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Comparative evaluation of granulometric distribution in grains processed by ball and hammer Mills.

Análisis comparativo de la distribución granulométrica de granos molidos en molino de bolas y molino de martillos.

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Abstract.
The grinding of grains is fundamental in industrial processes, where the resulting particle size distribution directly impacts product quality. This study aimed to compare the granulometric distribution of corn and soybeans processed using a hammer mill, ball mill, and their combination. Samples of corn and soybeans were ground using three configurations: hammer mill, ball mill, and sequential milling with both. The resulting material was sieved to determine weight retained per mesh and calculate characteristic diameters (D10, D50, D90). Additional particle microscopy and ANOVA were performed to evaluate significant differences. The hammer mill produced coarse, heterogeneous distributions, especially for soybeans ($D50 \approx 2.9$ mm). The ball mill generated a higher proportion of fine particles in corn ($D50 \approx 1.38$ mm) but was ineffective for soybeans ($D50 \approx 3.53$ mm). The mill combination achieved the most uniform distribution for both grains ($D50 \approx 1.05$–1.25 mm). ANOVA detected no global significant differences, though morphological and distributional disparities were observed in sieve analysis. The combined milling approach optimized granulometric distribution, overcoming the limitations of each individual equipment.

Keywords.
Granulometric distribution, Hammer mill, Ball mill, Corn grinding, Soybean grinding.

Resumen.
La molienda de granos es fundamental en procesos industriales, donde la distribución granulométrica resultante incide directamente en la calidad del producto. El objetivo fue comparar la distribución granulométrica de maíz y soja procesados en molino de martillo, molino de bolas y su combinación. Se molieron muestras de maíz y soja utilizando tres configuraciones: molino de martillo, molino de bolas y la secuencia de ambos. El material obtenido se tamizó, determinándose los porcentajes retenidos por malla y calculándose los diámetros característicos (D10, D50, D90). Adicionalmente, se realizó análisis microscópico de partículas y ANOVA para evaluar diferencias significativas. El molino de martillo produjo distribuciones gruesas y heterogéneas, especialmente en soja ($D50 \approx 2.9$ mm). El molino de bolas generó un mayor porcentaje de finos en maíz ($D50 \approx 1.38$ mm), pero fue ineficaz para soja ($D50 \approx 3.53$ mm). La combinación de molinos logró la distribución más uniforme para ambos granos ($D50 \approx 1.05$-1.25 mm). El ANOVA no detectó diferencias significativas globales, aunque se observaron disparidades morfológicas y de distribución en el análisis por tamices. La combinación de molinos optimizó la distribución granulométrica, superando las limitaciones de cada equipo por separado.

Palabras clave.
Distribución granulométrica, Molino de martillo, Molino de bolas, Molienda de maíz, Molienda de soja.

1. Introduction

Particle size reduction is a process implemented in various industries, which consists of reducing the physical dimension of solid materials through the application of mechanical forces. This process is essential in operations such as mixing, drying, sintering and chemical reactions, where particle size can influence the speed and uniformity of the process. Commonly used equipment for size reduction include ball mills, hammer mills, jaw crushers, and roller mills. The choice of the right equipment depends on the properties of the material and the desired particle size, being a critical factor for the optimization of industrial processes. [1]

In addition, particle distribution plays a key role, as it directly affects the quality and properties of the final product, such as flow, compaction and dissolution. Particle size analysis is an essential technique for evaluating the particle size distribution in a pulverized material, and the sieve is one of the most widely used pieces of equipment for this purpose. Accuracy in particle classification is vital to ensure product consistency. [2]

Grinding and size reduction not only increase the specific surface area of materials, but also improve their reactivity and facilitate downstream processes such as dissolution, extraction of compounds of interest, and homogenization into mixtures. In the food industry, for example, proper control of particle size helps to optimize the texture, solubility and bioavailability of nutrients, while in the pharmaceutical industry particle size uniformity is key to ensuring the dosage and controlled release of active ingredients. [3]

In the field of construction and mining materials, the efficiency of comminution equipment, such as ball mills

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and hammer mills, has a direct impact on energy consumption and operating costs. It is estimated that up to 50% of the total energy used in a mineral processing plant corresponds to milling operations, which makes equipment selection and particle size optimization strategic factors for process sustainability. In addition, excessive particle reduction can lead to material losses due to fines formation, affecting the overall efficiency of the system.[4]

The hammer mill is one of the most widely used equipment for grain size reduction due to its simplicity of design, low cost, and high processing capacity. Its operating principle is based on the repeated impact of rotary hammers on the particles, which generates rapid fractures and produces materials with a relatively heterogeneous particle size. This type of mill is widely used in the food and feed industry, as it allows grains such as corn, wheat and soybeans to be processed efficiently, although it has the disadvantage of generating a higher content of fines and dust. [5]

On the other hand, the ball mill operates under the principle of impact and friction, where spheres of steel or other grinding material rotate inside a cylindrical drum, causing the gradual reduction of the particle size. Unlike the hammer mill, this equipment allows for a more controlled and finer distribution of particles, with less variability in size. Ball mills are widely used in the mining, ceramics, and pharmaceutical industries, as well as in the research of new materials, although they require higher energy consumption and longer operating times compared to hammer mills. [6]

Particle size analysis by sieving, laser diffraction or other modern methods is used as a quality control tool to establish the size distribution in the processed products. The sieving technique, although traditional, is still one of the most widely used due to its low cost, simplicity and reproducibility compared to more sophisticated methods. The information obtained from these analyses makes it possible to establish correlations between the distribution of particles and the behaviour of the material in subsequent processes, guaranteeing the uniformity of the final product and contributing to the optimisation of the production chain. [7]

The choice between a hammer mill and a ball mill depends largely on the material to be processed and the desired properties in the final product. For grains, the hammer mill is preferred for its speed and efficiency in large volumes, while the ball mill is more appropriate when fine, uniform grinding is required. Both pieces of equipment play a fundamental role in the optimization of industrial processes, and their comparison from the perspective of particle size distribution allows us to identify competitive advantages and areas for improvement in the reduction of particle size. In this context, it is pertinent to highlight the importance of milling in massively used grains such as corn and soybeans, whose processing not only responds to industrial purposes, but also to the optimization of the nutritional and functional quality of the derived products. [8][9]

Despite the widespread use of hammer and ball mills in different industries, there are still gaps in the comparative understanding of their efficiency in the size reduction and in the final particle size distribution of grains such as corn and soybeans. While both equipment serves similar functions, differences in their operating principle, energy consumption, and product uniformity can significantly influence the quality and utilization of processed grains. Recent studies have highlighted that grinding parameters, such as rotation speed, ball loading or screen opening, have a direct impact on the distribution of particles and the nutritional quality of the final product. Comparative research has shown that hammer mills tend to generate more irregular particles and a higher content of fines, while ball mills produce more homogeneous distributions, although with higher energy consumption and operating time. However, most of these studies have focused on individual grains or specific experimental conditions, so a more comprehensive analysis is required that relates both equipment under controlled and comparable conditions. In this way, the present research seeks to provide quantitative and updated evidence that allows to guide technical and economic decisions in the processing of corn and soybeans, strengthening the scientific basis for the selection of the most efficient milling system.[10][11]

In the case of grains such as corn and soybeans, which are widely used in the food and feed industry, milling plays a key role in improving their functional and nutritional properties. In corn, the control of particle size influences the digestibility of starch and the quality of derived products such as flour and cereals, while in soybeans it determines the availability of proteins and lipids, in addition to facilitating their incorporation into balanced formulations for animal feed. Studies have shown that the adequate reduction of the particle size in these grains not only optimizes the performance of the extraction processes and digestibility, but also impacts the [12]energy efficiency of the milling and in the final quality of the product. [13]

Previous studies have specific limitations that require attention. For example, research showed that, in corn milling, the specific energy required varies considerably according to the fraction of the material (grain, stubble, rope), which suggests that the data cannot be directly extrapolated to processed commercial grains. Another study showed that the combination of mills (hammers + rollers) improves the uniformity of particle distribution, but it does not directly compare hammer mills vs ball mills in grains such as corn or soybeans. In the field of ball milling, a study looked at how the diameter of the medium affects milling efficiency, but in mineralization, not in agricultural grains, which leaves a gap in knowledge applicable to the food sector. Consequently, there is a lack of a direct comparison, under controlled conditions of food grains (corn and soybeans), between hammer mills and ball mills, which simultaneously quantifies particle size uniformity, energy consumption and their link with nutritional or procedural functionality. This gap gives relevance and urgency to the present research, aimed at ensuring a solid technical selection of the most suitable grinding system for its industrial application.[14][15][16]

Recent studies indicate that hammer milling can represent up to 50% of a power plant's total electricity consumption. On the other hand, research in biomass shows that the specific energy required for size reduction can vary between 35–65 kJ/kg**,** depending on the type of material and the grinding conditions. In addition, analyses with empirical models indicate that the energy required in ball mills can vary between [17]~**3–12** $kW\cdot h\cdot t^{-1}$ depending on the hardness and desired product size. Therefore, improper selection of the type of mill not only affects the quality of the grind and the particle size uniformity, but can also considerably increase the [18]Operating costs and the Energy consumption, impacting the viability and competitiveness of the industrial process.

Therefore, the objective of this study is to perform a comparative analysis of the particle size distribution of ground grains in ball mills and hammer mills, considering their application in the processing of raw materials such as corn and soybeans. This analysis seeks to establish relationships between the type of equipment, the grinding conditions and the uniformity of the particles obtained, in order to provide technical criteria that guide the selection of the size reduction system based on the efficiency and quality of the final product.

1.1. Grinding

Grinding is a unitary operation which is responsible for reducing the particle size to achieve a size required for a specific process, thus increasing the contact surface of the material for greater efficiency in the industrial process. This reduction is carried out by dividing or fractionating the sample by mechanical means until a required size can be reached.

For Chemical Engineering it is essential to understand the laws that govern disintegration in relation to energy consumption (time), the characteristics of the matter and the type of machines to be used, this demonstrates the study based on deductions and empirical observations. [1]

1.1.1. Types of Grinding

Different types of mills such as ball mill and hammer mill, have different mechanisms of action and efficiency, ball mills are efficient for fixed grinding and hammer mill is more for fragile materials. [19]

1.2. Sieving

The sieving method involves using a series of sieves with different openings to separate soil particles according to their size [20]

1.3. Granulometric analysis by sieving

It is the separation in size of a collection of solid particles according to a particle size scale. This separation is carried out with sieves placed in series, so that the sifting of the first sieve is the feed of the second and so on. [21]
Feeding to the sieve (F): It is the total mass that arrives at the sieve to be separated or classified.
Retained (R): It is the mass that remains on the surface of the sieve.
Sifting (C): It is the mass that passes through the openings of the sieve, that is, that passes through its surface.

1.4. Particle Size Distribution

Particle size distribution describes the proportion of different particle sizes present in a sample. It is essential to characterize the behavior of materials in various industrial processes. [22]

1.5. Granulometric curves

Particle size curves are graphical representations that show the particle size distribution in a sample. These curves are essential to understand the distribution and predictability of material behavior. [23]

2. Materials and methods.

Grinding tests were carried out with two types of grains (corn and soybeans) to evaluate the granulometry that could be obtained from grinding in the ball and hammer mills. We worked with a hammer mill model RBN rose, with 20 hammers with cast bar and 4 shafts, as well as with a tubular, discontinuous steel ball mill, single-chamber, with grate discharge. The calibration of the grinding and sieving equipment was carried out prior to the tests, verifying that all the components: chamber, grinding bodies, sieves and mesh were within their dimensional and mechanical specifications, and ensuring reproducible conditions between replicates. A set of sieves certified to standards equivalent to ASTM E11 / ISO 3310 were used for sieving, and the uniformity of the openings was checked with mesh calibration methods according to recommended procedures in the literature to ensure accuracy and minimize classification errors. The following are the case studies evaluated:

Case 1. Hammer mill grinding and sieving, fig. 1.
Case 2. Ball mill grinding and sieving, fig. 2.
Case 3. Grinding in a hammer mill, followed by the ball mill and sieving, fig. 3.

Once the three cases were carried out, a microscope (Digital Microscope USB) was used to examine the geometry obtained in each type of grinding.

The sampling protocol was established following criteria of representativeness and homogeneity recommended for granulometry studies in agricultural matrices. For each milling treatment, samples were collected immediately after unloading the equipment, employing the manual quartering method to reduce the volume and ensure that the fraction analyzed maintained the original batch distribution. This procedure is widely used in milling studies due to its effectiveness in minimizing size and density segregation biases, especially in grains such as corn and soybeans. Recent research emphasizes that correct homogenization and reduction of batch size is essential to ensure the reproducibility of the particle size distribution, since variations in the sampling protocol can generate differences of up to 15% in the percentage retained by sieve in impact or compression grinding systems. In addition, comparative studies in agricultural milling recommend using between 200 and 500 g as the minimum analytical mass to avoid losses of fine fractions and ensure sufficient representativeness, which was considered in the present work.[24]

For the representation and analysis of the collected data, granulometric distribution graphs of particle size distribution were used. These plots allow the relationship between particle size and the cumulative percentage of the sieved material to be visualized, providing a quantitative and comparative understanding of the particle size distribution.
Finally, the analysis of variance (ANOVA) of a single factor was applied using the Analysis Toolpak complement, which allowed the evaluation of significant differences between treatments.

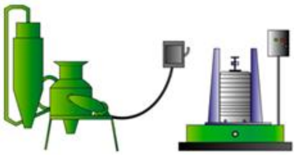


Fig. 1. Case 1. Hammer mill grinding and sieving.

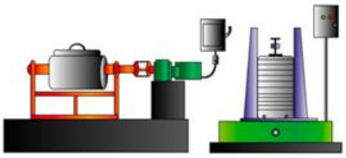


Fig. 2. Case 2. Ball mill grinding and sieving

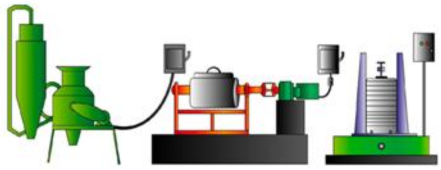


Fig. 3. Case 3. Hammer mill grinding, followed by ball mill and sieving

2.1. Raw material

4540 g of corn and soybeans were used, 2270 g of each grain. Corn with an average diameter of 0.78 mm and grain density of 0.75 g/cm3, soybeans with an average diameter of 0.57 mm and grain density of 0.85 g/cm3.
The moisture of the grain is a determining variable in the efficiency of the milling, as it modifies its hardness, its mechanical response and the resulting granulometry. To maintain experimental stability, the grains were kept in the same batch and stored in a dry environment at a controlled temperature of 22–24 °C, conditions that minimize hygroscopic variation and preserve the physical properties of the material. This approach coincides with recommendations from the literature, which highlight that the simultaneous control of temperature and environmental conditions avoids fluctuations in the internal humidity of the grain and, therefore, in its behavior during the comminution process. This ensures that the observed differences in grain size mainly reflect the performance of the grinding equipment.[25]

2.2. Ball Mill

A ball mill was used, with a ball load configured as indicated in table 1:

Table 1. Configuration of grinding bodies.

Grinding bodies	Average diameter (cm)	Total Weight (g)	% Weight
Small	2.46	5447	18.43
Medium	2.97	9286	31.43
Large	3.89	14815	50.14
Small	2.46	5447	18.43

Source: Bonilla, et al, 2024

The total weight of grinding bodies was 29548 g.
The average weight and equivalent diameter of grinding bodies were determined with the following equations:

$$Peso\ promedio = \frac{\text{peso total de cuerpos moledores}}{\text{número de cuespos moledores}} \qquad [1]$$

Average weight= 126.27 g

$$Diámetro\ equivalente = \left[\left(\frac{peso\ promedio}{densidad}\right)\frac{6}{\pi}\right]^{1/3} \qquad [2]$$

Equivalent diameter=. 3.12 cm

2.2.1. Parameter Calculations for Ball Mill

The ball mill was fed with 2270 g of each grain (corn and soybean) and the working parameters were determined by the following design equations:

Degree of filling (*f*):

$$f = \frac{Volumen\ de\ la\ carga}{Volumen\ del\ molino} x\ 100 \qquad [3]$$

Weight of Grinding Body Load (Q):

$$Q = \frac{\pi}{4} D^2 \; Li \; f \; Yq \qquad [4]$$

Where:
D: Inner diameter of the ball mill, m.
Li: length of the mill, m.
Yq: Equivalent weight of grinding bodies, t/m3

Critical mill speed (nc):

$$nc = \frac{42.3}{\sqrt{D}} \qquad [5]$$

Where:
D: Inner diameter of the ball mill, m

$$n = k \; \mathrm{nc} \qquad [6]$$

Where:
K: Percentage of Critical Speed (75%)
NC: Critical Speed, RPM

Power of the Ball Mill Motor (N):

$$N = c \; D \; Q \; n \qquad [7]$$

Where:
c: power consumption factor, dimensionless
D: inner diameter of the mill, m
Q: Loading weight of ball mill, t
N: Mill Operation Speed, RPM

Specific energy consumption (CEE):

$$CEE = \frac{N}{P} \qquad [8]$$

Where:
N: mill power, kW
P: Ball mill production, t

2.3. Hammer Mill

The grains were placed in the feed mouth, passed through the hammers in a period of 4 minutes and received at the unloading, for weighing and sieving.

2.4. Sieving

The sieves were placed in column in an ascending manner according to the sieve number, which means that the sieve with the highest number will receive the finest material. The column of sieves was placed in the vibrating machine for one minute and then each sieve was weighed and the weight of the retained sieve was collected.

The study process flowchart is shown below in Figure 4.

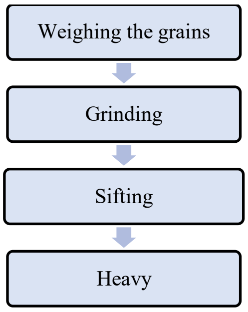


Fig.4. General flow diagram of the process.

2.5. Sieves

The column of sieves used in this study is shown in table 2 with their respective characteristics as follows:

Table 2. Sieve Classification

Mesh Number	Mesh Opening (mm)	Sieve Weight (g)
5	4,00	387
6	3,35	383
8	2,36	372
12	1,70	358
16	1,18	309
18	1,00	303
20	0,85	294
30	0,60	289
50	0,30	255
70	0,212	250
Base	-	270

Source: Bonilla, et al, 2024

3. Analysis and Interpretation of Results.

3.1. Grinding Operating Conditions

The following table 3 presents the working conditions in cases 2 and 3 with both corn and soybean grains.

Table 3. Operating conditions in milling

Parameter	Case 2		Case 3	
Grains	Corn	Soybeans	Corn	Soybeans
Temperature (°C)	27	27	27	27
f (%)	14,13	14,8	14,1	16,51
Q (t)	0,0280	0,0293	0,0279	0,0327
nc (rpm)	68,61	68,61	68,61	68,61
n (rpm) @ 75%	51	51	51	51
N (Hp)	0,194	0,203	0,194	0,203
CEE (kW h / t)	80,61	83,17	80,17	92,70

Source: Bonilla, et al, 2024

Table 3 indicates the conditions used in the ball mill in cases 2 and 3, for both grains worked at room temperature. The degree of filling (*f*) of case 2 with corn presents 14.13% and soybeans 14.8% respectively. The denser the grain, the higher the degree of filling. In case 3 with corn, it presents 14.1% and soybeans 16.51%, these results depend on factors such as the volume of loading of grinding bodies, volume of raw material and volume of the mill. Therefore, corn flour, being denser, occupies less volume in the mill in contrast to soybean meal that occupies a greater volume in it, for this reason a greater load of grinding bodies was required.

It was necessary to determine the critical speed (nc) at which the mill operates in order not to exceed it since it will cause the centrifugal force to equal the force of gravity and the grinding bodies would not descend to the grinding.

The specific energy consumption (CEE) calculated in case 2 with corn had a consumption of 80.61 kW hr/t for each ton processed, in contrast soybeans increased to 83.7 kW hr/t consumed for each ton processed, this is due to the fact that they worked with a higher load of grinding bodies for this grain so the mill had to consume more energy than with corn. finally, case 3, with corn, presented a consumption of 80.17 kW hr/t for each ton produced and soybeans consumed 92.70 kW hr/t for each ton produced, the difference in specific energy consumption (CEE) between the grains in case 3 is due to the density of the soybean grain. In other words, the higher the degree of filling, the higher the specific energy consumption. [26]

3.2. Mill yields

Table 4 compares the percentage of yield of the mills in the three case studies with corn and soybeans.

Case 1. Hammer mill.
The hammer mill presented a higher yield when processing corn grain compared to soybeans, with a difference of 3.5%. This variation is mainly attributed to the difference in densities of the two grains. Corn, being less dense, makes it easier to grind compared to soybeans.

Case 2. Ball mill.
In the ball mill, the highest yield was obtained when grinding both grains compared to the three cases analyzed, due to the ability of the ball mill to process almost all the grain fed with losses attributable to incrustations in the shielding and the mill cover.

Case 3. Hammer mill + ball mill.
The combination of the mills presents a difference between corn and soybeans of 5.47%, in turn it presents a higher percentage of loss compared to cases 1 and 2, this is because the grain goes through two milling processes.
The hammer mill had a superior yield with corn grain compared to soybeans, due to their differences in densities. The ball mill offers a similar performance in both cases, because it does not present a major loss at the time of processing.

Table 4. Mill yields.

	Yield (%)		
	Case #1	Case #2	Case #2
Raw material	Hammer Mill	Ball Mill	Hammer Mill + Ball Mill
Corn	77,05	96,34	74,89
Soy	73,57	96,17	69,47

Source: Bonilla, et al, 2024

3.3. Comparative particle size analysis

3.3.1. Case 1. Hammer Mill with Corn

Figure 5, showing the distribution of particles, which covers a range from 2.33 to 3.7 millimeters, indicates a lack of uniformity in the reduction of size. While the median diameter (D50) is approximately 2.8-2.9 millimeters.

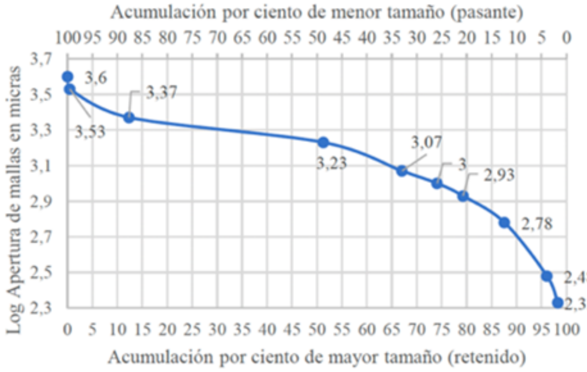


Fig.5. Particle size curve Case 1 (maize)

The data in Table 5 indicate a heterogeneous distribution with a massive concentration in the middle range. Sieve number 12 (2.03 mm/2030 microns) retains 38.94% of the total material, representing the maximum point of distribution. This indicates that the milling process predominantly generates medium-sized particles. Although the coarse fraction is adequately minimized (only 0.47% above 3.68 mm), the low proportion of fines (10.71% under 0.45 mm) suggests inefficiencies in the fracture mechanism, possibly related to rotor speed, residence time, or grain moisture.

Table 5. Experimental data % retained (maize)

Mesh Number	Average particle size (mm)	Average particle size (microns)	% Retained
5	4,00	4000	0,06
6	3,35	3680	0,41
8	2,36	2860	11,87
12	1,70	2030	38,94
16	1,18	1440	15,77
18	1,00	1090	7,04
20	0,85	930	5,18
30	0,60	730	8,32

50	0,30	450	8,50
70	0,212	260	2,21

Source: Bonilla, et al, 2024

3.3.2. Case 1. Hammer mill (soybean)

Figure 6 shows the distribution of particles in a wide range of sizes from approximately 2.3 mm to 3.7 mm, which indicates a heterogeneous grinding with simultaneous presence of fine and coarse particles. The D50 (medium size) is located around 2.9 mm, the point where 50% of the material is thinner and 50% thicker, a value that represents the characteristic size of the final product. The gentle slope of the accumulation curve suggests an extended distribution with significant dispersion in particle sizes. It is observed that approximately 30-35% of the material has sizes greater than 3.1 mm (coarse fraction), while only about 15-20% is below 2.5 mm (fine fraction), evidencing an imbalance towards larger particles**.** The accumulation of retained material indicates that there is a proportion of particles in the medium range (2.7-3.1 mm), representing between 40-50% of the total**.** This distribution suggests that the grinding process generates an excess of intermediate-sized particles, possibly due to operating parameters such as inadequate rotor speed, insufficient residence time, hammer wear, or excessive sieve opening.

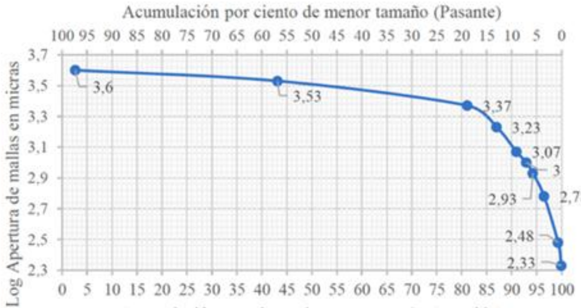


Fig.6. Particle size curve Case 1 (soybean)

The data in Table 6 indicate that the new sieves have a higher percentage of retention for particles in the range of 3680 to 2860 microns, which is associated with the presence of larger particles of soybeans. presence of larger particles of soybeans. In addition, a decrease in the retention percentage is observed for intermediate and small sizes. This trend indicates that the

Table 6. Experimental data % retained (soy)

Mesh Number	Average particle size (mm)	Average particle size (microns)	% Retained
5	4,00	4000	2,66
6	3,35	3680	40,49
8	2,36	2860	37,97
12	1,70	2030	5,87
16	1,18	1440	3,99
18	1,00	1090	1,96
20	0,85	930	1,33
30	0,60	730	2,24
50	0,30	450	2,80
70	0,212	260	0,63

Source: Bonilla, et al, 2024

3.3.3. Case 2. Ball Mill (Corn)

The particle size distribution obtained from the corn mill in the ball mill indicates a wide dispersion of particle sizes. The results in Figure 7 show that the D10 is about 0.48 mm, which means that only 10% of the material is smaller than this value, while the D50 is 1.38 mm, indicating that half of the material is below this size. The 1.96 mm D90 reveals that 90% of the material is smaller than this value. These indicators allow us to infer that the milling produces particles in a considerable range, mostly concentrated between 0.5 mm and 2 mm.

The cumulative distribution shows that the ground material has a significant proportion of coarse particles (>2 mm), approximately 8% of the total, which indicates that the ball mill does not achieve a completely fine grind for all the processed material. The dispersion of particle size is relatively high, as confirmed by the uniformity index **(**D90/D10 ≈ 4.08), indicating that there is a considerable mixture of fine and coarse particles. This characteristic is common in grinding done in ball mills.

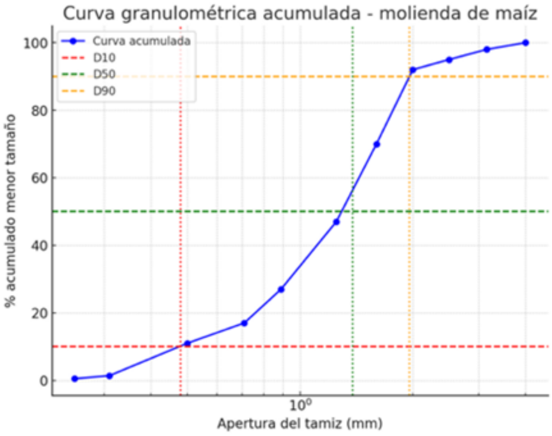


Fig.7. Cumulative particle size curve Case 2 (maize)

3.3.4. Case 2. Ball mill (soybean)

The particle size distribution of the ground soybeans in Figure 8 shows that the material is mostly coarse: the representative parameters are D10 ≈ 1.59 mm**,** D50 ≈ 3.53 mm **and** D90 ≈ 3.94 mm. This indicates that 10% of the particles are smaller than 1.59 mm, the median is 3.53 mm (half of the material is finer than this value) and that 90% is finer than 3.94 mm. These values place most of the mass in the range ~1.6–4.0 mm, with the median close to 3.5 mm. The pitch curve (the through-% in the meshes) has a steep slope in the span between approximately 2.86 mm (18.9% through) and 4.00 mm (97.34% through-screen), which means that a significant fraction of the material passes through large meshes and that the "cut-off zone" of the distribution is centered around 3–4 mm. The fraction of fines (<1 mm) is very small (through-% values at 0.45 mm and 0.26 mm are 0.70% and 0.07% respectively), therefore, the fines are practically insignificant in the final product. The dispersion of the distribution can be quantified with the uniformity index D90/D10 ≈ 3.94 / 1.59 ≈ 2.48, indicating a relatively narrow and fairly uniform distribution around coarse sizes (less dispersion than a very wide distribution). In other words, most of the material is clustered in a fairly compact range (mostly between ~1.6 and ~4 mm), without large tails of very fine particles or a very heterogeneous mix of sizes. From an operational and product quality point of view, this granulometry suggests that the milling process is producing a suitable product when looking for coarse or intermediate meal/particles (e.g. for certain industrial uses or animal feed). If the goal was to obtain finer fractions or increase the proportion of particles <1 mm, it would be necessary to intervene in the process (more grinding time, higher impact energy, adjust load and size of media, or use sorting and recirculation).

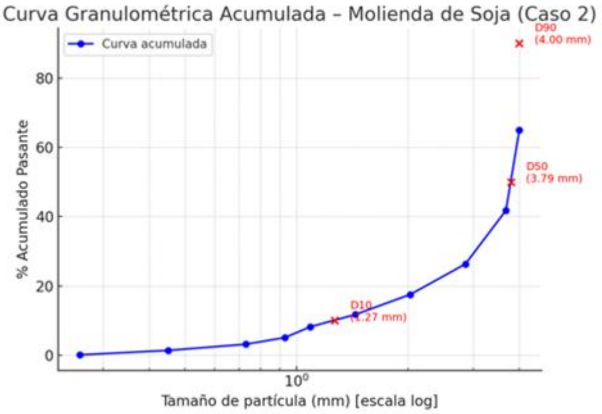


Fig.8. Cumulative particle size curve Case 2 (soybeans)

3.3.5. Case 3. Grinding Hammer Mill + Ball Mill (Corn)

Combined grinding (hammer + balls) generates an intermediate-sized product, with a D50 ≈ 1.08 mm, which means that half of the material is in the range of particles close to 1 mm. The D10 ≈ 0.60 mm indicates the finest fraction of the material, while the D90 ≈ 2.60 mm shows that 90% of the material is below this size, with a wide range of distribution.

The curve accumulated in Figure 9 shows that most of the material is concentrated between 0.6 and 2.6 mm, with a very low fraction of fines (<0.5 mm) (<1%). This indicates that the milling is efficient to produce medium granulometry, without excess powders, a favorable characteristic for uses in animal feed and processes that require an adequate flow without caking.

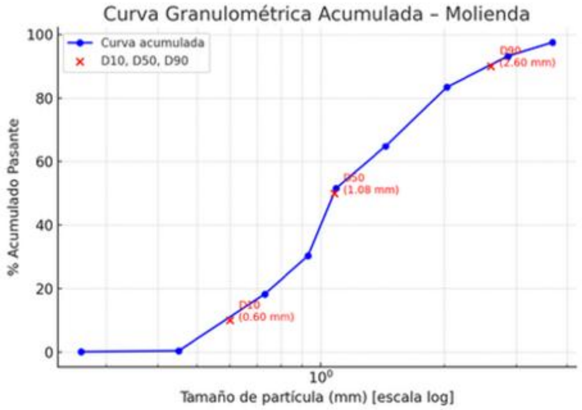


Fig.9. Cumulative particle size curve Case 3 (maize)

The uniformity index, calculated as D90/D10 ≈ 4.3, indicates a wide distribution, with coexistence of fine and coarse particles. This amplitude may be associated with the combination of grinding technologies: the hammer mill breaks more irregularly, and the ball mill refines, but maintains some dispersion.

3.3.6. Case 3. Grinding Hammer Mill + Ball Mill (soybean)

The resulting particle size distribution shows in Figure 10, a clear concentration in the range **≈0.9–1.5 mm**, with D50 ≈ 1.35 mm**,** which means that half of the mass is below that size. The sieving data indicate that the largest quantities were retained in 1.25 mm and 1.00 mm meshes (498 g and 588 g respectively), underlining that the "critical mass" of the material is around these sizes and that the process produced a product of intermediate particle size. The fraction of fines is very small: only 0.94% passes the 0.315 mm mesh and the accumulated through-that mesh is 0.94%, so particles smaller than ≈0.5 mm are practically insignificant. This means low dust generation and greater handling and transport facilities (less aerial dispersion and fewer problems of caking by fines), a positive aspect for logistics and for subsequent processes that benefit from less dusty material. The dispersion of the distribution can be quantified with the uniformity index D90/D10 ≈ 2.05 / 0.77 ≈ 2.66, a value that indicates a relatively narrow **and** homogeneous distribution around the median size. In practice this means that most of the material is grouped in a limited range (low fine tail and moderate coarse tail), which is desirable when looking for reproducibility in rheological, particle size and process properties (mixing, extrusion, pelletizing).

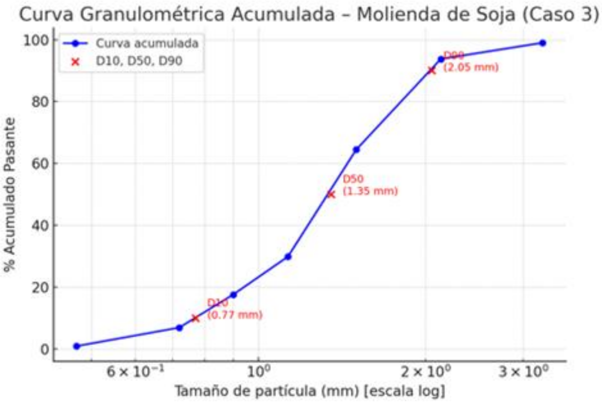


Fig.10. Cumulative particle size curve Case 3 (soybean)

From an operational point of view, these results suggest that the hammer + ball mill combination produced a sufficient reduction for applications requiring intermediate particles.

3.3.7. Comparison of the percentage of retention in each case in the sieves with the smallest and largest aperture.

Table 7 shows a comparison between the three case studies with respect to the percentage of retained obtained in the meshes with the largest aperture (4mm) and smallest aperture (0.121 mm), as well as the retention in the base (<0.212 mm).

Table 7. Comparison of the percentage of detainees.

No. Mesh	Openness (mm)	Case 1 (%)		Case 2 (%)		Case 3 (%)	
		corn	Soy	corn	Soy	corn	Soy
5	4	0,06	2,66	2,47	35,01	0,23	0,77
70	0,212	2,21	0,63	1,12	1,28	1,93	0,28
Base	< 0.212	1,69	0,07	0,04	0,09	0,12	0,14

Source: Bonilla, et al, 2024

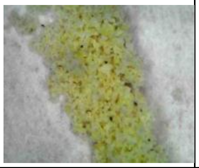
The highest percentage of retention in soybean milling was obtained in case 2 with 35.01%, due to the density of the grain compared to corn. In case 3, a decrease in retention is observed since, having a previous grinding in the hammer mill, smaller particles could be obtained. In the three case studies, it was possible to obtain smaller particles, however, the retention percentages do not exceed 3%. The highest accumulation of retained was obtained in corn milling in all three cases, due to the lower density of the grain. The soybean milling in the three case studies did not reach 1% in those retained in the particles less than 0.212 mm. However, in the maize milling, only in case 1 could 1.69% of retained with particle size less than 0.212mm be obtained.

3.3.8. Microscopic analysis of corn and soybean meal

The microscopic analysis of corn flour shows in table 8, differences in the shape of the particles produced by the different case studies.

Case 1 (Hammer Mill): The particles have a rectangular shape, this suggests that the hammer mill's impact mechanism tends to fragment the particles into angular shapes. Case 2 (Ball Mill). The particles have an oval shape, indicating that the abrasion process in the ball mill tends to round the particles. Case 3 (Hammer Mill + Ball Mill): An intermediate shape between rectangular and oval is observed. This may be due to the combination of both grinding processes, which produces a mixture of particle forms. [27]

Table 8. Microscopic analysis of corn flour

Case 1	Case 2	Case 3
		
Particle size: < 0.212 mm Particle shape: Rectangular.	Particle size: < 0.212 mm Particle shape: oval.	Particle size: < 0.212 mm Particle shape: Between rectangular and oval.

Source: Bonilla, et al, 2024

3.3.9. Microscopic analysis of soybean meal

Microscopic analysis of soybean meal shows the following observations in Table 9.

Case 1 (Hammer Mill): The particles have a rectangular shape, the direct impact of the hammer mill produces angular particles similar to those observed in corn. Case 2 (Ball Mill). Particles have an ellipsoid shape. The abrasion process of the ball mill rounds the particles, generating this shape by the mill's impact method and the characteristics of the grain. Case 3 (Hammer Mill + Ball Mill): A mixture of rectangular and ellipsoidal shapes is observed. This can be a result of process combinations, where pre-grinding in the hammer mill followed by abrasion in the ball mill produces a range of various shapes.

Table 9. Microscopic analysis of soybean meal

Case 1	Case 2	Case 3
		
Particle size: < 0.212 mm Particle shape: Rectangular.	Particle size: < 0.212 mm Particle shape: Ellipsoid	Particle size: < 0.212 mm Particle shape: Between rectangular and ellipsoid.

Source: Bonilla, et al, 2024

3.3.10. Statistical analysis

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An analysis of variance was performed for a factor that allowed in each case to determine if there are significant differences between the results.

3.3.10.1. Case 1. Hammer Mill

Table 10 shows the analyzed data on the weight of the retained in the sieves of corn and soybean grains.

Null hypothesis: The granulometric analysis does not show significant differences between the sieves used. ($p>0.05$)
Alternative hypothesis: The granulometric analysis shows significant differences between the sieves used. ($p<0.05$)

Table 10. Weights of Retained in Sieves Case 1

Mesh (mm)	**4**	**2,36**	**1,70**	**1,18**	**1,00**	**0,85**	**0,60**	**0,30**	**0,212**
Corn (g)	2	55	472	701	296	80	96	37	2.21
Soybeans (g)	38	543	84	57	28	19	32	40	2.93
Critical Value F						4,39			
Probability						0,33			

Source: Bonilla, et al, 2024

The one-factor analysis of variance (ANOVA) applied to the particle size distributions of corn and soybeans shows that there is no statistically significant difference between both milled products, evidenced by a p-value of 0.33, much higher than the usual significance level of 0.05, which indicates that the variations observed in the retained weights in each mesh can be attributed to the randomness of the process rather than to an actual effect of the type of material. However, it may mask relevant practical differences in milling patterns, such as the marked concentration of soybeans in the 2.36 mm (543 g) mesh versus a more uniform distribution of corn, suggesting that, although globally similar, the fracture mechanisms and breakdown characteristics of each material could be influenced by factors not captured by this univariate analysis.

3.3.10.2. Case 2. Ball Mill

Table 11 shows the analyzed data on the weight of the retained in the sieves of corn and soybeans.

Null hypothesis: The granulometric analysis does not show significant differences between the sieves used. ($p>0.05$)
Alternative hypothesis: The granulometric analysis shows significant differences between the sieves used. ($p<0.05$)

Table 11. Weights of Retained in Sieves Case 2

Mesh (mm)	**4**	**2,36**	**1,70**	**1,18**	**1,00**	**0,85**	**0,60**	**0,30**	**0,212**
Corn (g)	55	62	482	511	447	202	153	217	1.63
Soybeans (g)	762	338	192	127	77	68	42	39	1.28
Critical Value F						4,49			
Probability						0,61			

Source: Bonilla, et al, 2024

The analysis of variance (ANOVA) of a factor applied to the particle size distribution data of corn and soybeans ground in a ball mill indicates that there is no statistically significant difference between the distributions of both grains, evidenced by a p-value of 0.612, much higher than the significance level of 0.05, and an F-value (0.267) that does not exceed the critical value (4,494). Although the means of the retained weights differ numerically (maize: 236.74 g, soybean: 183.25 g), the high variance within each group (38,378.68 for maize and 58,008.20 for soybean) suggests that the dispersion of the data in each mesh is considerable, masking possible specific differences by particle size. This could be due to the heterogeneous nature of grinding in ball mills, where factors such as hardness, humidity or residence time generate variability that the global ANOVA fails to detect, recommending an analysis by specific particle size fractions to identify practical differences in the process.

3.3.10.3. Case 3. Hammer Mill + Ball Mill

Table 12 shows the analyzed data on the weight of the retained in the sieves of corn and soybeans.

Null hypothesis: The granulometric analysis does not show significant differences between the sieves used. ($p>0.05$)
Alternative hypothesis: The granulometric analysis shows significant differences between the sieves used. ($p<0.05$)

Table 12. Weights of Retained in Sieves Case 3.

Mesh (mm)	**4**	**2,36**	**1,70**	**1,18**	**1,00**	**0,85**	**0,60**	**0,30**	**0,212**
Corn (g)	4	23	121	255	287	418	349	213	1.92
Soybeans (g)	11	65	139	264	189	304	170	254	0.28
Critical Value F						4,49			
Probability						0,63			

Source: Bonilla, et al, 2024

The analysis of variance (ANOVA) of one factor applied to the particle size data of case 3, where corn and soybeans were processed by a hammer mill followed by a ball mill, indicates that there is no statistically significant difference between the particle size distributions of both grains. This is supported by a p-value of 0.637, much higher than the significance level of 0.05, and an F-value of 0.231 that does not exceed the critical value of 4.494. Although the mean retained weight differ (maize: 185.77 g, soybean: 155.14 g), the high variability within each group (variances of 24,235.87 for maize and 12,286.76 for soybeans) suggests that the observed differences may be due to the natural dispersion of the milling process and not to the type of grain. This result reflects that the grinding sequence (hammer + balls) homogenizes the distributions to the point of eliminating significant differences, possibly due to the combination of fracture mechanisms (impact and abrasion) that compensate for the individual properties of each material. However, an analysis by specific fractions could reveal differential behaviors in particular size ranges, not captured by the global ANOVA.

3.3.10.4. Diameters Comparisons in Corn

Table 13 shows the data analyzed for diameters D10, 50 and 90 for maize in its three case studies.

Null hypothesis: There are no significant differences between the values of D10, D50 and D90 in the particle size distribution of maize. ($p>0.05$)

Alternative hypothesis: At least one of the percentiles (D10, D50 or D90) differs significantly from the rest in the particle size distribution of maize. ($p<0.05$)

Table 13. Through-the-crop accumulation at D10, 50 and 90 for corn

Parameter	Case 1	Case 2	Case 3
D10 (mm)	3,39	0,48	0,60
D50 (mm)	2,80	1,38	1,08
D90 (mm)	0,30	1,96	2,60
Critical Value F	0,03		
Probability	0,97		

Source: Bonilla, et al, 2024

The analysis of variance shows that there are no significant differences between the values of D10, D50 and D90 for corn grain ($p > 0.05$). This indicates that, considering the three milling treatments, the variation between the characteristic particle size distributions (size percentiles) is statistically similar. In other words, milling generates particle sizes that, although different in numerical value, do not present sufficient variability for the differences between percentiles to be statistically detectable in corn.

3.3.10.5. Soybean Diameter Comparisons

Table 14 shows the data analyzed for diameters D10, 50 and 90 for maize in its three case studies.

Null hypothesis: There are no significant differences between the values of D10, D50 and D90 in the particle size distribution of soybeans. ($p>0.05$)
Alternate hypothesis: At least one of the percentiles (D10, D50 or D90) differs significantly from the rest in the particle size distribution of soybeans. ($p<0.05$)

Table 14 Accumulation of the through-a-basket in D10, 50 and 90 for soybeans

Parameter	Case 1	Case 2	Case 3
D10 (mm)	1.,8	1.,9	0,70
D50 (mm)	2,90	3,53	1,35
D90 (mm)	3,98	3,94	2,05
Critical Value F	4,04		
Probability	0,07		

Source: Bonilla, et al, 2024

In the case of soybeans, there is a trend towards differences between percentiles ($p = 0.773$), but these do not reach statistical significance at the conventional level of $\alpha = 0.05$. This suggests that soybeans have greater particle size variation than maize between D10, D50 and D90, probably due to their more fragile internal structure and greater heterogeneity in the fracture. However, statistical evidence is not sufficient to affirm significant differences, although it is possible that with a larger sample the results may be conclusive.

4.- Discussion

4.1.- Case 1. Hammer Mill

The particle size data reveal significant differences in the milling behavior between soybeans and corn using new sieves. Soybeans have a Extremely coarse distribution, with 81.12% of the material retained in the first three meshes (≥2.36 mm) and only 18.88% as through material in mesh 8. In contrast, corn shows a More balanced distribution, with 87.66% of through-material in mesh 8 and a progressive accumulation in intermediate meshes, reaching its inflection point (D50) around mesh 12 (1.7 mm). This difference is evident in the values of Smaller percentage accumulation size, where maize maintains significantly higher percentages across all meshes, indicating more efficient and uniform grinding. These findings are consistent with the grinding theory that states that the Physical properties of the material determine their response to the fracture. Soybeans, with a higher oil content and more flexible cell structure, have greater resistance to impact fracture, resulting in coarser particles. Maize, with vitreous endosperm and higher starch content, fractures more easily, generating a finer and more uniform distribution. The literature reports that materials with hardness greater than 45 kg/cm² (such as soybeans) require more grinding energy and produce coarser distributions, while cereals such as corn (hardness 25-35 kg/cm²) respond better to impact milling. The behavior observed in soybeans, with 81.12% of retained accumulated in mesh 8**,** It coincides with previous studies that report low milling efficiency in oilseed legumes due to their ability to absorb energy without fracturing completely. On the other hand, the distribution of maize conforms to the Gates-Gaudin-Schuhman model typical of brittle materials. In other studies, it reports 72-88% of material under 2 mm for corn, coinciding with our 87.66% through-mesh. [28] glassy nature of the endosperm**.** Just as it confirms that the

[29]Presence of oil in soybeans (18-22%) it acts as a shock absorber, reducing the generation of fines by 30-40% compared to dry materials. In contrast, in other research he obtains finer distributions (D50 ≈ 1.2 mm) using liquid nitrogen, suggesting that our conventional conditions limit efficiency. This shows that real-time adaptive adjustments can improve soybean uniformity by up to 60%, indicating optimization potential not explored in our study. Some studies claim that state-of-the-art mills with variable speed control can achieve narrower distributions than conventional equipment, in addition to the incorporation of current protocols recommends the humidity control implemented in the studios. These findings coincide with recent work on feed and PSD behavior in hammer milling, which shows how soybeans and corn respond differently to the same screening/screen and how moisture and composition affect fines generation and nutrient distribution by fraction. In particular, studies observed that, after hammer milling, soybeans tend to retain relatively coarse fractions and that the addition of moisture significantly modifies both the PSD and energy consumption, which supports the interpretation that grain properties (oil, structure) condition the hammer efficiency and the orientation of the particle size curve.[30][31] [32] [33] [34]

4.2.- Case 2. Ball Mill

Corn has a Significantly finer distribution than soybeans, with 91.6% of through-material in mesh 8 (2.36 mm) compared to only 26.32% in soybeans. The inflection point (D50) is located approximately at 1.3-1.4 mm for corn versus 3.0-3.2mm for soybeans, evidencing a marked difference in grinding efficiency. Soybeans show Fracture resistance, with 73.68% of retained accumulated in mesh 8, consistent with studies of *Chen et al. (2021)* on the ability of oilseed materials to absorb impact energy. Maize, with its vitreous endosperm, responds better to impact milling, generating a higher proportion of medium and fine particles. The results coincide in the higher milling efficiency of cereals versus oilseeds under similar conditions, but highlight the need to optimize specific operating parameters for each material. The interpretation of the results is based on recent scientific references, such as the study that explains the fracture resistance of soybeans due to their high oil content and flexible cell structure, which coincides with our findings of coarser particle size distributions compared to corn. Likewise [28] [35]**,** Other studies they highlight the influence of the elastic modulus on grinding, supporting the marked difference in D50 between the two materials. When comparing our results with the literature, there are coincidences, who report finer distributions for corn under similar milling conditions, while discrepancies arise when contrasted with those who used cryogenic milling in soybeans and obtained significantly finer distributions, suggesting that our conventional operating conditions limit the efficiency of the process. Reviews and experimental work confirm that the ball mill is very effective in fractionating and reducing particles when the material is essentially friable or rich in polysaccharides, but its performance in dense oilseeds can be limited without parameter adjustments (time, media, atmosphere). This is consistent with our results: corn (endosperm) is effectively reduced, soybeans are not, except by operative changes or combined treatments.[36][28] [30] [37]

4.3.- Case 3. Hammer Mill + Ball Mill

The granulometric analysis of the Case 3 shows a noticeably finer and more uniform distribution compared to previous cases, where the corn presents a D50 ≈ 1.05 mm (near mesh 18) and the soybeans a D50 ≈ 1.25 mm (between 16-18 meshes), evidencing a more efficient grinding. This improvement is attributed to the possible use of hammer mill followed by ball mill, a combination that according to Some studies in this case It optimizes the fracture of heterogeneous materials by integrating impact and abrasion mechanisms. The results coincide with those who report distributions with D50 between 0.9-1.2 mm for corn under sequential milling, while discrepancies persist with respect to soybeans, whose studies indicate D50 >1.5 mm in conventional milling, suggesting that our sequential process partially mitigates its fracture resistance. Among the limitations, the absence of humidity control and unmonitored sieve wear may have affected reproducibility, while equipment bias underestimates the potential for cryogenic grinding. These factors highlight the need to incorporate energy-specific metrics (in future research to validate the efficiency of the sequential process. So it is evident that fragmentation methods will impact directly on the particle size as well as the shape obtained in your flour. . In recent literature, it has been shown that the use of sequential stages or multi-stage milling can decrease energy consumption per unit of reduction (depending on humidity and target sizes) and stabilize the production of intermediate/fine particles; In addition, the pre-fragmentation stage facilitates the action of subsequent fine grinding and less contact time needed to reach the target size. [30] [28] [35] [33] [38][39] [40]

Although the results obtained show clear differences between grains and treatments, there are inherent limitations to the experimental design and biophysical factors of the grain that could modulate the milling efficiency. In the Internal composition (lipid content, proteins, cell structure) and the grain moisture influence their susceptibility to fracture. For example, a recent study shows that when humidity increases, grains (corn, rice and soybeans) modify their mechanical behavior: they go from brittle to viscoelastic, changing the fracture force and the energy required. These variations can alter the fragmentation under milling, suggesting that intrinsic factors of the grain beyond the type of mill may condition the final particle size distribution.[41]

Another hypothesis to explain the lower milling efficiency in soybeans, compared to corn, is the buffering effect of oil content. In soybean milling, it has been reported that higher lipid contents limit size reduction: the oil reduces brittleness and favors agglomerates or coarse particles after impact grinding. Additionally, friction grinding or fine grinding studies show that mechanical methods affect grains with a starch-rich matrix differently versus those with high lipid content, modifying the efficiency, particle shape and dispersibility. Therefore, the current results could reflect an interaction between the milling technique and the biochemical properties of the bean; This alternative hypothesis deserves to be explored in future work through characterization of oil, protein and cell structure, and rigorous humidity control.[42][28]

5.- Conclusions

The hammer mill (Case 1) showed a heterogeneous distribution**,** with a D50 ≈ 2.8-2.9 mm for corn and ≈2.9 mm for soybeans, evidencing an inefficient milling in soybeans, where 81.12% of the material was retained in ≥2.36 mm meshes. In contrast, the ball mill (Case 2) generated finer distributions for corn (D50 ≈ 1.38 mm), but was ineffective for soybeans (D50 ≈ 3.53 mm), confirming that soybeans, due to their higher oil content and flexible structure, resist fracture by impact and conventional abrasion.

The combination of mills (Case 3) achieved the most balanced distribution**,** with D50 ≈ 1.05 mm for corn and **≈1.25 mm for soybeans**, reducing the heterogeneity observed in the individual cases. This suggests that the synergy between impact (hammer) and abrasion (balls) mechanisms mitigates the limitations of each method separately, although greater dispersion persists in corn (uniformity index D90/D10 ≈ 4.3) versus soybeans (≈2.66)

The ball mill (Case 2) had the highest specific energy consumption (CEE): 92.70 kW·h/t for soybeans versus 80.17 kW·h/t for corn in Case 3, associated with the higher density and resistance of soybeans. However, this high consumption did not translate into a fine grind for soybeans, indicating energy inefficiency in oilseed processing under standard conditions.

The ANOVA applied showed $p > 0.05$ in all three cases, indicating "no significant differences" between corn and soybeans. However, the particle size data reveal critical operational disparities**,** such as the concentration of 40.49% of soybeans in the 3.35 mm mesh (Case 1) versus a more uniform distribution in corn. This exposes the insensitivity of univariate ANOVA to capture differences in complex distributions, underscoring the need for fraction-specific analysis.

The results of the ANOVA for maize ($F = 0.0314$; $p = 0.9692$) show a total absence of significant differences between the particle size parameters D10, D50 and D90 according to the milling method, evidencing a uniform behavior. In soybeans, although the ANOVA shows $F = 4.0430$ and $p = 0.0773$, the difference does not reach statistical significance**,** but suggests a tendency to variation, possibly influenced by its higher oil content and different mechanical response to fracture.

Microscopic analysis revealed that the hammer mill generates angular (rectangular) particles, while the ball mill produces rounded shapes (oval or ellipsoidal). In Case 3, a combination of morphologies was observed, which affects functional properties such as flow, compaction and reactivity. This highlights the importance of selecting the grinding technology according to the desired characteristics in the final product.

The findings of this study can be applied in the optimization of milling processes in the feed, flour and vegetable oil industry, where particle size control directly influences digestibility, mixture homogeneity and extrusion efficiency. The sequential grinding configuration (hammer + balls) is emerging as a viable alternative to reduce energy consumption and improve particle size consistency in continuous production lines. It is recommended to deepen the analysis of the specific milling energy and its relationship with the moisture and composition of the grain, as well as to evaluate the effect of particle size on the nutritional and functional quality of the final product. In addition, it would be valuable to explore the implementation of hybrid technologies (such as cryogenic or ultrasound-assisted milling) to increase the efficiency and reproducibility of the process, especially in hard-to-fracture oilseeds.

6.- Author Contributions (Contributor Roles Taxonomy (CRediT))

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3. Formal analysis: Alejandro Noblecilla
4. Acquisition of funds: Not applicable
5. Research: Iván Torres, Alejandro Noblecilla
6. Methodology: Iván Torres, Alejandro Noblecilla, Stefanie Bonilla, Carlos Valdiviezo.
7. Project management: Stefanie Bonilla
8. Resources: Iván Torres, Alejandro Noblecilla
9. Software: Not applicable.
10. Supervision: Stefanie Bonilla
11. Validation: Stefanie Bonilla, Carlos Valdiviezo
12. Visualization: Alejandro Noblecilla
13. Writing - original draft: Iván Torres, Alejandro Noblecilla
14. Writing - proofreading and editing: Stefanie Bonilla, Carlos Valdiviezo

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