus, it can be concluded that the washing may affect the superfine grinding performance of wheat bran at low temperatures.

The aim of this study is to find out the effects of low temperature and washing on the vibration superfine grinding performance of wheat bran. Therefore, UWB and WWB were selected as grinding samples, and a low-temperature vibration grinding experimental platform was constructed. By adjusting the grinding temperature, the vibration grinding experiments of WWB and UWB, respectively, were carried out to reveal the effects of low temperature on the particle size distribution and powder yield. On this basis, the effects of washing on the particle size distribution and yield of wheat bran powder were investigated by comparative analysis.

## 2 Materials and methods

### 2.1 Preparation of sample

The raw material of wheat bran, named Yannong 19, was purchased from Zhengzhou Jinyuan Flour Mill. As the wheat bran from the flour mill contains multiple grain sizes of bran particles, it had to be sieved using standard 5 mesh and 20 mesh test sieves, and the bran under the 5 mesh and on the 20 mesh sieve were taken as grinding samples. At present, to ensure the quality of the flour, the mill has not further processed and brushed the bran, resulting in a large amount of white endosperm remaining on the side of the aleurone layer of wheat bran. To investigate the effect of low temperature and washing on the vibration grinding performance of wheat bran, it was necessary to wash the bran containing endosperm with water, and then obtain the WWB sample by drying and sieving. The bran containing endosperm was referred to as the UWB sample. The specific preparation process of the wheat bran sample is shown in Figure 1.

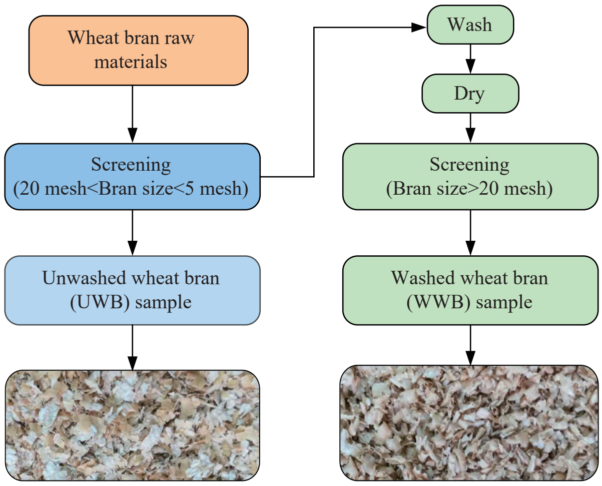


Figure 1 Flow chart for preparation of wheat bran samples

The moisture content of the WWB sample was approximately 10.42%. The moisture content of the UWB sample after moisture adjustment was approximately 10.65%. The difference between the two was 2.21%. Therefore, the effect of the moisture difference on the superfine grinding performance of wheat bran can be ignored. The UWB is flaky in shape and light amber in color, while the WWB is curly in shape and dark amber in color.

### 2.2 Instruments and equipment

The instruments and equipment used in the experiments are shown in Figure 2, which mainly included a small experimental vibration mill, a low-temperature coolant circulation pump, a powder particle size analyzer, an electronic balance, a moisture tester, a standard test sieve (5 mesh, 20 mesh, 60 mesh, 200 mesh), and a spherical stainless steel grinding media ($\Phi$14 mm). Prior to the experiment, the vibration mill was installed in the T-groove of the cast iron test platform using a T-nut and hexagon bolt. Then, the low-temperature circulating pump was connected to the cooling plate of the vibration mill through the low-temperature hose to form the low-temperature coolant circulation circuit, thus forming the low-temperature grinding environment of wheat bran.

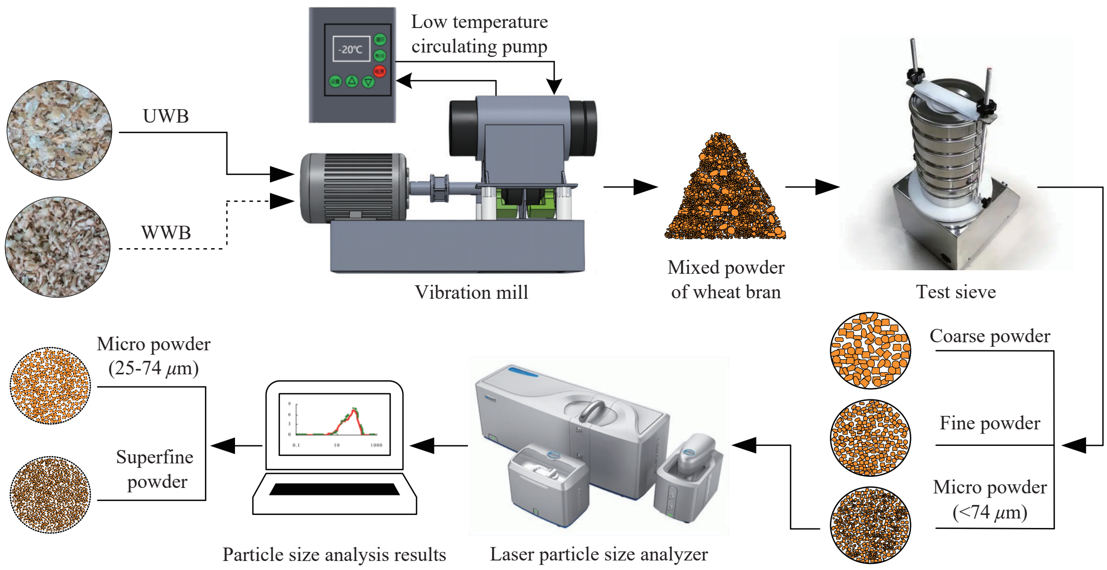


Figure 2 Flow chart of low-temperature vibration grinding experiments for wheat bran

### 2.3 Experiment scheme

To ensure identical vibration characteristics of the vibration mill, 200 g of UWB or WWB samples and 4 kg of stainless steel spherical grinding media were taken. The grinding time was set to 1 h, and the excitation frequency of the polarization block of the vibration mill was set to 50 Hz. Considering that the temperature adjustment range of the low-temperature circulating pump was −40°C-30°C, the temperature of the grinding experiment was set to 30°C, 0°C, −10°C, −20°C, and −30°C, respectively. Accordingly, AU, BU, CU, DU, and EU were used to denote the low-temperature grinding test items for UWB, and AW, BW, CW, DW, and EW were used to denote the low-temperature grinding test items for WWB. In order to investigate the effect of low temperature on the vibration grinding performance of wheat bran, 30°C was considered as the ambient temperature and used as the comparative analysis standard. The process of low temperature vibration grinding experiment of wheat bran is also shown in Figure 2.

To save time and research costs, only three grinding experiments were carried out for each experiment item during the experimental research. For the convenience of data processing and analysis, the ground bran powder was first mixed and then sieved. Finally, the particle size distribution characteristics of the wheat bran micro powder were analyzed using a particle size analyzer. Therefore, it can be assumed that all the experimental data in this study are the average of the three grinding experimental results. However, the standard deviation of these experimental data cannot be described. The specific classification method of wheat bran powder is listed in Table 1. Here, superfine powder generally refers to wheat bran powder with a particle size of less than 25 $\mu$m[23].

**Table 1 Classification method of wheat bran powder**

| Type of powder | Classification method | Mesh number | Particle size $d_A$/$\mu$m | Markings of powder mass |
|---|---|---|---|---|
| Uncrushed bran | Screening | >20 | >900 | $m_{wu}$ |
| Coarse powder | Screening | 20-60 | 280-900 | $m_{wc}$ |
| Fine powder | Screening | 60-200 | 74-280 | $m_{wf}$ |
| Micro powder | Particle size analysis | 200-500 | 25-74 | $m_{wm}$ |
| Superfine powder | Particle size analysis | <500 | <25 | $m_{ws}$ |

### 2.4 Analysis method of experiment results

2.4.1 Differences in the yield of wheat bran powder

As shown in Figure 2, the mass of superfine powder in the fine powder can be calculated after obtaining the percentage of superfine powder by particle size analysis. Taking into account the loss of bran powder in the sieving process, the total mass of bran powder, called $m_w$, is as follows:

$$m_w = m_{wu} + m_{wc} + m_{wf} + m_{wm} + m_{ws} \tag{1}$$

The mass fractions of the bran powder can be obtained by dividing the mass of each powder by the total mass of the bran powder as follows:

$$\begin{cases} M_{wc} = m_{wc}/m_w \times 100\% \\ M_{wf} = m_{wf}/m_w \times 100\% \\ M_{wm} = m_{wm}/m_w \times 100\% \\ M_{ws} = m_{ws}/m_w \times 100\% \end{cases} \tag{2}$$

where, $M_{wc}$, $M_{wf}$, $M_{wm}$, and $M_{ws}$ are the mass fractions of uncrushed bran, coarse powder, fine powder, and micro powder, respectively, %. The mass fraction of wheat bran powder was selected as the yield index, and the difference rate of its yield index was calculated by Equation (3).

$$DR = (CV - RV)/RV \times 100\% \tag{3}$$

where, $DR$ is the difference rate of bran powder yield, %; $CV$ is the current value of the mass fraction of bran powder, %; $RV$ is the reference value of the mass fraction of bran powder, %. If $DR$<5%, it indicates that the yield difference is not significant. If $DR$>5%, it indicates that the yield difference is significant.

2.4.2 Similarity of the particle size distribution of wheat bran powder

The particle size distribution characteristics of wheat bran micro powder were chosen as the quality index. In order to explore the changing rules of wheat bran powder quality as a whole, the Euclidean distance method was used to calculate the similarity of the particle size distribution characteristic curves[24]. Suppose $A$ and $B$ are any two points in n-dimensional space, and the coordinate vector of point $A$ is $X=(x_1, x_2, ..., x_n)$, the coordinate vector of point $B$ is $Y=(y_1, y_2, ..., y_n)$, then the Euclidean distance between point $A$ and point $B$ is as follows:

$$d(X,Y) = \sqrt{\sum_{i=1}^{n}(x_i - y_i)^2} \tag{4}$$

where, $d(X, Y)$ is the Euclidean distance between any two points in n-dimensional space. Then the similarity is as follows:

$$W_{AB} = 1/[1 + d(X,Y)] \tag{5}$$

where, $W_{AB}$ is the similarity of any two points in n-dimensional space. The greater the similarity is, the smaller the difference between $A$ and $B$ becomes. Conversely, the smaller the similarity is, the greater the difference between $A$ and $B$ becomes.

2.4.3 Sensitivity of wheat bran powder yield

Having established a functional relationship between the mass fractions of the bran powder and the grinding temperature by regression analysis, the sensitivity analysis can be carried out. If their relationship can be expressed as $y_M = f(x_m)$, then the sensitivity is as follows[25]:

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

where, $S$ is the sensitivity, %/°C, and its value can be positive or negative; $y_M$ is the mass fraction of bran powder, %; $x_m$ is the grinding temperature,°C.

## 3 Results and discussion

### 3.1 Experimental results

As shown in Figure 2, the vibration grinding experiments of UWB and WWB were carried out, respectively. After the experiments were completed, the wheat bran powders were sieved and classified, and then the particle size distributions of the micro powders were analyzed. The experimental results are listed in Table 2.

According to Table 2, the mass of uncrushed bran of UWB and WWB decreased with the decrease in grinding temperature, while the mass of wheat bran micro powder increased with the decrease in grinding temperature. It was shown that the low temperature could improve the vibration superfine grinding performance of wheat bran. These results were consistent with the results of Hemery et al.[19] and Cheng et al.[20] on the mechanical properties of wheat bran at low temperature. Therefore, it is more economical to produce superfine powder of wheat bran using the low temperature grinding process.

**Table 2 Experimental results of vibration grinding of wheat bran at different grinding temperatures**

| Test item | | Grinding temperature/ °C | Mass of uncrushed bran/g | Mass of coarse powder/g | Mass of fine powder/ g | Mass of micro powder/ g | Volume fraction of superfine powder/ % | Total mass of powder/ g |
|---|---|---|---|---|---|---|---|---|
| UWB | AU | 30 | 64.1 | 66.4 | 30.1 | 37.0 | 39.45 | 197.6 |
| | BU | 0 | 43.9 | 68.7 | 42.6 | 42.2 | 40.94 | 197.4 |
| | CU | −10 | 41.0 | 73.9 | 33.0 | 46.2 | 35.59 | 194.1 |
| | DU | −20 | 32.5 | 66.9 | 40.5 | 55.9 | 33.61 | 195.8 |
| | EU | −30 | 27.7 | 61.2 | 42.2 | 61.8 | 29.29 | 192.9 |
| WWB | AW | 30 | 39.1 | 92.9 | 41.2 | 26.7 | 23.71 | 199.9 |
| | BW | 0 | 33.1 | 89.9 | 46.1 | 31.6 | 24.82 | 200.7 |
| | CW | −10 | 30.3 | 95.4 | 41.5 | 32.3 | 26.18 | 199.5 |
| | DW | −20 | 23.4 | 93.2 | 43.6 | 38.1 | 24.77 | 198.3 |
| | EW | −30 | 24.8 | 89.4 | 46.3 | 40.6 | 21.85 | 201.1 |

Note: The fine powder mass here refers to the total mass of 200 mesh under the screen without separation of the superfine powder, i.e., the sum of the fine powder mass $m_{wm}$ and the superfine powder mass $m_{ws}$ in Table 1.

### 3.2 Effects of low temperature on grinding performance of UWB

#### 3.2.1 Particle size distribution of UWB micropowder

To analyze the effect of low temperature on the quality of UWB powder, the particle size distribution characteristic curves of wheat bran powder at different grinding temperatures are shown in Figure 3.

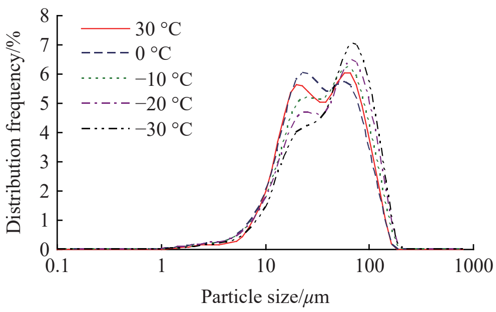


Figure 3 Particle size distributions of UWB micro powder under different grinding temperatures

As shown in Figure 3, a double particle size peak phenomenon appeared in the particle size distribution characteristic curve of wheat bran micro powder, indicating that the wheat bran micro powder has an agglomeration effect at two particle sizes[26]. In fact, UWB can be considered as a complex composed of pure wheat bran and endosperm. Due to the significant difference in the grinding mechanical properties of pure wheat bran and endosperm, the particle size distribution curve of UWB micro powder shows a double particle size peak phenomenon[15]. Compared with the ambient temperature (30°C), the primary and secondary particle size peaks of wheat bran micro powder at 0°C were reversed. The particle size of the primary peak changed from a large particle size to a small particle size. This means that the quality of the superfine grinding of wheat bran was improved. With the continuous decrease in grinding temperature, the particle size of the primary peak changed from a small particle size to a large particle size, and the double particle size peak gradually changed to a single particle size peak. The peak particle size tends to be stable, and the distribution frequency shows an increasing trend. When the grinding temperature reached −30°C, the double particle size peak of wheat bran powder had been completely changed into a single particle size peak. The results showed that low temperature was beneficial to obtain bran micro powder with higher yield and more concentrated particle size distribution, but the quality of micro powder was not further improved at the same time. This is fully consistent with the research result of Hemery et al.[19]

The particle size and distribution frequency values of the primary peak and secondary peak of the particle size distribution curves of wheat bran micro powder at different grinding temperatures were given, as shown in Columns 2-5 of Table 3. As the grinding temperature decreased, the distribution frequency of the primary peak increased and the distribution frequency of the secondary peak decreased. The minimum value of the primary peak particle size of bran powder appeared around 0°C. Meanwhile, the particle size of the primary peak remained stable at 64.94 μm. The median particle size ($D_{50}$) of bran micro powder first decreased and then increased, reaching the minimum value around 0°C, as shown in Column 6 of Table 3. The results indicated that 0°C was favorable for the superfine grinding of UWB. Taking the experimental item AN as a comparison standard, the similarity of the particle size characteristic curves of bran powder was listed in Column 7 of Table 3. As the grinding temperature decreased, the similarity between each experimental item and AU showed a decreasing trend, with a maximum decrease of 58.97%. The results showed that the effect of low temperature on the quality of UWB powder was significant.

**Table 3 Particle size distribution characteristic parameters of UWB micro powder at different grinding temperatures**

| Test item | Primary peak | | Secondary peak | | $D_{50}$/ μm | Similarity/ % |
|---|---|---|---|---|---|---|
| | Particle size/μm | Distribution frequency/% | Particle size/μm | Distribution frequency/% | | |
| AU | 56.90 | 6.06 | 19.77 | 5.63 | 32.78 | — |
| BU | 22.56 | 6.04 | 56.90 | 5.74 | 30.76 | 36.51 |
| CU | 64.94 | 6.25 | 25.75 | 5.22 | 36.15 | 31.84 |
| DU | 64.94 | 6.49 | 25.75 | 4.68 | 39.79 | 20.54 |
| EU | 64.94 | 7.03 | 0 | 0 | 44.79 | 14.98 |

#### 3.2.2 Mass fractions of UWB powder

According to Table 2, the relationship curves between the mass fractions of different bran powders and the grinding temperature are shown in Figure 4. With the decrease in grinding temperature, the mass fractions of bran coarse powder first increased and then decreased, showing quadratic non-linear characteristics, and reaching the maximum value at −10°C. The mass fractions of bran fine powder first increased, then decreased, and then continued to increase. It had cubic nonlinear characteristics, and its local maximum was close to 0°C. The mass fractions of bran superfine powder and fine powder increased in one direction. There was an approximately linear relationship between the mass fractions of superfine powder and the grinding temperatures.

Still using test item AU as a comparison standard, the difference rates in the mass fraction of bran powder caused by the grinding temperature are listed in Table 4. The negative value indicates a decrease in yield, while the positive value indicates an increase in yield. For the same type of bran powder, the difference rates between the mass fractions of fine, micro, and superfine powders were much higher than 5%. The yield of fine and micro powders changed the most at −30°C, reaching 43.66% and 100%, respectively. The yield of superfine powder changed the most at −20°C, reaching 29.91%. The results showed that the effect of low temperature on the grinding performance of wheat bran was not uneven. Due to the change in grinding temperature, the difference rates ($DR_{max}$) between the maximum and minimum mass fractions of different powders were much greater than 5%, and the difference rate ($DR_{max}$) of micro powder was close to 100%. It was found that low temperature had a very significant effect on the yield of wheat bran powder. Since the $DR_{max}$ of the superfine bran powder was close to 30%, it was possible to improve the superfine grinding performance of UWB by adjusting the grinding temperature.

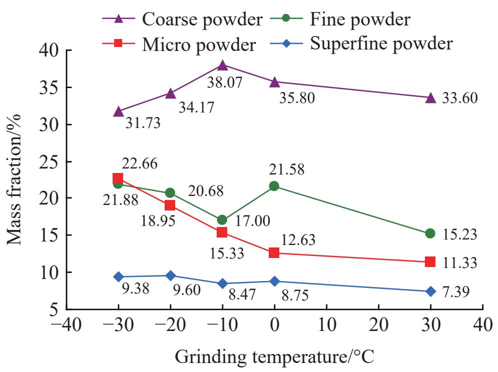


Figure 4 Relationship between mass fractions of UWB powder and grinding temperatures

**Table 4 Difference rate of powder mass fraction of UWB caused by grinding temperatures**

| Type of powder | Difference rate/% | | | | |
|---|---|---|---|---|---|
| | $DR_{BU\text{-}AU}$ | $DR_{CU\text{-}AU}$ | $DR_{DU\text{-}AU}$ | $DR_{EU\text{-}AU}$ | $DR_{max}$ |
| Coarse powder | 6.55 | 13.30 | 1.70 | −5.57 | 19.98 |
| Fine powder | 41.69 | 11.62 | 35.78 | 43.66 | 43.66 |
| Micro powder | 11.47 | 35.30 | 67.26 | 100.00 | 100 |
| Superfine powder | 18.40 | 14.61 | 29.91 | 26.93 | 29.91 |

### 3.3 Effects of low temperature on grinding performance of WWB

#### 3.3.1 Particle size distribution of WWB micro powder

Figure 5 illustrates that the particle size distribution curves of WWB micro powder at different grinding temperatures were extremely similar, showing the right-leaning distribution of single particle size peaks. It was quite different from the particle size distribution curves of the UWB micro powder.

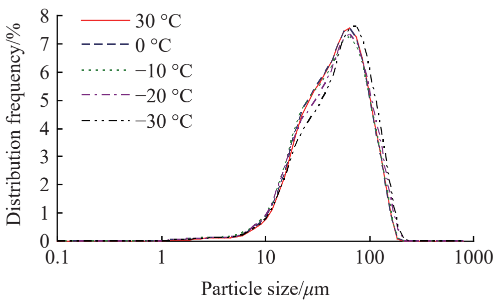


Figure 5 Particle size distributions of WWB micro powder at different grinding temperatures

According to Table 5, the maximum particle size was around 64.94 μm, and the volume distribution frequency did not change much. The median particle size ($D_{50}$) of bran powder first decreased and then increased with the decrease in grinding temperature, and the particle size was the smallest around −10°C. When the test item AW at ambient temperature was used as a comparison standard, the rate of change of the volume distribution frequency was −4.62%. The results showed that when the grinding temperature was −10°C, the quality of the bran powder was the best, and the effect on its yield was the least. When the grinding temperature dropped to −30°C, the rate of change of the median particle size ($D_{50}$) of the bran powder reached 10.84%. However, the volume distribution frequency at this time was the same as that of the test item AW. The results indicated that the lower grinding temperature could not further improve the quality of the WWB powder. The similarity of the particle size distribution curves of the bran powder decreased as the grinding temperature decreased, reaching 60.51%. In short, the effect of low temperature on the quality of WWB powder could not be ignored. However, compared to UWB, this effect was not significant.

**Table 5 Particle size distribution characteristic parameters of WWB micro powder at different grinding temperatures**

| Test item | Primary peak | | $D_{50}$/ μm | Similarity/ % |
|---|---|---|---|---|
| | Particle size/μm | Distribution frequency/% | | |
| AW | 64.94 | 7.57 | 45.20 | - |
| BW | 64.94 | 7.52 | 44.19 | 65.79 |
| CW | 64.94 | 7.22 | 43.51 | 48.47 |
| DW | 64.94 | 7.31 | 45.86 | 41.98 |
| EW | 64.94 | 7.57 | 50.10 | 25.98 |

#### 3.3.2 Mass fractions of WWB powder

Figure 6 shows the relationship between the mass fractions of WWB powder and the grinding temperature. As the grinding temperature decreased, the mass fractions of the bran fine, micro, and superfine powders showed an increasing trend. The mass fractions of the fine powder showed a strong increasing trend.

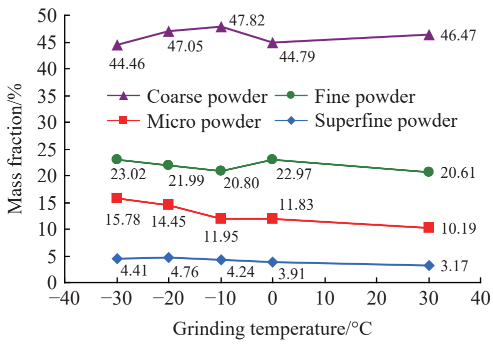


Figure 6 Relationship between mass fractions of WWB powder and grinding temperatures

The mass fractions of superfine powder as a whole increased linearly and reached the maximum at −20°C. The mass fractions of fine powder showed a cubic non-linear characteristic, first increasing, then decreasing, and then increasing. On the contrary, the mass fractions of the coarse powder first decreased, then increased, and then decreased.

Taking the test item AW as a comparison standard, the difference rates of the mass fraction of the WWB powder caused by the grinding temperature are given in Table 6. The difference rates of coarse powder yield were less than 5%, which could ignore the effect of low temperature on the yield of coarse powder. The yield of fine powder and micro powder changed the most at −30°C, and the difference rates reached 11.69% and 54.86%, respectively. The yield of superfine powder also changed the most at −20°C, reaching 50.16%. In general, the difference rates ($DR_{max}$) between the maximum and minimum mass fractions of different powders caused by the grinding temperature were very much larger than 5%. It has been shown that low temperature has an important influence on the yield of WWB powder, and thus the superfine grinding performance of WWB can also be optimized by adjusting the grinding temperature.

**Table 6 Difference rate of WWB powder mass fraction caused by grinding temperatures**

| Type of powder | Difference rate/% | | | | |
|---|---|---|---|---|---|
| | $DR_{BW\text{-}AW}$ | $DR_{CW\text{-}AW}$ | $DR_{DW\text{-}AW}$ | $DR_{EW\text{-}AW}$ | $DR_{max}$ |
| Coarse powder | −3.62 | 2.91 | 1.25 | −4.33 | 7.56 |
| Fine powder | 11.45 | 0.92 | 6.70 | 11.69 | 11.69 |
| Micro powder | 16.09 | 17.27 | 41.81 | 54.86 | 54.86 |
| Superfine powder | 23.34 | 33.75 | 50.16 | 39.12 | 50.16 |

### 3.4 Effects of washing on the grinding performance of wheat bran

Based on the results of the vibration grinding tests of the two types of wheat bran at different temperatures mentioned above, the effects of washing on the vibration superfine grinding performance of wheat bran can be analyzed comparatively.

#### 3.4.1 Quality of wheat bran micro powders

Figure 7 shows the comparison results of the particle size distribution curves of UWB and WWB micro powders at different grinding temperatures. It could be observed that the particle size distribution curves of the two types of wheat bran micro powders had significant differences based on Figure 7. When the grinding temperature was 0°C, −10°C, and −20°C, the particle size distribution curves of UWB micro powder were the double particle size peak curves, while the particle size distribution curves of WWB micro powder were always the single particle size peak curves. As the grinding temperature decreased, the particle size distribution characteristics of the UWB powder gradually changed from a double particle size peak to a single particle size peak. When the grinding temperature was reduced to −30°C, the particle size distribution curve of the UWB micro powder changed completely to a single particle size peak curve. However, due to the presence of endosperm in UWB, the left half of the particle size distribution curve of UWB micro powder was always higher than that of WWB micro powder. In other words, the particle size distribution range of UWB micro powder was always larger than that of WWB micro powder. At the same time, it was found that the distribution frequency of the peak particle size of WWB micro powder was always higher than that of UWB micro powder.

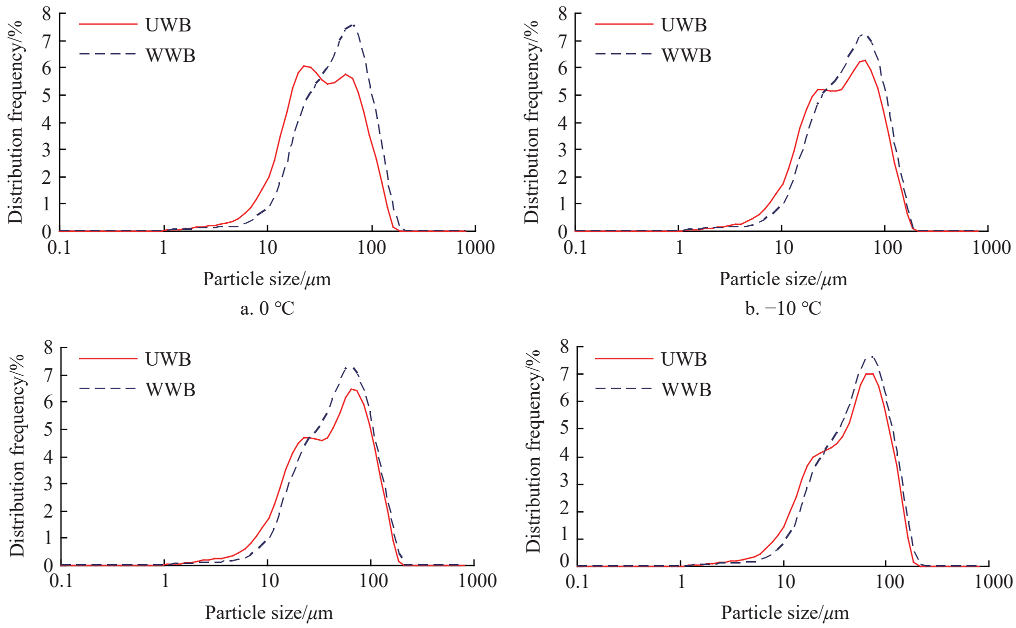


Figure 7 Comparison of particle size distribution of UWB and WWB micro powder at different grinding temperatures

According to Figure 7, the similarities of the particle size distribution curves of the two types of wheat bran micro powder at grinding temperatures of 0°C, −10°C, −20°C, and −30°C were 12.54%, 20.65%, 22.18%, and 25.43%, respectively. The results showed that the similarity of the particle size distribution curves of the two types of wheat bran powder increased monotonically with the decrease of the grinding temperature. According to Table 3 and Table 5, the difference rates of the median particle size ($D_{50}$) of the two types of bran micro powder at the grinding temperatures of 0°C, −10°C, −20°C, and −30°C were 43.66%, 20.36%, 15.26%, and 11.86%, respectively. At present, the difference rate showed a decreasing trend, but its value was much higher than 5%. The results showed that low temperature can reduce the difference in particle size distribution characteristics of the two types of wheat bran micro powder, but cannot completely eliminate the difference caused by different substance components. In conclusion, the effect of washing on the quality of wheat bran micro powder is significant, and low temperature can reduce the difference in the quality of wheat bran micro powder between WWB and UWB.

#### 3.4.2 Yield of wheat bran powders

According to Figure 8, the changing trend of the mass fraction of the two types of wheat bran powder was consistent at the same grinding temperature. The mass fractions of the two types of wheat bran coarse powder reached their maximum values at −10°C. This was in good agreement with the phenomenon of minimum value of tensile mechanical property parameters of wheat bran at −10°C[19,20]. The mass fractions of the two types of bran powders had maximum values near 0°C. Similarly, the Euclidean distance method could also be used to calculate the similarity of the mass fraction curves of the coarse, fine, micro, and superfine powders, and the results were 3.72%, 12.58%, 10.01%, and 8.80%, respectively. From this, it could be seen that the washing does not change the overall trend of wheat bran grinding performance with grinding temperature, which also indicates that the experimental results in this paper have high reliability and repeatability.

At the same time, it was found that the mass fractions of WWB coarse powder and fine powder were greater than those of UWB. However, the mass fractions of UWB micro powder and superfine powder were greater than those of WWB micro powder and superfine powder. Their difference rates are listed in Table 7. The results showed that it was easier to obtain a high yield of coarse and fine powder from WWB at the same grinding temperature, while it was more advantageous to obtain fine and superfine powder from UWB. It was also indicated that it was more difficult to superfine grind WWB than UWB. It could also be seen from Table 7 that the difference rates of the mass fractions of different powders of the two types of wheat bran were greater than 5%, indicating that washing has an important effect on the grinding performance of wheat bran. Meanwhile, the difference rates of the mass fractions of the superfine powders were more than 50%, further indicating that washing has the most significant effect on the superfine grinding performance of wheat bran.

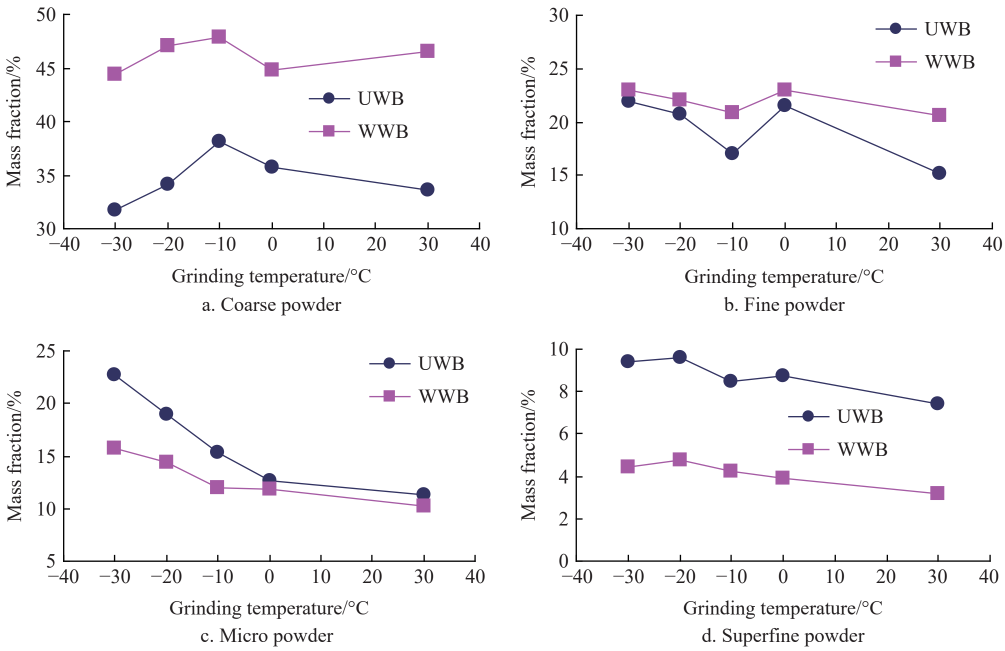


Figure 8 Comparison of powder mass fractions of UWB and WWB at different grinding temperatures

**Table 7 Difference rates of powder mass fractions between UWB and WWB**

| Type of powder | Type of bran | Grinding temperature/°C | | | | |
|---|---|---|---|---|---|---|
| | | 30 | 0 | −10 | −20 | −30 |
| Coarse powder | WWB/% | 46.47 | 44.79 | 47.82 | 47.05 | 44.46 |
| | UWB/% | 33.60 | 35.80 | 38.07 | 34.17 | 31.73 |
| | Difference rate/% | 38.30 | 25.11 | 25.61 | 37.69 | 40.12 |
| Fine powder | WWB/% | 20.61 | 22.97 | 20.80 | 21.99 | 23.02 |
| | UWB/% | 15.23 | 21.58 | 17.00 | 20.68 | 21.88 |
| | Difference rate/% | 35.33 | 6.44 | 22.35 | 6.33 | 5.21 |
| Micro powder | WWB/% | 10.19 | 11.83 | 11.95 | 14.45 | 15.78 |
| | UWB/% | 11.33 | 12.63 | 15.33 | 18.95 | 22.66 |
| | Difference rate/% | −10.06 | −6.33 | −22.05 | −23.75 | −30.36. |
| Superfine powder | WWB/% | 3.17 | 3.91 | 4.24 | 4.76 | 4.41 |
| | UWB/% | 7.39 | 8.75 | 8.47 | 9.60 | 9.38 |
| | Difference rate/% | −57.10 | −55.31 | −49.94 | −50.42 | −52.99 |

Note: Difference rate =(WWB–UWB)/UWB×100%

According to Table 7, the mass fractions of the UWB powder changed from less than those of the WWB powder to more than those of the WWB powder as the particle size of the bran powder decreased. The differences in the mass fractions of the two types of wheat bran powder increased. The results showed that the effects of washing on the yield of the two types of bran powder were different at the same grinding temperature. There was a monotonically decreasing trend between the mass fractions of the two types of wheat bran superfine powder and the grinding temperatures. Based on Figure 8 and Table 7, the linear fit relationship between them was obtained as follows:

$$\begin{cases} y_{s\mathrm{UWB}} = -0.0354x + 8.5056, & (R^2 = 0.8705) \\ y_{s\mathrm{WWB}} = -0.0245x + 3.9496, & (R^2 = 0.8746) \end{cases} \quad (7)$$

where, $y_{s\mathrm{UWB}}$ and $y_{s\mathrm{WWB}}$ are the mass fractions of UWB and WWB superfine powder, respectively, %; $x$ is the grinding temperature, $-30°\mathrm{C} \leq x \leq 30°\mathrm{C}$. According to Equation (7), the sensitivity of UWB and WWB superfine powder yield to grinding temperature, $S_{s\mathrm{UWB}}$ and $S_{s\mathrm{WWB}}$, were −0.0354 and −0.0245, respectively. Since $S_{s\mathrm{UWB}} > S_{s\mathrm{WWB}}$, it showed that the UWB superfine powder is more sensitive to the grinding temperature, and it is easier to obtain UWB superfine powder by vibration grinding. In the superfine grinding process of wheat bran, the wheat bran containing residual endosperm can be treated without washing.

### 3.5 Discussion

3.5.1 Effects of low temperature on superfine grinding performance of wheat bran

In terms of the perspective of bran tissue structure, the inner side of UWB contains residual endosperm. This leads to the differences in tissue structure, chemical composition, mechanical properties, and thermal properties between UWB and WWB[27]. Therefore, UWB can be considered a composite material composed of pure wheat bran and residual endosperm[15,28]. Their structural relationship is shown in Figure 9.

Based on the mixing law of composite materials, the relationship between UWB and pure wheat bran, which can be approximated to WWB, and residual endosperm can be described in terms of Young's modulus and density as follows[29]

$$\begin{cases} E = \varphi E_1 + (1-\varphi) E_2 \\ \rho = \varphi \rho_1 + (1-\varphi)\rho_2 \end{cases} \tag{8}$$

where, $E_1$ and $E_2$ are the Young's modulus of pure wheat bran and residual embryo, respectively, MPa; $\rho_1$ and $\rho_2$ are the densities of pure wheat bran and residual endosperm, respectively, kg/m³; $\varphi$ is the volume fraction of pure wheat bran, and $0<\varphi<1$.

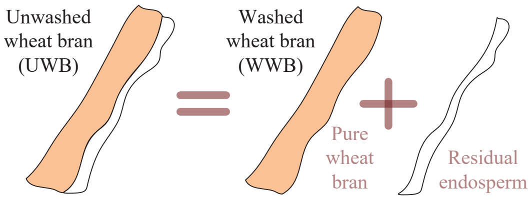


Figure 9 Structural relationship between UWB and WWB

According to Equation (8), Young's modulus and density of UWB should be between those of pure wheat bran and endosperm, resulting in different grinding mechanical properties of UWB and WWB. Tian et al.[30] found that the difficulty of superfine grinding of endosperm was much lower than that of wheat bran under the same vibration grinding conditions. Therefore, it is reasonable that there is a difference in the superfine grinding performance between UWB and WWB, as listed in Table 7. Furthermore, it can be roughly assumed that the different powders of UWB are mixed with the same types of WWB powder and endosperm powder. Due to the different grinding mechanical properties of these two substances, it can be considered that the existence of a double particle size peak in the particle size distribution curves of UWB powders is also reasonable[15,31], as shown in Figure 3. Here, the smaller particle size peak belongs to the endosperm powder, while the larger particle size peak belongs to the bran. With the continuous decrease of grinding temperature, the brittleness of pure wheat bran in UWB is further increased, which is closer to the mechanical properties of endosperm, and the particle size distribution curve of micro powder gradually changes from double particle size peak to single particle size peak. This is fully consistent with the mechanical properties of wheat bran at low temperatures[19,20]. As shown in Figure 8d, when the grinding temperature is −30°C, the particle size distribution curves of UWB and WWB micro powders are single particle size peaks. Therefore, low temperature can change the particle size distribution characteristics of UWB micropowder.

As mentioned above, because the residual endosperm in UWB is a brittle material and its density is higher than that of pure wheat bran[32], it is easier to obtain superfine powder by low-temperature grinding. As shown in Figure 8d, the yield of the superfine powder of UWB was always higher than that of WWB. When the grinding temperature was lowered, there was always a difference in the yield of superfine powder of UWB and WWB. When the grinding temperature is too low, the two types of wheat bran start to become brittle and hard materials, resulting in a gradual decrease of their micro powder quality, as shown in Figure 10. The variations of particle size parameters $D_{50}$ and $D_{90}$ of the two types of wheat bran micro powders with grinding temperature are consistent. Meanwhile, when the grinding temperature is −30°C, the superfine powder yields of UWB and WWB start to decrease, as shown in Figure 8d. Therefore, too low a grinding temperature is not always conducive to improving the vibration superfine grinding performance of wheat bran[23,33]. The selection of the optimum grinding temperature is crucial to achieve the desired grinding fineness of wheat bran.

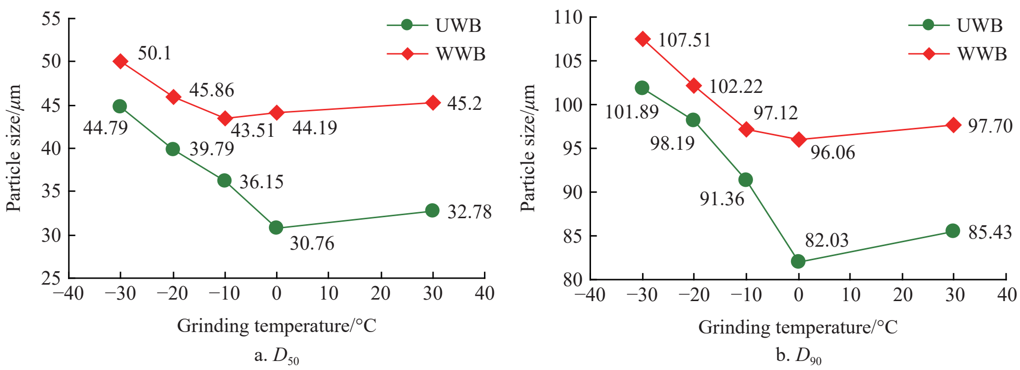


Figure 10 Comparison of particle size parameters ($D_{50}$, $D_{90}$) of UWB and WWB at different grinding temperatures

3.5.2 Effects of washing on superfine grinding performance of wheat bran

As shown in Figure 9, WWB can be obtained after washing the UWB. At this stage, it is equivalent to eliminating the residual endosperm in the UWB. George et al.[22] found that washing has a significant effect on the physicochemical properties such as water binding capacity, thermal properties, and components such as insoluble dietary fiber, soluble dietary fiber, and total dietary fiber of wheat bran. In addition, the temperature also affects the release of some temperature-sensitive substances during the drying process of wheat bran[34]. The color of wheat bran changed from light amber to dark amber due to the washing, which changed the content of different components in wheat bran. Therefore, in theory, WWB is not completely equivalent to pure wheat bran, and there are still some differences between them. Of course, the effect of this difference on the superfine grinding performance of wheat bran is smaller and can be ignored. Therefore, according to Equation (7), the relationship between the mass fraction of superfine powder of residual endosperm in UWB and the grinding temperature can be approximately obtained as follows:

$$y_{s\text{RE}} = y_{s\text{UWB}} - y_{s\text{WWB}} = -0.0109x + 4.5560 \tag{9}$$

where, $y_{s\text{RE}}$ is the mass fraction of residual endosperm micro powder, %. Of course, Equation (9) is not really accurate, but it can at least qualitatively characterize the relationship between the yield of superfine powder and the grinding temperature of residual endosperm in UWB. As the grinding temperature decreases, the yield of residual endosperm superfine powder increases continuously. Therefore, the superfine grinding performance of endosperm can also be improved by reducing the grinding temperature[34], but the sensitivity of its yield is less than that of WWB and UWB.

As mentioned above, the density of UWB should also be between the density of pure wheat bran and the density of endosperm. Due to the different densities of UWB and WWB, the suspension and volume distribution of the two types of wheat bran in the grinding cylinder of the vibration mill will also be different, thus affecting their superfine grinding performance[35,36]. As shown in Figure 8, although the changing trend of the mass fraction of the two types of wheat bran powder at low temperature is consistent, there are still some differences, as shown in Table 7. In summary, the differences are mainly caused by the changes in the physical and chemical properties and components of wheat bran after washing, and these differences are uneven.

## 4 Conclusions

This paper not only investigated the effect laws of low temperature on the vibratory superfine grinding performance of UWB and WWB, but also explored the action mechanism of washing on the vibratory superfine grinding performance of wheat bran. This study can provide references and ideas for the optimization of the yield and quality of wheat bran superfine powder, and contribute to the rapid development of whole wheat foods. The following conclusions were obtained from the low-temperature vibration grinding experiments of wheat bran:

1) The effect of low temperature on the micro powder quality of UWB was greater than that of WWB. The particle size distribution curves of UWB powder changed from the double particle size peak curves to the single particle size peak curves, but the particle size distribution curves of WWB powder were always single particle size peak curves. The similarity of the particle size distribution curves of the two types of bran micro powder decreased with the decrease in the grinding temperature.

2) The effects of low temperature on the yield of superfine powders of UWB and WWB were both very significant and uneven. The mass fractions of the two types of wheat bran superfine powders showed a trend of first increasing and then decreasing with the decrease of grinding temperature, and both had a maximum value at −20°C. Therefore, it is possible to increase the yield of wheat bran superfine powder by adjusting the grinding temperature.

3) Washing reduced the micro powder quality and superfine powder yield of UWB, but did not change the change rules between the powder yields of UWB or WWB and the grinding temperatures. It is more difficult to superfine grind WWB than UWB based on the particle size distribution curves of micro powder and the yields of superfine powder.

4) The residual endosperm in wheat bran not only affects the particle size distribution of the micro powder but also affects the yield of the superfine powder, which leads to the difference in the vibration superfine grinding performance between UWB and WWB. The sensitivity of superfine powder yield of residual endosperm to grinding temperature is lower than that of WWB and UWB. In general, UWB can be ground directly by the low-temperature vibration mill without washing.

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