A comparison between lab scale and pilot scale ball mill for the grinding of wet Switchgrass

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Abstract. Over the past two decades, lignocellulosic biomass has attracted growing interest for the development of second-generation biofuels. Among these, Switchgrass offers several advantages, including high sugar yields during fermentation processes and low water requirements for cultivation. To improve the accessibility of sugars to enzymes, new co-processing methods incorporating a grinding step between two fermentation phases are currently being developed to facilitate the mechanical breakdown of the material. Since drying steps are particularly costly in terms of energy and economics, the biomass must be ground to a moisture content corresponding to fermentation conditions, under which the material exhibits particularly complex rheological properties. This work proposes a combined DEM-experimental study to compare the grinding of wet Switchgrass in laboratory-scale and pilot-scale mills, with the aim of identifying the parameters governing the fragmentation processes.

1. Introduction

Dry and saturated milling processes have been extensively studied and are quite well now understood due to their numerous industrial applications, particularly in the mining and pharmaceutical industries [1,2]. However, growing interest has recently emerged in the milling of unsaturated materials, especially for biofuel applications involving the grinding of lignocellulosic biomass. Understanding the milling behavior of such unsaturated lignocellulosic biomasses requires accounting for the rheological variability of the material over a wide range of moisture content, from wet biomasses to concentrated suspensions. Although the presence of water can significantly affect grinding efficiency [3], the careful selection of process parameters remains crucial to achieve efficient feedstock milling in terms of both energy consumption and particle size reduction.

To address these two research questions, this paper presents a combined DEM modelling and experimental study, focused on the unsaturated grinding of Switchgrass. This work was conducted in the context of the American project “Center for Bioenergy Innovation”, which focuses on the development of second-generation biofuels for civil aviation from lignocellulosic biomass. Rajaonarivony et al. [4] demonstrated that ball mills are among the most efficient grinding devices for reducing particle size of fibrous materials, owing to the high frictional forces induced by grinding media. Building on this premise, the present study compares two ball mills at laboratory and pilot scales in order to evaluate the effects of material rheology and process parameters on energy efficiency and particle size reduction.

2. Materials and Methods

2.1. DEM modelling

An in-house discrete element model implemented in C++ was developed to simulate the grinding chamber geometry of two ball mills: the laboratory-scale MM500 vibratory ball mill (Retsch®, DE) and a pilot-scale ball mill prototyped in the laboratory by Femag Industry®, FR. The discrete element method (DEM) was applied exclusively to the grinding media, using a Hertz contact model to analyse media dynamics and contact energy evolution during the grinding process.
From these simulations, frictional and impact energies dissipated during contact were quantified and analysed.

2.2. Experimental framework

2.2.1. Raw material

The raw material used in this study is Switchgrass from Dartmouth College (NH, USA). Its initial D_{50} was measured to be 371 µm.

2.2.2. Milling process

In this study, two different mills were used. At the laboratory scale, experiments were carried out using a vibratory ball mill (MM500, Retsch®, DE) equipped with

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6 mm beads. The 125 mL grinding chamber is subjected to horizontal vibrations, with a frequency adjustable between 0 and 30 Hz.
At the pilot scale, a stirred ball mill prototype developed by Femag Industries®, FR, was used. The cylindric grinding chamber has a volume of 3 L, and bead motion is induced by the rotation of an impeller, with a speed adjustable between 0 and 300 rpm. The geometry of each mill is shown in Figure 1.

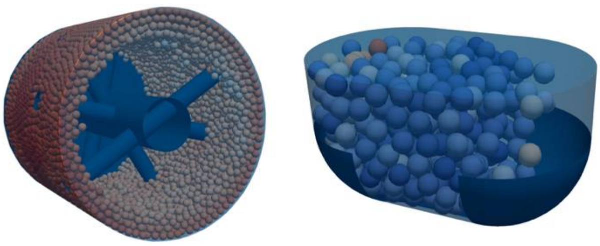

Figure 1. Grinding chamber geometries for pilot scale mill Femag (left) and lab scale mill MM500 (right).

2.2.1. Experimental design

A three-factor experimental design was conducted in each mill. The three factors selected for the study are: m_s, the dry mass of Switchgrass; m_b, the mass of 6 mm beads; and m_w, the mass of water. These parameters were chosen to cover a range of filling volumes (V_f), ratios between the dry mass of Switchgrass and the bead mass ($R = m_s/m_b$), and water contents (W). The values selected for V_f, R, and W are detailed in Table 1. For each water content, the cohesion of Switchgrass was measured using a Jenike shear cell [5], in accordance with the Mohr–Coulomb criterion. All determined values are reported in Table 2.

Table 1. Variables used in experimental design

Variables			
R	0.05	0.06	0.07
V_f (%)	27	50	73
W (%)	60	70	90

Table 2. Cohesion measurements performed at different water contents

$\boldsymbol{W}$(%)	**60**	**70**	**90**
$C\ (Pa)$	147	330	4

Two response variables were chosen for this experimental design: E (in MJ), the energy consumed by the mill, and ΔS (in m²·kg⁻¹), the specific surface area created after 2 h of grinding. Based on these response variables and factors, multivariable linear regressions based on the least squares method were performed according to the following expression:

$$y = \beta_0 + \sum_i \beta_i . m_i + \sum_{i \leq j} \beta_{ij} . m_i m_j + \epsilon \tag{1}$$

Where y is the response variable and $i,\ j \in \{s, b, w\}$

3. Results

3.1. Numerical modelling

Figure 2 shows the evolution of the dissipated friction energy and power for both mills as a function of the rotation speed and grinding frequency ranges allowed by each piece of equipment. The first notable observation is that the energy dissipated by friction is markedly higher in the pilot-scale mill compared to the laboratory-scale mill, with an increase of approximately a factor of 20.
While the MM500 appears to reach a quasi-steady state almost instantaneously, the Femag requires a longer transient before the grinding media are fully set in motion and this regime is established.
In both cases, friction increases with increasing rotation speed or frequency following an exponential law. A significant rise in friction is observed above Ω = 150 rpm, which can be attributed to the onset of the centrifugal regime leading to a maximization of frictional energy.
Since efficient milling of fibrous materials such as lignocellulosic biomass relies on maximizing frictional energy, a grinding frequency of 25 Hz and a rotation speed of 300 rpm are selected for the experimental work.

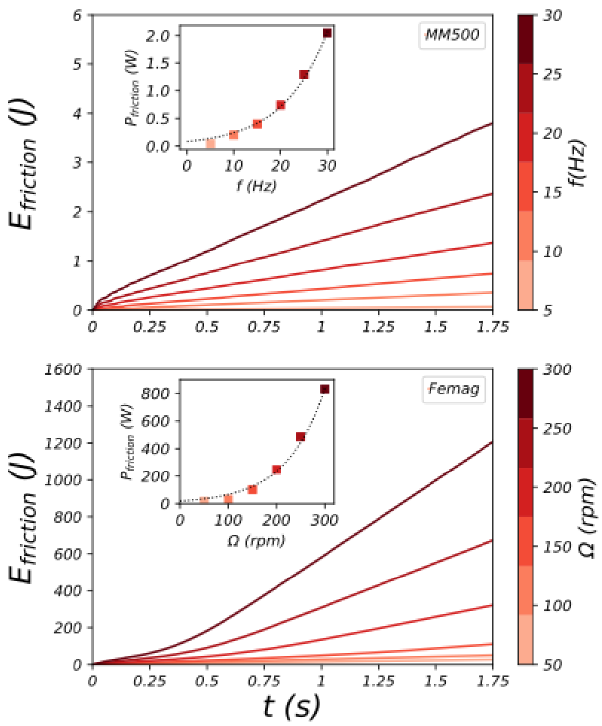

Figure 2. Dissipated friction energy and power in each mill as function of grinding frequency f or rotation speed Ω .

3.1. Experimental study

Figure 3 illustrates the linear regression performed on the response variables ΔS and E.

This regression highlights that the specific surface areas obtained with both mills are relatively similar and remain within a narrow range. In contrast, the energy consumption shows a markedly different behaviour: the laboratory-scale mill exhibits an almost constant energy demand across the tested conditions, whereas the pilot-scale mill displays three distinct clusters around 2 MJ, 3.5 MJ, and 6.5 MJ. Experimentally, these three groups correspond to the three levels of V_f.

Based on these observations, an efficiency indicator, denoted SPI (Score Power Index), was calculated for each mill as follows:

$$SPI = (\Delta S \cdot m_s)/E$$

This indicator is intended to account for the dry mass of Switchgrass processed during the comminution process. Linear regression was performed using this new indicator, and significant variables for each mill were identified based on a 5% significance level. Consequently, the following expressions relating ΔS and E were established for the two mills:

$$\frac{\Delta S}{E} \approx \frac{k}{m_b} \text{ (Femag)} \qquad (2)$$

$$\frac{\Delta S}{E} \approx m_s[ax^2 + (bm_b + c)x] \text{ (MM500)} \qquad (3)$$

Where $x = \frac{W}{1-W}$ and a, b, c, k constants.

For the pilot-scale ball mill Femag (Equation (2)), particle size reduction is governed mainly by bead mass. This observation is consistent with the numerical simulations, which revealed very high frictional energy levels, likely dominating over the cohesion or drag forces associated with the presence of water.

For the lab-scale mill MM500 (Equation (3)), water appears to play a central role. The experimental results suggest that particle size reduction is enhanced at higher cohesion levels. Indeed, a more cohesive material tends to adhere to the walls of the milling chamber, facilitating its attrition by the grinding media. However, this beneficial effect of cohesion is moderated by the filling volume of the chamber as an excessively low filling ratio reduces the contact surface between the cohesive material and the beads.

Based on the previous observations, Figure 4 illustrates the relationship between the cohesion value (previously determined using a Jenike cell), the filling volume, and ΔS/E for the MM500. The data were fitted using the following expression (Equation 4):

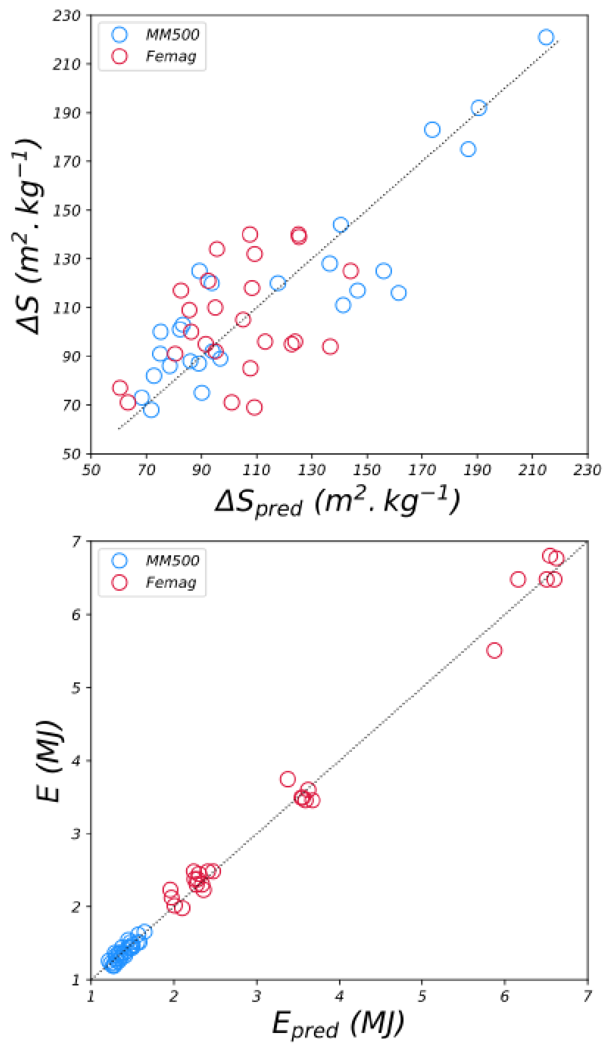

Figure 3. Measured response variables as function of the response variables predicted by the linear regressions.

$$\frac{\Delta S}{E} \approx f(C).V_f \qquad (4)$$

Where $f(C) = 0.01.C^3 - 5.5.C^2 + 959.C$

Equation (4) shows that $\Delta S/E$ tends toward zero for very low values of C. In the case of Switchgrass, this condition is reached at very high-water contents, corresponding to highly diluted systems for which the creation of specific surface is difficult. To explain this, several hypotheses can be proposed.

First, the large amount of water may reduce bead velocity and, consequently, frictional energy, due to the presence of drag and lubrication forces. Moreover, in these diluted systems, the very low amount of dry Switchgrass significantly decreases the probability of interactions between fibers and grinding media, leading to poor particle size reduction.

Consequently, at the lab scale, rheology strongly impacts grinding efficiency but must be considered alongside the filling volume. While a diluted system will not be effectively ground regardless of the filling volume, cohesive materials require a high filling volume to maximize the contact surface between the beads and the feedstock, thereby ensuring efficient grinding.

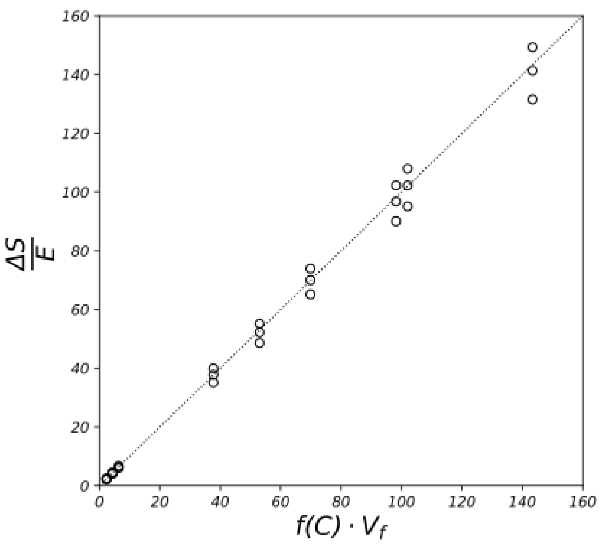

Figure 4. Relationship between the cohesion of the feedstock, the filling volume and the grinding efficiency for the lab-scale mill (MM500).

4. Conclusion

This combined DEM-experimental approach provides a deeper understanding of how process parameters and feedstock rheology affect the grinding efficiency of two ball mills. The numerical modelling was used to guide the selection of process parameters with the objective of maximizing friction.

Experimentally a relationship was established between water content, process parameters, and particle size reduction.

At the laboratory scale, water content and cohesion strongly influence particle size reduction. In contrast, in the pilot-scale mill, the change in geometry and the large number of grinding media, which generate substantial frictional energy, appear to dominate, largely overriding the rheological effects of the feedstock.

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References

[1] Matsanga, N., Nheta, W., Chimwani, N. (2023) A review of the grinding media in ball mills for mineral processing. *Minerals*, 13, 1373.

[2] Malamatari, M., Taylor, K.M.G., Malamataris, S., Douroumis, D., Kachrimanis, K. (2018) Pharmaceutical nanocrystals: production by wet milling and applications. *Drug Discovery Today*, 23, 534–547.

[3] Thouret, M., Mayer-Laigle, C., Richefeu, V., Lampoh, K., Delenne, J.-Y. (2025) A modified Rittinger model for the grinding of wet granular material. *Powder Technology*, 121775.

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

[5] Richefeu, V., El Youssoufi, M.S., Radjai, F. (2006) Shear strength properties of wet granular materials. Physical Review E—Statistical, Nonlinear, and Soft Matter Physics, 73(5), 051304.