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Performance Evaluation of Ball Mill Type Grinding Machine for Particle Size Reduction of Porang Glucomannan Crystals

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ABSTRACT

The purpose of this research was to analyze and determine the performance of a ball mill machine for refining porang flour. Research was conducted at PT Daud Teknik Maju Pratama from January – May 2023 by testing a machine with two treatment factors, namely rotational speed (21.2 and 41.6 rpm) and processing time (0.5, 1.0, 1.5, and 2 h). The testing was carried out using 150 g sample for each treatment in triplicates. The response variables included capacity, percentage of size reduction, material losses, engine power, and flour quality. Results showed that the optimum capacity of the ball mill was 12.5 kg/batch. The highest size reduction (96.27%) and lowest material loss (3.73%) was obtained at 21.2 rpm and 0.5 h of milling process. Milling at 41.6 rpm for 2 h produced the best flour quality with moisture content of 11.87% and yield of fine flower (100-mesh) of 63.97%. The power requirements of electric motor was 0.8063 kW at 21.2 rpm and 0.9101 kW at 41.6 rpm. The best milling capacity (1.56 g/min) was resulted at speed of 62.27% CS. The ball mill machine is superior as compared to a disk mill which was not able to grind the glucomannan crystals up to 100-mesh size.

1. INTRODUCTION

Porang (*Amorphophallus muelleri*) is a type of tuber plant originated from West Africa. Porang thrives in lowland areas with an altitude of 100–600 masl (meter above sea level). The ideal conditions for porang cultivation include a temperature range of 25–35°C and an annual rainfall of 1,000–1,500 mm (Saleh *et al*., 2015). Tropical climates, like in Indonesia, are suitable for porang cultivation. According to the Ministry of Agriculture (Kementan, 2021), the existing area of porang in Indonesia was 19,950 ha in 2020, increasing to 47,461 ha in 2021. By 2024 it is targeted that the porang plantation area will reach 100,000 ha.

Hidayah *et al*. (2022) demonstrated that porang tubers can reach a weight of 3 kg. Porang tubers, rich in glucomannan content, are commonly utilized because glucomannan is a water-soluble chemical functioning as a thickening agent (Swasembada, 2021). Research by Wigoeno *et al*. (2013) indicated that glucomannan content in porang tubers ranges from 50.84% to 70.70%. Porang tubers also contain high levels of starch, along with proteins, fiber, and fats, making them a viable alternative for food sources (Syaefulloh, 1990). Saputro *et al*. (2022) found that glucomannan flour can be used as a heat-resistant chocolate mixture. These benefits drive high market interest in porang commodities. Porang flour has superior content in glucomannan as compared to other tubers. Its exceptionally high glucomannan content makes porang highly valued in the food, pharmaceutical, and cosmetic industries. Porang glucomannan flour is known for its excellent quality in forming high viscosity gel, a desirable trait in industrial applications.

Hamdhan (2020) noted that in recent years, porang has become one of the sought-after export commodities. According to IQFAST (2021), porang exports from Indonesia increased by 160.72% in 2021 compared to that 2019, reaching 14,800 tons. BPS (2021) recorded the export value of porang commodities at US$ 29.4 million. Wigoeno *et al*. (2013) mentioned that producing 1 kg of glucomannan flour requires 2–3 kg of porang tubers. The price of 3 kg of porang tubers, equivalent to 1 kg of pure glucomannan flour, is Rp 6,600, while 1 kg of pure glucomannan flour is priced at Rp 400,000. The significant price difference between porang tubers and glucomannan flour emphasizes the importance of processing. Glucomannan flour production involves refining porang flour into wet glucomannan crystals with a particle size of 60 mesh (Prawiro, 2011). These wet glucomannan crystals are then dried until the moisture content is <12%. Further refinement is needed to achieve the market-required glucomannan flour specifications, which are 100–140 mesh (SPB, 2022).

A ball mill grinding machine can be utilized for the refining process of glucomannan flour. According to (Widjanarko *et al*., 2015), the ball mill method is promising compared to other machines such as disk mills and hammer mills. The principle of a ball mill is to crush and rub particles evenly due to friction and impact forces. Research by (Mustofa, 2014) showed that finned ball mill can achieve particle sizes down to 100 mesh. Performance testing of the ball mill grinding machine for refining porang glucomannan crystals is necessary as a reference for machine operation feasibility. The aim of this study is to analyze the performance of the ball mill grinding machine to demonstrate regarding the refining yield of porang glucomannan crystals, determining the batch refining capacity, particle size reduction percentage, flour quality, machine working capacity, and energy required in one batch refining process.

2. MATERIALS AND METHODS

This research was conducted from January to May 2023. Equipment testing and sample collection took place in Bogor Regency, specifically at the PT Daud Teknik Maju Pratama. The testing of the refining product was carried out at the Post-Harvest Laboratory and the Food Processing and Agricultural Products Engineering Laboratory, Department of Mechanical and Biosystems Engineering, IPB University. The equipment used in this study included (a) a ball mill grinding machine, (b) a disk mill grinding machine for comparison purposes, (c) a roll meter, (d) a digital scale, (e) a clamp meter, (f) a multitester, (g) a stopwatch, (h) plastic materials, (i) a tachometer, (j) a 100-mesh sieve, (k) a moisture meter, (l) writing tools, a mobile phone, and a laptop. The material used in this study is porang flour that has undergone extraction to obtain crystalline glucomannan content.

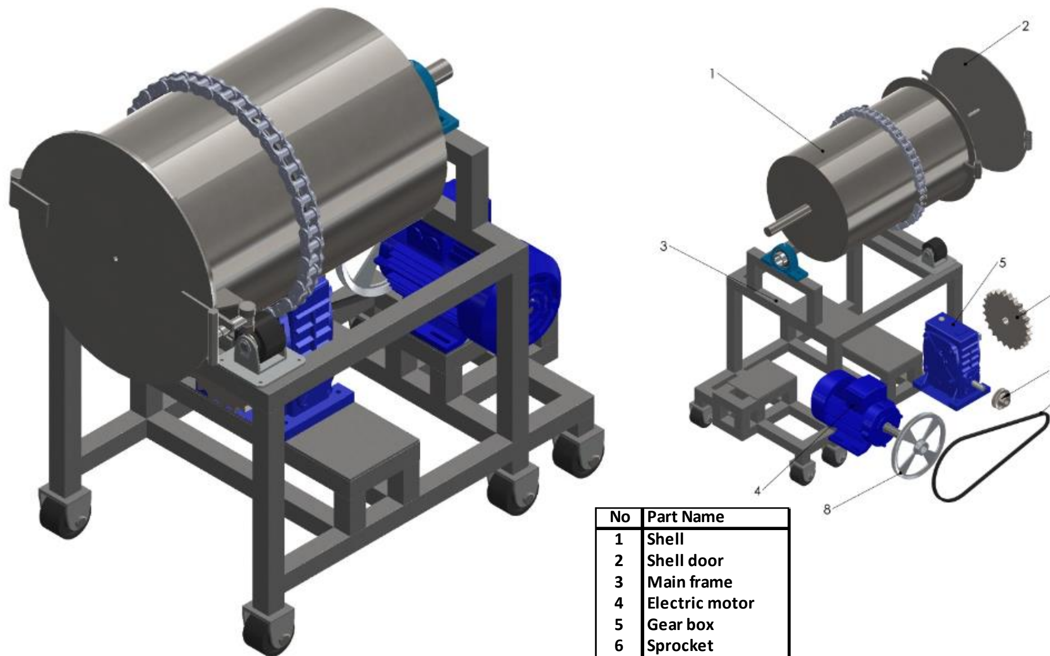
2.1. Machine Construction

The ball mill grinding machine consists of six main parts: the input/output door, shell, assembly frame, transmission system, drive motor, and sound dampener. The construction of the ball mill machine was illustrated in Figure 1.

1. Shell
   The shell is the grinding chamber, shaped like a cylinder with an inner diameter of 40 cm and a length of 60 cm. The inner side of the shell is fitted with four L-iron strips of 3 cm x 3 cm x 60 cm, serving as baffles to ensure the balls and materials falling properly. The shell is filled with iron balls of three different sizes: large (volume: 46.78 cm^3), medium (volume: 41.71 cm^3), and small (volume: 14.91 cm^3). The outer wall of the shell is equipped with a sprocket for transmission, allowing the shell to rotate.

2. Input/output door
   The input/output door functions as an entrance for loading materials before the grinding process and as an exit for processed materials. The door is circular with an inner diameter of 40 cm and an outer diameter of 48 cm. It is equipped with one hinge, one lock, and one handle. The door is also featured with a rubber seal to prevent material leakage during the grinding process, and an air vent to ensure the circulation of hot air generated during the grinding process.

3. Frame
   The frame serves as the support for all machine components, including the motor, gearbox, and shell. The dimension of the frame is 50 cm x 60 cm x 70 cm.



No	Part Name
1	Shell
2	Shell door
3	Main frame
4	Electric motor
5	Gear box
6	Sprocket
7	3-in pulley
8	10-in pulley
9	Belt

Figure 1. Ball mill machine construction

4. Transmission system
   The machine's transmission system consists of a shaft, pulleys, V-belt, gearbox, sprockets, chain, and bearings.
   a) The shaft stabilizes the rotation of the shell during the grinding process and is located behind the shell, connected to bearings.
   b) Pulleys serve as the seat for the belt and regulate the machine speed. The ball mill machine uses two pulleys: the first is connected to the electric motor (10-inch diameter), the second to the gearbox (3-inch diameter).
   c) The V-belt (B-44) transmits rotation from the pulley of the electric motor to the machine's gearbox.
   d) The gearbox reduces the speed from the electric motor. The input shaft is connected to a 3-inch pulley, and the output shaft is connected to a sprocket. The gearbox ratio used in the ball mill grinding machine is 1:60.
   e) Sprockets transmit force from the gearbox to the shell. The sprocket used has a diameter of 8 inches.
   f) A chain is installed around the shell tube with a diameter of 16 inches. The chain receives force from the gearbox and rotates the shell tube.
   g) Bearings support the shell shaft to rotate smoothly. Bearings are mounted on the frame assembly for stability.

5. Drive motor
   The grinding machine is powered by a three-phase electric motor with a delta connection, supplied with a voltage of 380 volts. The power used is 1.5 kW with a rotational speed of 1400 rpm.

6. Sound silenter
   The sound silenter is designed to reduce noise generated by the ball collisions during the grinding process. The sound silenter box of 70 cm x 110 cm x 120 cm is lined internally with egg crate foam as the primary sound-absorbing material.

2.2. Data Collection

The data collection process began with preparing the materials and tools, followed by checking the ball mill machine for testing. The initial checking included testing the condition and functionality of the equipment and inspecting the specifications of the ball mill machine. Inspection involved measuring the dimensions of each machine part, motor specifications, transmission system from motor to shell, and the quantity and size of balls used. The crystal glucomannan material underwent initial characteristic measurements, including moisture content and particle size. Moisture content was measured using a moisture meter with three repetitions. The average moisture content of the crystal glucomannan was determined to be 16.5%. Particle size measurement was conducted using a 100-mesh sieve. A 100-gram sample of crystal glucomannan was sieved for 5 minutes, with three repetitions. The percentage of crystal glucomannan material passing through the 100-mesh sieve was found to be 1.1%.

The research method for refining crystal glucomannan using the ball mill machine involves two factors, namely the rotational speed of cylindrical shell and grinding duration. The rotational speed factor had 2 levels, achieved by changing motor pulleys to sizes 5 inches and 10 inches. The measured rotational speeds of were 21.2 rpm and 41.6 rpm. The grinding duration factor had 4 levels, referring to a study by Widjanarko *et al*. (2015): 0.5 h, 1 h, 1.5 h, and 2 h, with 3 repetitions. A total of 24 experimental units were required to test the ball mill machine. Testing using a 2880 rpm disk mill was also conducted for comparison. The disk mill testing involved 3 repetitions.

The material used was glucomannan crystal, weighed at 150 grams for each experimental unit before grinding. During the grinding process, electric current was measured using an ampere clamp and voltage was measured using a multimeter on the ball mill's electric motor. Measurements were repeated three times for each shell rotational speed factor. The refined crystal glucomannan was then weighed and its moisture content was measured. Subsequently, 100 grams of the resulting flour was taken for sieving using a 100-mesh sieve for 5 minutes, with three repetitions. The sieved flour was weighed to determine the yield of the fine flour.

2.2.1. Critical Rotational Speed

Critical speed (CS) is the rotational speed at which the centrifugal force equals the gravitational force on the surface within the shell. The balls will stick to the shell wall, and no ball will fall from its position to the shell (POA, 2022). The larger the diameter value within the shell, the smaller the CS value will be. The *CS* (rpm) value was calculated using Equation (1) (Energosteel, 2020), where D is the inner diameter of the shell (m).

$$CS = \frac{42.3}{\sqrt{D}} \tag{1}$$

2.2.2. Batch Milling Capacity

Batch milling capacity is the ability to accommodate a certain mass or volume within a machine. The determination of the batch milling capacity of a machine begins with establishing the volume of the shell cylinder using Equation (2):

$$V_s = (\pi \times r^2 \times l) - (4 \times V_\Delta) \tag{2}$$

where V_s is volume of the shell, r is the radius of the shell cylinder (m), l is the length of the shell cylinder (m), and V_Δ is the volume of the triangle within the shell (m^3)

Once the volume of the shell is known, the calculation of the volume capacity of the material is performed. The optimal composition for the ball mill shell space is recommended to be 50% balls, 25% material, and 25% empty space (POA, 2022). Subsequently, the refining volume capacity (*KVP*) was determined using Equation (3):

$$KVP = 0.25 \times V_s \tag{3}$$

The milling capacity (*KTP*) can be determined using the density of the glucomannan crystal, ρ_t (kg/m^3). The capacity of each refining batch was determined using Equation (4):

$$KTP = \rho_t \times KVP \tag{4}$$

2.2.3. Machine Working Capacity

Machine working capacity is the ability of a machine to perform a process with a specific quantity and time. The machine capacity value was obtained by comparing the mass of the material with the processing time of the machine. The determination of the performance capacity of the ball mill machine was done using Equation (5):

$$KKP = \frac{m_l}{t} \tag{5}$$

where *KKP* is the machine working capacity (g/min), m_l is the refining batch capacity (g), and *t* the refining time (min)

2.2.4. Size Reduction of Glucomannan Crystals

The percentage size reduction (η) is the percentage of the resulting flour mass compared to the processed material mass (Sugandi *et al*., 2019). The calculation was done using Equation (6):

$$\eta = \frac{m_t}{m_o} \times 100\% \tag{6}$$

where m_t the weight of the refined flour, and m_o is the initial weight of the material (g).

2.2.5. Refining Loss Percentage

Refining loss percentage (*ST*) is the percentage of the lost flour mass compared to the processed material mass (Sugandi *et al*., 2019). The *ST* was calculated using m_{tc} (the weight of the lost flour, g) according to Equation (7):

$$ST = \frac{m_{tc}}{m_o} \times 100\% \tag{7}$$

2.2.6. Machine Energy Requirement

The determination of the energy requirement for the ball mill machine starts with determining the power requirements of its electric motor. The power of a 3-phase electric motor is obtained from the calculation of voltage, electric current, and power factor (cos φ). According to Bird (2007), in a star connection, the line current (*IL*) is equal to the phase current (*IP*), but the line voltage (*VL*) is equal to √3 times the phase voltage (*VP*). Therefore, the power output per phase is given by Equation (8):

$$P_P = (\frac{1}{\sqrt{3}} \times V_L) \times I_P \times \cos\varphi \tag{8}$$

The output power was determined for each phase, so that three electric motor power values were obtained. The determination of the total electric motor power (P_{out}) was done by using Equation (9):

$$P_{out} = P_{PR} + P_{PS} + P_{PT} \tag{9}$$

where P_{PR}, P_{PS}, and P_{PT} are the power (W) in phases R, S, and T, respectively. The energy requirement (*W*) for the ball mill machine was determined using Equation (10):

$$W = P_{out} \times t \tag{10}$$

The total cost of electricity expenditure (*TBL*) at each processing time was calculated using the electricity tariff (*TL*, Rp/kWh) according to Equation (11):

$$TBL = W \times TL \tag{11}$$

2.2.7. Quality of Glucomannan Flour

The quality of flour was determined based on standardized parameters of glucomannan flour quality, including moisture content and particle size. The moisture content of glucomannan flour was determined using a moisture meter and was repeated three times for each sample. The determination of the particle size of glucomannan flour was done by sieving the flour. Sieving is a method of classifying grains that can be separated into one or more groups, separating fine particles that pass through the sieve and those left on the sieve are coarse (Syamsunarto & Yohanes, 2018). The sieving process was performed manually using a 100-mesh sieve. Sieving was done by taking 100 g from each sample. The sample is then placed on the sieve, and hand movement was used to tap and rotate the sieve for 5 min with three repetitions. The percentage of fineness (*TH*) of glucomannan flour was calculated using Equation (12), where m_f is the weight of the flour passing through a 100-mesh sieve (g), and m_s is the sample weight (g).

$$TH = \frac{m_f}{m_s} \times 100 \tag{12}$$

2.3. Data Analysis

The obtained data was then processed to determine the refining batch capacity, machine performance capacity, size reduction percentage, fines loss in refining, machine energy requirements, standard deviation, and flour quality.

3. RESULTS AND DISCUSSION

3.1. Critical Rotational Speed

The rotational speed of the shell in a ball mill machine is a key factor influencing the refinement outcomes of materials. The shell's rotational speed in a ball mill machine is closely related to the critical speed. Critical speed (CS) is the rotational speed at which centrifugal force equals gravitational force at the surface within the shell of the ball mill machine. The balls will adhere to the shell's wall if the rotational speed of the shell exceeds its critical speed. The optimum rotational speed of the shell is typically between 60% and 65% of its critical speed value (POA, 2022). The research was conducted using a shell with a specified diameter of 40 cm, which results in critical speed (*CS*) of the ball mill machine 66.8 rpm. Machine testing was carried out by varying the pulley size on the electric motor, with two speed factors. The pulleys used had diameters of 5 inches and 10 inches. The measured rotational speeds of the shell using a tachometer showed consecutive average speeds of 21.2 rpm and 41.6 rpm. The critical speed values utilized in this study are presented in Table 1.

Table 1. Percentage of critical speed values for ball mill machine

Machine Type	Pulley Size (inch)	Shell Rotational Speed (rpm)	Shell Rotational Speed (%*CS*)
Ball mill	5	21.2	31.73
Ball mill	10	41.6	62.27

The lowest critical speed percentage in the ball mill machine testing was 31.7% CS using a 5-inch diameter pulley. According to (POA, 2022), this rotational speed is expected to result in minimal energy imparted to the material by the balls, leading to suboptimal material refinement. The critical speed percentage with a 10-inch diameter pulley is 62.27% CS. This value represents an optimal rotational speed for the ball mill machine (POA, 2022), and material refinement at this speed is expected to be more effective. A comparison illustration of the shell's rotational speed between 31.73% CS and 62.27% CS is shown in Figure 2.

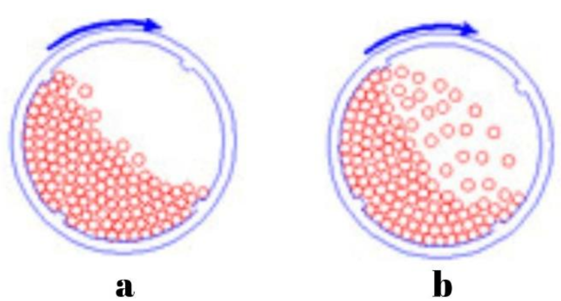


Figure 2. Comparison of rotational speed as the %CS values (POA, 2022): (a) 31.73% CS, (b) 62.27% CS

3.2. Optimum Machine Capacity

The machine's working capacity indicates its ability during milling with a specific quantity and time. The calculation of the working capacity begins by determining the material holding capacity per batch of refinement. The calculation involves determining the optimal volume capacity of the material (25% of shell volume) (POA, 2022). After obtaining the optimal volume capacity value, the material holding capacity is calculated using the density of glucomannan crystal. The result of the mass capacity per batch is then divided by the testing time to obtain the machine's working capacity. The values for the ball mill machine's working capacity in this study are presented in Table 2.

Table 2. Relationship between milling time and optimum batch work capacity

Milling time (h)	0.5	1.0	1.5	2.0
Milling capacity (kg/h)*	25.00	12.50	8.33	6.25

Note: *at a constant capacity of 12 kg/batch

The volume shell calculation results in a value of 74,280 cm^3, leading to an optimal material volume capacity (25% of shell volume) of 18,570 cm^3. The measurement of the optimal material holding capacity is done by multiplying the optimal material volume by the density of glucomannan crystal, which is measured at 0.673 g/cm^3. The material holding capacity is found to be 12,502.63 g or equivalent to 12.5 kg. The ball mill machine used in this experiment is batch-type so that the capacity of the machine will be consistent at 12.5 kg/batch. The calculation of the machine's working capacity per unit time is done by dividing the batch working capacity by the testing time. This study was conducted with four time process variables: 0.5 h, 1 h, 1.5 h, and 2 h. The machine's working capacity values for ball mill testing at 0.5 h, 1 h, 1.5 h, and 2 h are 25 kg/h, 12.50 kg/h, 8.33 kg/h, and 6.25 kg/h, respectively. The machine's capacity decreases with increasing time during the milling process due to a fixed input mass and increasing process duration. An illustration of the optimum ball mill capacity is shown in Figure 3.

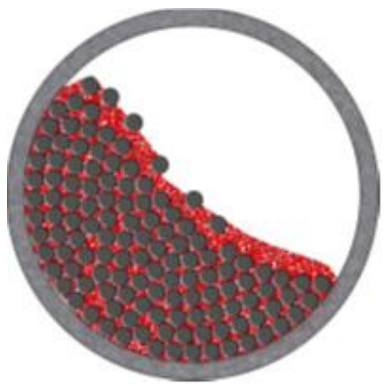


Figure 3. Illustration of optimum capacity

3.3. Loss Percentage in Grinding

The loss percentage indicates the ratio between the weight of spilled material and the weight of milled material, multiplied by 100%. The loss percentage is obtained by calculating the amount of flour lost during the grinding process. The relationship diagram of the loss percentage against milling time is shown in Figure 4. The results indicate that the average loss percentage in the grinding process using the ball mill machine ranges from 3.73% to 20.11%. The highest loss percentage using the ball mill machine at a rotational speed of 62.27% CS during a 2-h process has an average loss percentage of 20.11%, while the lowest value is 3.73% at a rotational speed of 31.73% CS during a 0.5-h process. The loss percentage value for the disk mill machine is 5.73% at a rotational speed of 2880 rpm. The relationship diagram between loss percentage and time shows an increase in the loss percentage value with the increasing milling process time. Additionally, higher rotational speeds of the ball mill machine result in higher loss percentages. The difference in loss percentage values between rotational speed of 31.73% CS and 62.27% CS is small at a processing time of 0.5 h, at 0.49%. The difference becomes relatively higher at a processing time of 2 h, reaching 10.07%. This difference tends to increase with the extended milling process time. The spilling of flour occurs because the ball mill machine is designed with doors for material entry and exit, along with ventilation openings, allowing flour to escape through these spaces. The shell door and air ventilation are shown in Figure 5. These ventilation openings allow flour to escape from the milling chamber. The relatively high speed causes flour to fly in

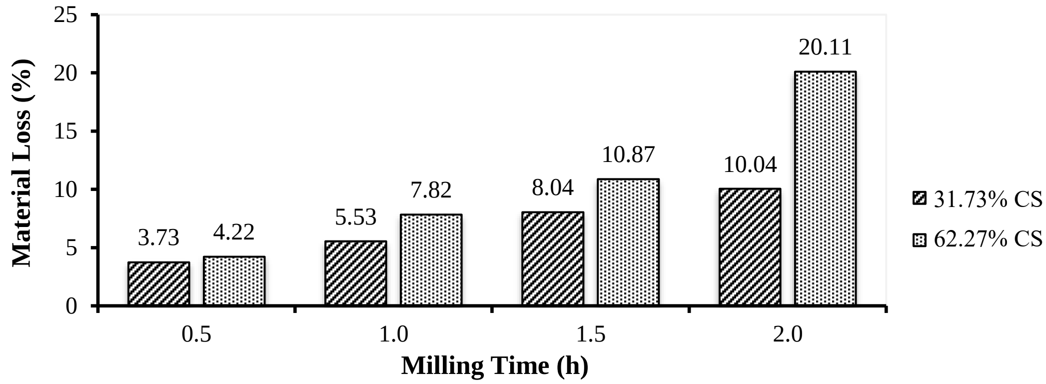


Figure 4. Relationship between material loss and milling duration

Figure 5. Ball mill machine air ventilation

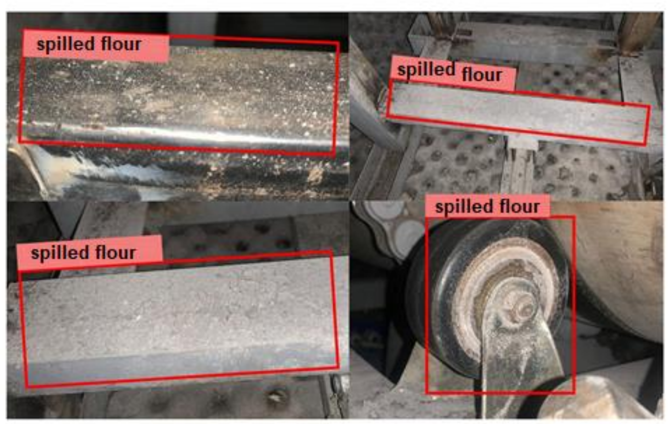


Figure 6. Observation of spilled flour during a 2-h milling process

the milling chamber and be pushed out through ventilation. The 2-h milling process leads to an increased amount of flour being expelled through the air vents. A good solution to increase particle size reduction percentage is to add a collector equipped with a sieve to the ventilation holes of the ball mill machine. This allows the flour to collect while maintaining air circulation. Observations show spilled flour around the ball mill machine, as illustrated in Figure 6.

Based on observations during testing, this occurs because the longer the milling process, the more flour adheres to the inner walls of the shell and the balls. This may be due to the still relatively high moisture content of the material. Therefore, reducing the moisture content during testing is necessary to minimize flour adhesion to the shell walls. Documentation of the shell condition after the milling process is shown in Figure 7.

Figure 7. Shell condition after a 2-h milling process

Table 3. Electric motor power requirement for the ball mill machine

RPM	Line Voltage (V)			Phase Current (A)			Phase power (W)			Power (W)
	V_{RS}	V_{ST}	V_{RT}	I_R	I_S	I_T	P_R	P_S	P_T	
21.2	396	398	400	1.60	1.53	1.37	285.5	274.8	246.0	806.3
41.6	397	399	401	1.80	1.63	1.63	321.5	293.5	295.2	910.2

3.4. Machine Power Requirement

Power requirement is obtained from the calculation of voltage and current on the electric motor. Measurements were taken at two shell rotational speeds: 21.2 rpm and 41.6 rpm. The values for the electric motor power requirement can be seen in Table 3. The ball mill machine is powered by a three-phase electric motor with a star connection. Three-phase electricity is commonly used in the industrial sector. Current and voltage values were measured using a clamp meter and multimeter, while power factor value was obtained from the specifications of the electric motor. Based on the data, the power required by the electric motor at a shell speed of 21.2 rpm is 806.3 W, and is 910.2 W at a shell speed of 41.6 rpm. The difference in power for different motor speeds is significant, and it occurs due to the increased shell rotational speed. This is supported by the statement of Sumariana (2008) that high rotational speed requires a proportionally higher power for the milling process. Based on the calculation, the power requirement for each milling process time and the corresponding electricity cost for each process are shown in Table 4. The electricity tariff values in Table 4 refer to electricity power prices PLN (2023) from April to June 2023 for the B-2 category, which is Rp 1444.70. This is because the B-2 category is for large businesses with a power range of 6600 VA – 200 kVA. The calculated total electricity expenses for the ball mill machine have an average cost range of Rp 582.00 to Rp 2630.00. The lowest cost is for the ball mill machine at a rotational speed of 21.2 rpm during a 0.5-h process, at Rp 582.00, while the highest cost is Rp 2630.00.

Table 4. Electric power requirement and total electricity cost for the ball mill machine

Rotational speed (rpm)	Time (h)	Power (kW)	Power requirement (kWh)	Electricity tariff (Rp/kWh)	Total cost (Rp)
21.2 (31.73% CS)	0.5	0.8063	0.403	1444.7	582
	1.0		0.806		1165
	1.5		1.209		1747
	2.0		1.613		2330
41.6 (62.27% CS)	0.5	0.9101	0.455	1444.7	657
	1.0		0.910		1315
	1.5		1.365		1972
	2.0		1.820		2630

3.6. Flour Quality

The quality testing of flour in this study consists of two factors: flour moisture content and particle size quality. According to SPB (2022), the good quality standards for glucomannan flour are a moisture content of ≤ 12% and particle size passing through mesh 100 – mesh 140..

3.6.1. Moisture Content

Moisture content is the amount of water contained in a material. Moisture content measurement for flour was conducted on the initial material and the material after the milling process. Initial moisture content measurements were performed with three repetitions, resulting in an average initial moisture content of 15.5%. Final moisture content measurements were taken after the milling process for each testing sample. The graph showing the relationship between material moisture content and milling time is illustrated in Figure 8.

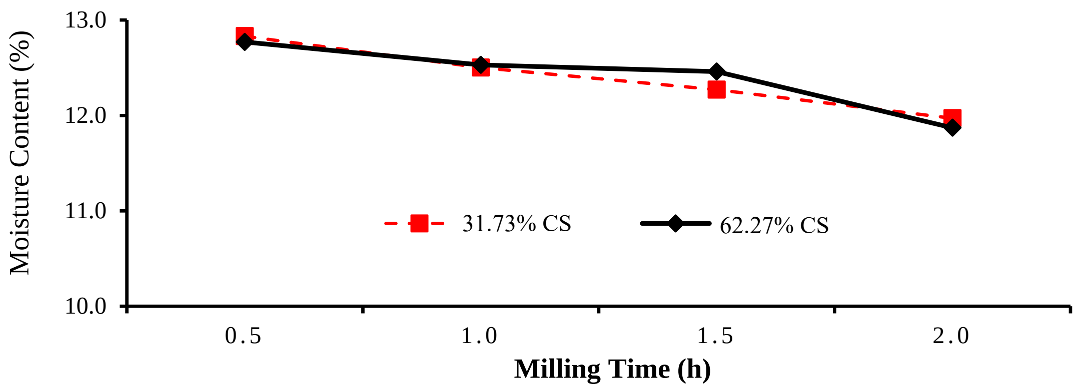


Figure 8. Relationship between final moisture content and milling time

Results of the moisture content measurements show that the average percentage of the final moisture content in the material using the ball mill ranges from 11.87% to 12.83%, while the average final moisture content for the disk mill machine is 13.83%. These findings indicate that the moisture content of the flour using the ball mill is better compared to the disk mill. However, when compared to the standard moisture content for glucomannan flour (≤ 12%), the results do not fully meet the standard. The glucomannan flour moisture content that meets the standard is only observed in treatments with rotational speeds of 31.73% CS and 62.27% CS during a 2-h process, with values of 11.97% and 11.87%, respectively. This outcome may also be attributed to the high water content in the crystalline glucomannan material. To address this, it is essential to consider reducing the water content in the material for more optimal results.

The graph in Figure 8 illustrates that the grinding process using the ball mill results in a decrease in the moisture content of the flour. The reduction in flour moisture content appears to be consistent with the duration of the milling process. The difference in moisture content reduction concerning rotational speed does not show significant variations. Calculations indicate that the average moisture content reduction using the ball mill ranges from 2.67% to 3.63%, while the reduction in moisture content using the disk mill is 2.67%. The highest reduction in moisture content is achieved with the ball mill at a rotational speed of 62.27% CS during a 2-h process, with an average value of 3.63%, while the lowest is 2.67% with the ball mill at a rotational speed of 31.73% CS during a 0.5-h process. The reduction in moisture content is a result of the size reduction process. The particle size reduction causes the separation of water molecule bonds in the material, leading to evaporation due to the heat generated during the collision process. The duration of the process is directly proportional to the reduction in size, so at a 2-h treatment, the moisture content of the flour is lower compared to a 0.5-h treatment.

3.6.2. Particle Size

Particle size is a concept introduced to compare the dimensions of solid particles. According to SPB (2022), good quality glucomannan flour should have particle sizes between 100 mesh and 140 mesh. Therefore, the measurement of glucomannan flour particle size was conducted using a 100-mesh sieve. Sieving was done manually by tapping and rotating with hands. The fineness percentage is the result of dividing the mass of flour passing through a 100-mesh sieve by the mass of the material to be sieved, multiplied by 100%. Initial fineness measurements were repeated three times, with an average initial fineness of 1.1%. The relationship diagram between flour fineness and milling time is shown in Figure 10.

The measurement data on flour fineness quality shows that using the ball mill machine can reduce the size of glucomannan crystal particles to pass through a 100-mesh sieve. The average percentage range of flour fineness is between 15.90% and 63.97%. The comparative data for grinding using the disk mill at a rotational speed of 2880 rpm shows that the disk mill machine is still unable to reduce the size of glucomannan crystal particles effectively. The average glucomannan flour fineness that the disk mill machine can achieve is 3.07% over a 60-min process. The highest percentage of flour fineness is achieved with the ball mill machine at a rotational speed of 62.27% CS during a 2-h process, with an average value of 63.97%, while the lowest is 15.90% with the ball mill machine at a rotational speed of 31.73% CS during a 0.5-h process.

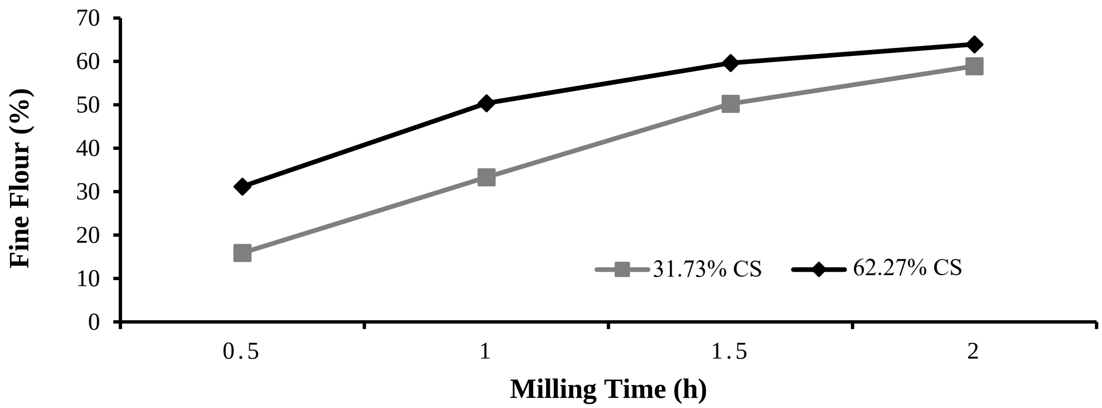


Figure 10. Relationship between flour passing through a 100-mesh sieve and milling time

The graph in Figure 10 indicates that the milling duration influences flour fineness. The longer the milling process, the finer the flour produced in each process. This is also supported by research (Sigit, 2013) on the milling of porang chips using a ball mill machine, which states that a longer milling treatment produces smaller particle sizes. Particle size reduction is influenced by the friction and pounding forces applied by the grinding balls continuously over an extended period in the ball mill drum. (Barbosa-Cánovas *et al*., 2005) state that the grinding balls, as pounding media, also overlap each other and provide frictional force to the material being pounded. The comparison of fineness results with shell rotational speed also shows significant differences. Grinding results with a shell rotational speed of 62.27% CS show better results compared to a rotational speed of 31.73% CS. This aligns with the statement of POA (2022) that a shell rotational speed of 60%–65% CS is an optimum speed for the ball mill machine in size reduction because it provides optimum energy.

3.7. Milling Capacity

Milling capacity is the machine's ability to process or mill a certain amount of material within a specific period (Naito *et al*., 2018). Milling capacity is calculated by dividing the amount of finely milled material by the processing time. The determination of milling capacity involves finding the processing time to mill 50 g of material at two rotational speeds (21.2 rpm and 41.6 rpm). The results show that treatment at 21.2 rpm requires a processing time of 60.04 min, while 41.6 rpm requires 32.05 min.

Figure 11 illustrates the results of the milling capacity values at two rotational speeds (21.2 rpm and 41.6 rpm). The calculations show that the milling capacity of the ball mill machine at 21.2 rpm is 0.83 g/min, while the milling capacity at 41.6 rpm is 1.56 g/min. These results indicate that the ball mill machine at a rotational speed of 41.6 rpm is the best treatment. The milling capacity of the ball mill machine at 41.6 rpm is 187.3% better than the milling capacity of the ball mill machine at 21.2 rpm. This suggests that the optimum rotational speed for the ball mill machine is 41.6

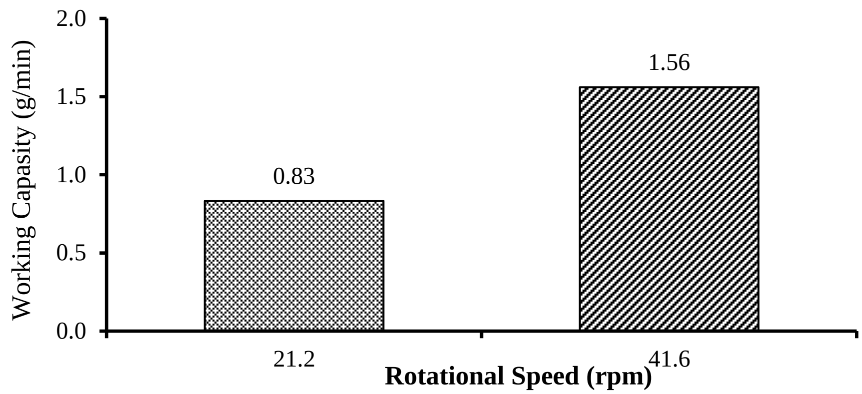


Figure 11. Relationship between milling capacity and rotational speed

rpm (62.27% CS), as per POA (2022), representing the best speed for grinding glucomannan crystals. The optimum speed of the ball mill machine produces optimal collision energy, resulting in faster production of fine flour. The rotational speed of 21.2 rpm (31.73% CS) shows less favorable results because, at this rotational speed, the collision energy provided is relatively lower compared to the optimum speed of 41.6 rpm (62.27% CS).

The comparative disk mill machine shows a significantly lower capacity than the ball mill Calculations indicate that the milling capacity of the disk mill machine is 0.051 g/min. This indicates that the disk mill machine used as a comparison is still unable to effectively grind glucomannan crystals to a particle size that passes through a 100-mesh sieve.

4. CONCLUSIONS AND RECOMMENDATION

The results of the ball mill type grinder machine test indicate the performance of the ball mill machine in grinding glucomannan crystals into glucomannan flour. The machine's loading capacity is 12.5 kg/batch. The best machine performance is observed at a rotational speed of 62.27% CS. Grinding at this speed for a 2-h process shows that the amount of glucomannan flour passing through a 100-mesh sieve is 63.97%. This treatment also demonstrates a water content quality that meets the standard, specifically at 11.87%. A rotational speed of 62.27% CS shows the best milling capacity value, which is 1.56 g/min. The use of a disk mill has not been able to refine glucomannan crystals to a 100-mesh size, while the ball mill machine successfully achieves this. The energy required for the ball mill machine at a rotational speed of 62.27% CS is 0.9101 kW, and at a rotational speed of 31.73% CS, it is 0.8063 kW.

It is recommended to enhance the percentage of flour size reduction in a short period, a modification of the machine is required through the installation of a filter on the machine's ventilation. The solution for the less tight shell door is by replacing the hinges and lock of the shell door. Additionally, it can also involve modifications to the rubber sealing material. This research can be further developed by introducing variables such as grinding time, rotational speed, and the quantity of material to achieve optimal machine performance.

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