Hemp fibre decortications using a planetary ball mill

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Baker, M.L., Y. Chen, C. Laguë, H. Landry, Q. Peng, W. Zhong, and J. Wang. 2010. **Hemp fibre decortications using a planetary ball mill**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada. 52: 2.7–2.15. Hemp fibre is a renewable resource that has the market potential for producing new fibre-based products as well as replacing existing ones. Decortication constitutes a key step in the production of high-quality hemp fibres. A hemp decortication experiment was conducted using a lab-scale planetary ball mill. Varying treatments, including three grinding durations (2, 4, and 6 min) and seven grinding speeds (100, 150, 200, 250, 300, 350, and 400 rpm) were studied using retted hemp feedstock. Under these treatments, fibre yield, core yield, and amount of chaff were determined following decortication. The detaching efficiency (defined as the reduction in the amount of fibre-bound-to-core), along with the performance index, were also determined to evaluate the overall performance of the ball mill for hemp decortication. Results showed that grinding duration and speed impacted all the measured variables. The lowest grinding speeds, 100 rpm, resulted in a poor detaching efficiency (52.6%). The highest grinding speed, 400 rpm, allowed for a greater detaching efficiency (99.7%), but reduced fibre yields (0% yield for 6 min grinding duration) and increased chaff production (up to 100% chaff). Given all these facts, the best performance of the mill was found at 200 and 250 rpm grinding speeds, regardless of grinding duration, in terms of fibre yield and detaching efficiency. **Keywords:** hemp, decortication, ball mill, fibre, core, yield, grinding, speed, duration.

La fibre de chanvre constitue une ressource renouvelable pouvant être utilisée pour la production de nouveaux produits à base de fibres ou pouvant remplacer des produits existants. La décortication constitue une étape cruciale dans la production de fibres de chanvre de haute qualité. Une étude de la décortication du chanvre en laboratoire au moyen d'un broyeur centrifuge à billes a été complétée. Des échantillons pré-conditionnés de chanvre ont été soumis à des traitements expérimentaux comportant trois durées de broyage (2, 4 et 6 minutes) et sept vitesses de rotation (100, 150, 200, 250, 300, 350 et 400 tours par minute). Suite à chacun de ces traitements, les proportions de fibres de chanvre et de sous-produits (coeurs de tiges, résidus finement broyés) ont été déterminées. De plus, l'efficacité de détachement (correspondant à la réduction de la quantité de fibres attachées au coeur de la tige) et l'indice de performance ont été calculés afin d'évaluer l'efficacité globale du broyeur centrifuge à billes pour la décortication du chanvre. Les résultats obtenus ont démontré que les deux paramètres de fonctionnement testés (durée de broyage, vitesse de rotation) affectaient toutes ces variables dépendantes. Une vitesse de rotation lente (100 tpm) a résulté en une faible efficacité de détachement (52,6%). Bien qu'une vitesse de rotation élevée (400 tpm) ait permis d'atteindre une grande efficacité de détachement (99,7%), cela a également résulté en de très faibles rendements en fibres (0% pour une durée de broyage de 6 minutes) et de très grandes quantités de résidus finement broyés (jusqu'à 100%). À la lumière de ces résultats, il a été déterminé qu'une vitesse de rotation de l'ordre de 200 à 250 tpm résultait en une performance optimale du broyeur centrifuge à billes en termes de rendement en fibres et d'efficacité de détachement et ce peu importe la durée de la période de broyage. **Mots clés:** chanvre, décortication, broyeur à billes, fibre, coeur, rendement, broyage, vitesse, durée.

INTRODUCTION

Hemp (*Cannabis sativa*) is a temperate climate plant grown mostly in Europe, Russia, and Canada. In April of 1998, hemp was legalized for industrial cultivation in Canada. The legalization of hemp allowed for its use as a natural fibre. Hemp fibre can be used in the textile and biocomposite industries as well as in other industries that make use of artificial or natural fibres (Kostuik et al. 2007). Biocomposites have been used to replace glass fibres mostly in non-structural applications, such as automobile components (Wambua et al. 2003), as well as building materials.

The increasing interest in hemp fibre is due to its many desirable properties, such as low density, acceptable strength, good thermal insulation, reduced dermal and respiratory irritation, recyclability, and biodegradability (Li et al. 2000; Gassan 2002; van de Weyenberg et al. 2003; Baiardo et al. 2004; Wong et al. 2004; Park et al. 2006). Hemp fibre is comparable to glass fibre in high volume applications in regards to its tensile and modulus strength, and durability (Williams and Wool 2000). In a study conducted by Facca et al. (2007), hemp fibre showed a tensile strength of approximately 200 MPa, which is approximately two-thirds of the tensile strength of E-glassfibre (325 MPa) and twice that of wood fibre (90 MPa). Its high tensile strength and light weight make hemp fibre an acceptable choice for biocomposite materials.

To obtain fibre, hemp needs to go through a decortication process. Decortication of hemp stems separates the fibre (the outer fibrous layer) from the core materials (the inner layer). This is also referred to as the detaching process in which the bonds between the outer fibre and the inner core are broken by mechanical forces applied. Decortication can be achieved with several mechanical devices, such as hammer mills, crushing rollers, and cutterheads. These machines produce shear, compressive, or impact forces, or a combination of these forces to break the bonds between fibre and core in order to separate them. The resulting processed material is a mixture of fibre, core, and fines. This mixture then needs to go through a cleaning system where cores and fines are removed from the mixture to obtain clean fibres.

Hammer mills consist of rotating hammers that generate impact and shear forces. The cutterhead decorticator adapted from a forage harvester features knives and scutching bars (Gratton and Chen 2004). When it rotates, cutting and impact forces are generated. These forces are involved in fibre detaching process when hammer mill and cutterhead are used for decortications. Another method of decortication involves crushing rollers, which are widely used to grind wheat into flour (Fang et al. 1997). Crushing rollers have been studied for flax fibre decortications (Anthony 2002). When used for decortication, crushing rollers utilize fluted, pinned, and flat rollers to crush the fibre stalk, which breaks the bond between fibre and core. The major detaching force generated from rotating rollers is a compressive force.

All these machines were adapted for hemp decortication from other applications. In general, hammer mill and cutterhead methods have high processing capacity, but generate low fibre purity and do not allow for an entire detachment of fibre from core (Fürll and Hempel 2000). For example, a maximum fibre yield of 61% with a purity of 52% was observed by a cutterhead decorticator (Gratton and Chen 2004). Crushing rollers may produce cleaner fibre when hemp is retted. However, their processing capacity is low. All these decortication machines have problems of fibre wrapping around the rotating parts (such as shafts and bearings) of the machines. In some cases, wrapping can cause permanent damage to the machines. To avoid wrapping problem, a ball mill is an alternative for fibre decortication.

In a ball mill, the material being processed does not contact any rotating machine parts. Material is placed into a specific size and type of grinding container along with an appropriate size, type, and number of grinding balls. When the container rotates, centrifugal forces cause the balls to travel along the wall of the grinding container. The faster the container rotates, the farther the balls are moved inside the container (Prasad et al. 2005). The moving balls grind the material with impact and shear forces. Ball mills have a wide range of research and industrial applications, such as milling aspen wood (Fukazawa et al. 1982), medical compounds (Garmise et al. 2006), and metal materials (Périgo et al. 2007). The milling process of the ball mill could be potentially used for detaching natural fibre.

In summary, some research has been performed on the decortication of hemp using hammer mills, crushing rollers, and cutterheads, but no research has been done on the decortication of hemp using a planetary ball mill. The objective of this study was to investigate the performance of a planetary ball mill for hemp decortication under different grinding durations and grinding speeds. The performance indicators measured included fibre yield, core yield, and detaching efficiency.

MATERIALS and METHODS

Description of hemp feedstock

Field retted hemp feedstock was used for the grinding tests in this study. Hemp (USO 31 variety) was collected at Baker Farms, located in Dauphin, Manitoba, Canada. The moisture content of the feedstock was 9.7% (air dry condition), as measured by the oven-dry method at 60°C for 72 h. The hemp crop was swathed using a mower-conditioner in the second week of August 2007, and left to ret in the field for approximately 6 wk prior to being baled. Bales were stacked and stored outside. Samples for grinding tests were handpicked from a randomly selected bale (Fig. 1) in July 2008, and bagged in poly-woven grain bags to be transported to the laboratory at the University of Manitoba.

A lab-scale Planetary Mono Ball Mill (Fig. 2a) (Model Pulverisette 6, Fritsch, Idar-Oberstein, Germany) was used to decorticate hemp stalk. The mill was securely fastened to a level surface during decortication. Inside the mill housing, there is a grinding bowl holder and disc which supports the grinding bowl (Fig. 2b). The grinding bowl (Fig. 2c) has an agateliner inside and its net volume was 250 mL. The grinding media were fifteen 20-mm diameter agate balls (Fig. 2d). During the grinding operation, the grinding bowl, filled with the grinding balls and hemp feedstock, is first clamped onto the bowl holder. The grinding bowl rotates about its own axis and at the same time rotates with the support disc in the opposite direction (Fig. 3a). Thus, the centrifugal forces alternately act in the same and opposite directions (Fritsch 2005). This results in the grinding balls running along the inner

Fig. 1. Hemp bale from which the feedstock was taken for the grinding tests.Planetary ball mill.

Fig. 2. Decortication equipment; (a) the planetary ball mill; (b) inside the mill housing; (c) grinding bowl; and (d) agate grinding balls.

wall of the grinding bowl (Fig. 3b) causing shear and impact effects on the material being ground. The control panel of the mill allowed for the selection of rotational speeds in the range of 100 to 650 rpm in 10 rpm intervals, and grinding durations from 1 min to 99 h.

Experimental design

A randomized complete block design was used for this hemp decortication experiment using the planetary ball mill. Two independent variables were considered: grinding speeds (seven levels: 100, 150, 200, 250, 300, 350, and 400 rpm) and grinding durations (three levels: 2, 4, and 6 min). These speeds and durations were selected based on preliminary trials to observe the impact of different speeds and grinding durations on the fibre product. Results from the preliminary trials showed that grinding durations greater than 6 min, in combination with the grinding speed greater than 400 rpm, produced entirely chaff (fine particulate matter), which was not desired. The factorial combinations of grinding speed with grinding duration resulted in 21 different experimental treatments, which were replicated four times for a total of 84 tests.

Test procedure

The hemp feedstock was cut to a length of approximately 40 mm before being fed into the mill (Fig. 4a). A length of 40 mm was chosen as it was the most appropriate length for the production of biocomposites. In a commercial

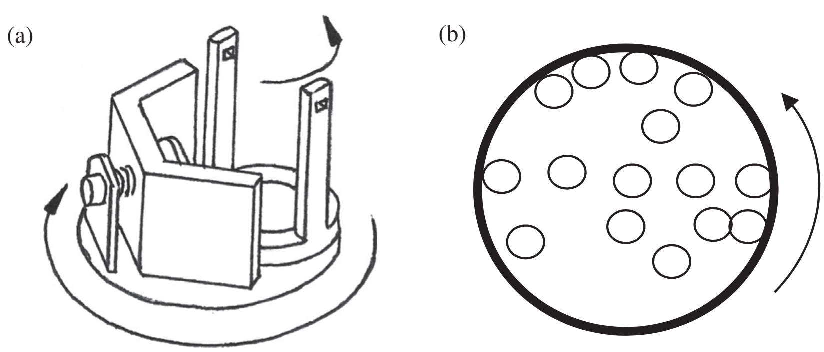

Fig. 3. Diagram showing the working principle of the planetary ball mill; (a) opposite rotational directions of grinding bowl holder and support disc (Fritsch 2005); and (b) diagram showing the top view of balls running along inner wall of grinding bowl.

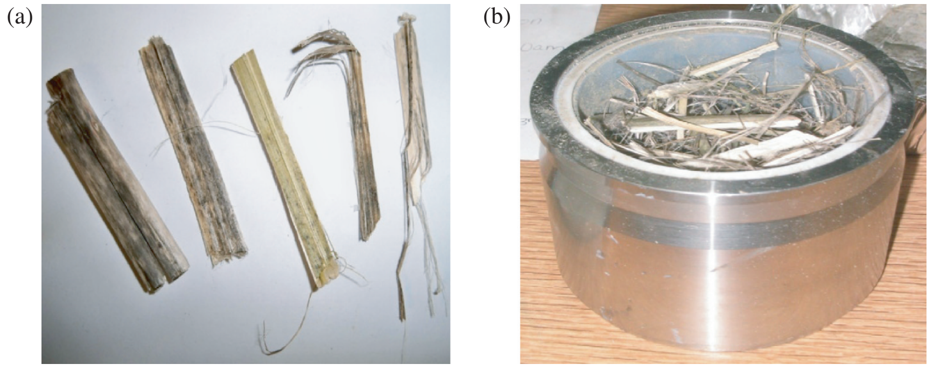

Fig. 4. Hemp feedstock; (a) 40 mm cut lengths; and (b) loaded in grinding bowl prior to milling.

scale operation, a cutting device would have to be introduced in the processing line to pre-cut hemp stalks. As hemp stalks comes from baled material in Canada, pre-cutting would be a challenging task and require further research. In this research, pre-cutting was done manually using a heavy-duty paper cutter. Three-gram hemp feedstock was selected based on the ball mill feeding capacity. Feedstock masses were weighed using an electronic scale (Mars, Model MS200, NorthYork, ON, Canada). For grinding tests, the 3 g feedstock samples were placed on top of the grinding balls in the bowl (Fig. 4b), and the bowl was clamped into the bowl holder in the mill housing. The bowl was securely fastened and the lid was closed, milling commenced for the appropriate grinding duration and grinding speed. Once milling stopped, the ground sample was collected and placed in small plastic bags for later analysis. The grinding bowl and grinding balls were cleaned between milling tests.

Measurements

To classify the products, ground samples were separated using a sieve shaker (Retsch AS200, Hann, Germany) (Fig. 5). The shaker vibrated in the horizontal plane, causing a sliding motion of the material on the screens of the shaker. This separated the material into different fractions based on particle size. The two screen opening sizes used were: 20 and 5 mm. Thus, the ground sample was separated into three length categories: long ($\geq$20 mm); short (5–20 mm); and chaff (<5 mm). Following sieving, material of each length category was further separated into three products: fibre, fibre-bound-to-core (fibre remained attached to the core), and core. Each fraction was weighed using a digital scale (Mars, Model MS200, North York, ON, Canada). The mass of each fraction was recorded. The designations of the mass fractions measured are summarized in Table 1.

Fibre was the desired end-product of the decortication process, while core was the by-product. Fibre-bound-to-core was the undesired product, reflecting that the detachment process was not effective. In practice, fibre-bound-to-core in the fibre stream will decrease the purity of the fibre; while fibre-bound-to-core in the core stream will decrease the fibre yield or increase the fibre loss. The following parameters were derived from those fractions

Fig. 5. Retsch sieve shaker: screens and collecting pan used for sizing ground materials.

listed in Table 1 to evaluate the performance of the decortication using the mill.

Fibre yield Fibre yield was defined as the mass of fibre after milling divided by the mass of feedstock. Long fibres

Table 1. Symbols of mass fractions of hemp products after milling.

	Length category		
Product	Long (>20 mm)	Short (5–20 mm)	Chaff (<5 mm)
Fibre	m_{Lf}	m_{Sf}	
Fibre-bound-to-core	$m_{Lf/c}$	$m_{Sf/c}$	
Core	m_{Lc}	m_{Sc}	
Total	m_{Lt}	m_{St}	m_{ch}

were expected to have more industrial applications than short fibres. Thus, yields for long and short fibres were determined separately, using the following equations:

$$Y_{Lf} = \frac{m_{Lf}}{M} 100 \quad (1a)$$

$$Y_{Sf} = \frac{m_{Sf}}{M} 100 \quad (1b)$$

$$Y_f = \frac{m_{Lf} + m_{Sf}}{M} 100 \quad (1c)$$

where Y_{f}, Y_{Lf}, and Y_{Sf} are the yields for total, long, and short fibre (%), respectively, and M is the mass of feedstock sample (3 g).

Core yield Core yield was defined as the mass of core after milling divided by the mass of feedstock. Long cores and short cores were expected to have similar market values. Thus, yields for long and short cores were combined to the total core yield (Y_{C}):

$$Y_C = \frac{m_{Lc} + m_{Sc}}{M} 100 \quad (2)$$

where Y_{C} is the yield for core (%).

Chaff Percentage of chaff was determined using the following equation:

$$Y_{Ch} = \frac{m_{Ch}}{M} 100 \quad (3)$$

where Y_{ch} is the percentage of chaff (%).

Detaching efficiency To assess the effectiveness of the decortication process, the reduction in the amount of fibre-bound-to-core and chaff was used to determine the detaching efficiency. This parameter shows how much fibre was detached from the core for a given grinding speed and duration. The detaching efficiency was defined as:

$$\eta = \frac{M - m_{Lf/c} - m_{Sf/c}}{M} 100 \quad (4)$$

where: η is the detaching efficiency (%).

Performance index Detaching efficiency represents the amount of fibre being detached from the core. It does not represent the final state of the fibre, such as the amount of fibre produced. For example, when the mill works at higher detaching efficiencies, the output could be shorter fibres or more chaff. Thus, detaching efficiency alone cannot be used to completely assess the performance of the mill. Fibre yield should also be taken into consideration to evaluate the performance of the mill. Therefore, a performance index was introduced and it was defined as:

$$I = \eta Y_f \quad (5)$$

where I is the performance index (dimensionless).

Data analysis Analysis of variance (ANOVA) was performed on data under each length category with Statistical Analysis Software (SAS/STAT V9.13) to detect any significant differences among treatments. Statistical Analysis Software macro procedure ‘‘pdmix800.sas’’ (SAS 2001) was used in combination with LSD test to detect differences among treatment means at a significance level of 0.05.

RESULTS and DISCUSSION

The results of the ANOVA are summarized in Table 2. Although the data were highly variable, significant effects of the experimental factors (grinding speed and duration) were observed in most cases. When interactions of the experimental factors were significant, effects of the combinations of experimental factors were presented. Otherwise, effects of a single experimental factor were presented.

Fibre yield

Long fibre The combined effects of grinding speed and duration on long fibre yields (Y_{Lf}) are presented (Fig. 6), due to the significance of the interaction between these two experimental factors (Table 2). The 2-min grinding duration showed no significant differences in Y_{Lf} among the seven grinding speeds, and the average Y_{Lf} over all speeds was 36.0%. However, the Y_{Lf} for 4 and 6 min durations showed a significant increasing and then a significant decreasing trend among the grinding speed range from 100 to 400 rpm. The peak Y_{Lf} was observed at the 200 rpm for the 4 min grinding duration and at 250 rpm for the 6 min grinding duration. Beyond the peak value, Y_{Lf} rapidly decreased to 10.8% for the 4 min duration and to 0% for the 6 min grinding duration when grinding at the highest speed (400 rpm). The increasing trends before the peak yields were possibly due to an increase in grinding intensity as the grinding speed increased, and therefore more fibre was detached from the core. The decreasing trends after the peak yields may be explained by the fact that the hemp feedstock was subjected to an excessive grinding action at high grinding speeds. The excessive grinding resulted in the fibres being ground into short fibre or chaff. These results are in agreement with Prasad et al. (2005) who observed that with intense milling some fibre bundles are opened up and develop into powder.

Short fibre According to the ANOVA results of short fibre yield (Table 2), interactions between the experimental factors were not significant. Thus, the separate effects of the single experimental factor are presented (Fig. 7a, b). The grinding process generated little short fibre, as demonstrated by the short fibre yields (Y_{Sf}), which were 10 times lower than those of long fibre. The value of Y_{Sf} increased from 100 to 150 rpm, remained fairly constant

Table 2. **Results of analysis of variance (ANOVA).**

		Source					
		Duration		Speed		Duration*Speed	
Variables	Symbol	F	Pr > F	F	Pr > F	F	Pr > F
Fibre yield							
Long fibre	Y_{Lf}	5.17	0.0085*	10.58	< 0.0001*	10.85	< 0.0001*
Short fibre	Y_{Sf}	4.28	0.0183*	2.97	0.0131*	0.90	0.5506
Total fibre	Y_f	7.70	0.0011*	12.93	< 0.0001*	3.41	0.0230*
Core yield	Y_C	2.29	0.1100	7.24	< 0.0001*	1.27	0.2602
Chaff	Y_{ch}	11.45	< 0.0001*	55.73	< 0.0001*	3.85	0.0002*
Detaching efficiency	η	0.35	0.7073	63.59	< 0.0001*	1.20	0.3013
Performance Index	I	6.23	0.0035*	12.01	< 0.0001*	2.40	0.0129*

*Statistically significant ($P < 0.05$).

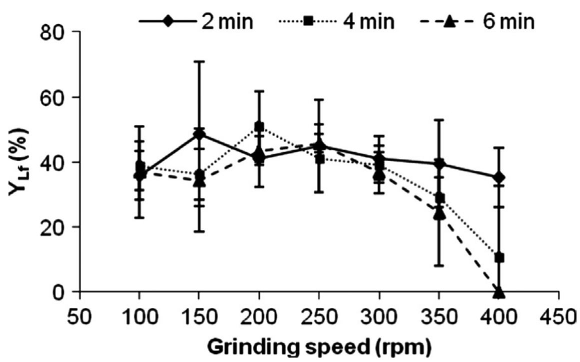

Fig. 6. Long fibre yield (Y_{Lf}) and standard deviation bars versus different grinding speeds for different grinding durations.

between 150 and 350 rpm, and then significantly decreased at 400 rpm (Fig. 7a). The effect of grinding duration resulted in a slight decrease of Y_{Sf} after being ground for 4 and 6 min, when compared to 2 min (Fig. 7b).

Total fibre The total fibre yields (Y_f), that correspond to the sum of long and short fibre yields, are presented in Fig. 8. As short fibre yields were very low relative to long fibre yields, the data of Y_f followed the same trends as the data of long fibre yields, in terms of effects of grinding speed and duration. In summary, no Y_f differences were found among the seven grinding speeds for the 2 min duration. Peak values of Y_f occurred at 200 rpm for the 4 min grinding duration and at 250 rpm at the 6 min grinding duration. The higher range of grinding speeds, 350 to 400 rpm, may not be used in combination with the grinding durations longer than 4 min, due to the significantly decreased Y_f at these combinations.

Core yield

As the effects of grinding speed on core yields (Y_C) did not significantly interact with those of grinding duration (Table 2), the separate effects of each single experimental factor are presented for the core yield data. Grinding speed had a significant effect on the Y_C (Fig. 9). Values of Y_C increased from 12.5 to 20.3% when the grinding speed was increased from 100 to 200 rpm, implying more cores were being separated from the fibre as the speed was increased. The maximum Y_C was observed at 200 and 250 rpm speeds. Beyond these speeds, more and more cores were further ground into chaff, resulting in decreased Y_C down to 1.8% at 400 rpm. These results agree well with a study done by Hobson et al. (2001), who observed that with vigorous processing, core was reduced in size and ultimately lost to the chaff fraction. Effects of

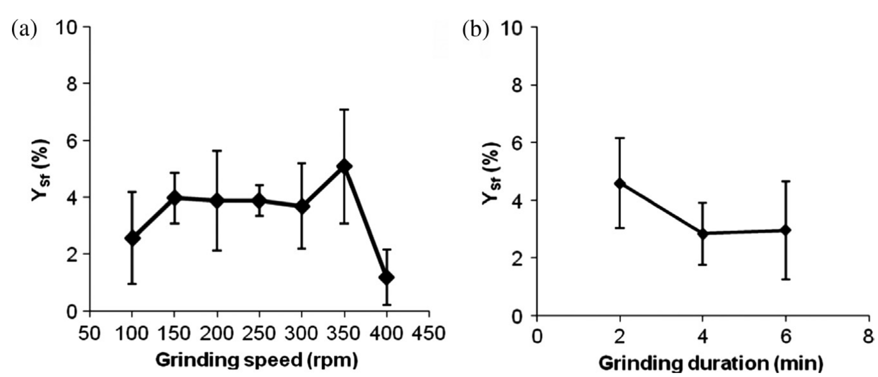

Fig. 7. Short fibre yield (Y_{Sf}) and standard deviation bars for (a) different grinding speeds; (b) different grinding durations.

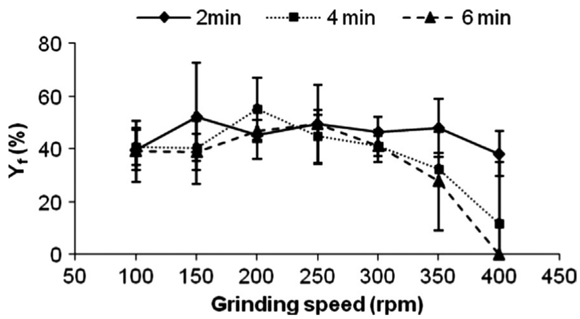

Fig. 8. Total fibre yield (Y_f) and standard deviation bars versus grinding speed for different grinding durations.

grinding duration on Y_C were not significant (Table 2), and the data are not shown.

As core is a by-product from the decortication process, core yield data alone cannot justify which grinding speed is desirable. However, core yield data demonstrated effects of experimental factors on the outputs of a decortication process, and those data, together with the fibre yield data, are useful to identity the optimal grinding speed or duration for the most efficient and effective decortication process.

Chaff

The interactions between grinding speed and grinding duration on chaff yield were significant (Table 2), and their combined effects are presented in Fig. 10. The general trend was that with increasing grinding speed and grinding duration, the amount of chaff produced increased, as expected. Little chaff was produced at 100 and 150 rpm, regardless of grinding duration. The chaff accounted for as much as 81 and 100% when the hemp was ground at 400 rpm for the 4 and 6 min durations, respectively. These results implied that grinding at these conditions would give fibre or core yields as low as 0%. These high percentages of chaff were due to that intensive ball milling at high speeds resulted in a greater percentage of fine material (Schwanninger et al. 2004). The brittleness of the hemp feedstock with low moisture content (9.7%) may also have contributed to the high percentage of chaff. The chaff data explained the yield data shown in Fig. 8 in

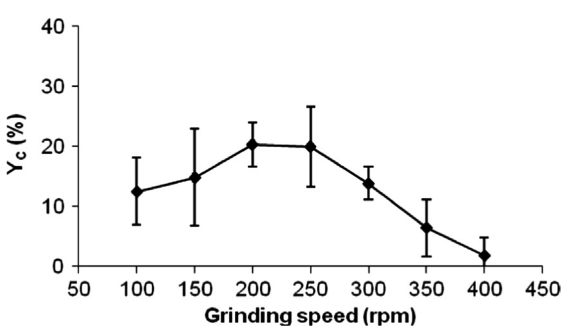

Fig. 9. Core yield (Y_C) and standard deviation bars for different grinding speeds.

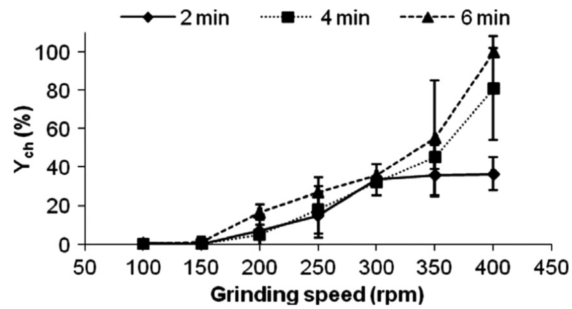

Fig. 10. Chaff (Y_{ch}) versus grinding speed for 2, 4, and 6 min grinding durations.

that fibre yields were inversely proportional to the amounts of chaff.

Detaching efficiency

The effects of grinding duration on detaching efficiency (η) were not significant (Table 2). Therefore, only the effects of grinding speed are presented (Fig. 11). With greater grinding speeds, greater forces were generated to break apart the bonds between fibre and core, resulting in a greater η. The increasing trend was non linear. At 100 rpm, η was 52.6%; then η slightly increased at 150 rpm (57.1%). A rapid increase in η was found at 200 rpm (80.8%). After 250 rpm, slower increase in η was the case from 300 to 400 rpm. It is expected that the energy requirements of the grinding process would be proportional to the grinding speed. Thus, a speed in the 200 or 250 rpm range would be a good compromise between the energy consumption and η.

Performance index

The interactions between grinding speed and grinding duration on the performance index were significant (Table 2), and their combined effects are presented (Fig. 12). The performance index (*I*) assessed the performance of the mill with respect to the detaching efficiency and the final product of grinding. The lower range of grinding speeds resulted in lower *I* due to the lower detaching efficiency. The higher range of grinding speeds resulted in a decrease in *I* due to the lower fibre yield. The peak values of *I* for the 4 and 6 min grinding durations were approximately 45 and 48, which occurred at 200 and 250 rpm. That for the 2 min grinding duration was 48 at 350 rpm. Thus, these are the grinding speeds which give

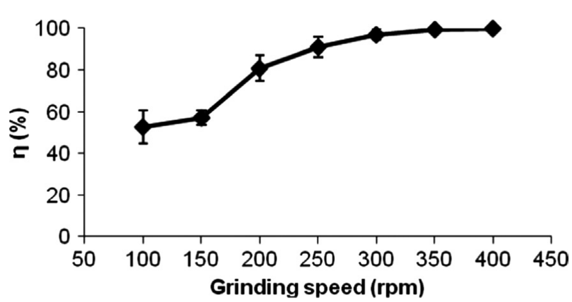

Fig. 11. Detaching efficiency (η) and standard deviation bars for different grinding speeds.

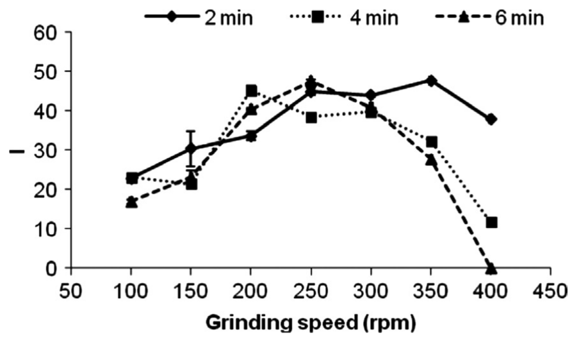

Fig. 12. Performance index (I) and standard deviation bars versus grinding speed for 2, 4, and 6 min grinding durations.

the best performance, in terms of fibre yield and fibre detachment. However, the core yield data (Fig. 9) demonstrated that the Y_c at 350 rpm were not so good. Thus, one can conclude that the optimal grinding speeds were 200 and 250 rpm, in terms of both I and Y_c.

Applications of the results

The planetary ball mill produced up to 55% fibre yield, which was better than the performance of a hammer mill which produced up 40% fibre yield for the same retted hemp (Baker 2009). Comparisons with other mills reported in the literature, such as cutterheads and roller mills, could not be made, as they were not tested using the same feedstock. However, among all mills that have been used for hemp decortications, the ball mill was the only machine that did not have fibre wrapping problems. This advantage of ball mill over other mills make ball mill a promising machine for fibre decortications.

The results obtained from this study were from a small lab-scale planetary ball mill. Caution should be taken when using the results for large scale ball mills. However, the results may be easily extended to large scale, because ball mills have been well documented, in terms of the ratio of feedstock and ball volume, and rotational speed versus the ball mass (Rajamani et al. 2000; Suryanarayana 2001; Budin et al. 2008). Since the tests done in this study followed the manufacturer instruction regarding the ratio of feedstock and balls, the optimum grinding speed and duration obtained from this study could be applicable to large ball mills.

Other factors, including the cutting length and moisture content of feedstock, may also affect the results. Effects of these factors were not studied and the feedstock used had a constant cutting length of 40 mm under the air dry condition. Also, this study used retted hemp as feedstock; a longer grinding duration may be required for unretted hemp. Further research is required to investigate effects of different retting conditions, cutting length and moisture conditions.

CONCLUSION

When using a planetary ball mill for decortications of retted hemp, grinding speed and duration had significant effects on fibre yield, core yield, chaff, detaching efficiency, and performance index. The 2-min grinding duration produced reasonably good long and total fibre yield (43.3% on average), regardless of grinding speed. Similar fibre yields were observed for the longer grinding durations (4 and 6 min) when grinding speeds were ower than 200 rpm. The highest core yield (20.1%) was observed around the grinding speed of 200 and 250 rpm. For the grinding speeds higher than 250 rpm, fibre and core were ultimately lost to the chaff stream, resulting in high chaff production.

Grinding speed and detaching efficiency showed a nonlinear direct relationship; as speed increased so did the detaching efficiency. However, higher detaching efficiency at higher grinding speeds may mean a greater loss of fibre. The highest performance index was observed at grinding speeds of 350 rpm for the 2 min duration, 200 rpm for the 4 min duration, and 250 rpm for the 6 min duration. Given these observations and the results of the highest core yields at 200 and 250 rpm, it is suggested to operate the planetary ball mill at 200 or 250 rpm for decortication of retted hemp.

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