Optimization of wheat debranning using laboratory equipment for ethanol production

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Abstract: Ethanol production from starchy cereal grains is increasing rapidly due to increasing demand for alternative fuels. In Canada, wheat is the primary feedstock in ethanol plants. To improve the productivity of the ethanol plants in terms of product quality and yield, debranning of wheat grains may be employed. Debranning is advantageous in two ways. Firstly, bran removal increases the starch content of the feedstock, improving the fermentation efficiency of the ethanol plants. Secondly, bran, a valuable co-product can be used as an animal feed ingredient. In this study, experiments to optimize the debranning process were carried out using two kinds of abrasive equipment, the Satake and the TADD (tangential abrasive dehulling device) mills. Wheat samples (30 and 200 g) were debranned in the Satake mill at 1 215, 1 412, and 1 515 r/min rotational speeds, 30, 36, and 40 grit sizes, and 30, 60, and 90 s retention times, and in the TADD mill at 900 r/min rotational speed, 30, 36, 50, and 80 grit sizes, and 120, 180, 240, and 300 s retention times. In addition to debranning efficiency, the starch separation efficiencies of the two mills were calculated in different debranning conditions. In the Satake mill, the 30 g and 200 g sample size, 1 412 r/min and 1 515 r/min rotational speeds, all grit sizes, and 60 s of retention time demonstrated the highest debranning efficiency. Correspondingly, optimal results in the TADD mill were obtained with 200 g sample size, 900 r/min rotational speed, 50 and 80 grit sizes, and 180 s and 240 s retention times. However, based on the experimental results, Satake mill provided better debranning values compared to the TADD mill. The starch separation efficiency values supported these results.

Keywords: wheat debranning, ethanol production, Satake mill, tangential abrasive dehulling device, grit size, retention time, rotational speed, starch separation efficiency

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1 Introduction

Ethanol production is a fast growing industry and has shown considerable impact on decreasing the world's reliance on fossil fuels. In order to maintain the growth of the ethanol industry, there is a need for sustainable supply of feedstock[1]. Similar to the global scenario, ethanol production has increased tremendously in Canada, specifically in the Canadian prairies[2]. As a direct result of growth of the ethanol industry, the agricultural industry enjoys such benefits as job openings and more avenues of marketing for grain producers[3]. Most of the ethanol plants in operation throughout Canada are grain-based. Therefore, it is important that feedstock needed for ethanol production has sufficient availability. Inadequate corn production in the Canadian prairies and better economics on usage of locally grown wheat varieties makes wheat the first choice for ethanol production[4]. Moreover, the quantity of wheat produced in Western Canada is sufficient for human and animal

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consumption, and as ethanol feedstock[2].

With sufficient feedstock for utilization, the Canadian ethanol industry is bound to grow. A study by Licht[5,6] showed that in general, fuel ethanol production and consumption in Canada was low in the year 2004, which was only about 250 million L. With increase in the economic and agricultural benefits associated with ethanol production, the ethanol production is expected to rise[2]. The availability of feedstock[4], job opportunities, and the local economic impact[7] were also some of the reasons for the increase in ethanol production. Also, high-grade wheat preferred for human consumption (varieties having low starch and high protein) is not being used in ethanol production[8]. Instead, wheat varieties having high starch and low protein[9] content are preferred. The survey results of Saunders and Levin[8] showed that in 2010, ethanol production in Canada reached 1.7 billion L and 3.1 billion L using wheat and corn as feedstock, respectively.

Due to increased availability of suitable (high starch, low protein) local wheat varieties, most of the ethanol processing plants in Canada use wheat as the primary feedstock. Almost 0.5 million t of wheat is used for manufacturing ethanol[10]. Wheat varieties suitable as ethanol feedstock often represent a good crop rotation fit, as reported by Reimer[11]. The ethanol industry also provides farmers with an additional local outlet for marketing the grain. Ethanol production provides the opportunity to use poor quality grain (affected by weather or disease) as feedstock[12]. The Canadian wheat varieties and their protein contents, as shown in Table 1, help in easier selection of feedstock for ethanol production. Wheat proteins contain the essential amino acid and lysine, and have better quality in terms of food and feed applications. High starch and low protein wheat varieties[13] have appreciable starch conversion efficiency, and are preferred for ethanol production at the industrial level. The Canadian Prairie Spring, Canadian Western Red Winter, and Canadian Western Soft White wheat varieties are suitable for ethanol production[14].

High protein, low starch wheat is less preferred in ethanol production for three reasons. Firstly, the starch content in the grain should be high to be suitable for ethanol production[13]. Secondly, higher protein makes the mash adhesive, which is undesirable in ethanol production. Thirdly, poor solubility of wheat proteins affects the downstream processing of the spent grains[15]. In addition, non-starch polysaccharides hinder processing by increasing the viscosity of the mash. The protein content of soft white wheat is 8%-9%, which is much closer to the protein levels of corn. Hard red spring wheat has higher protein content, and is less preferred. On the other hand, winter wheat can also be used because it has yield higher than spring wheat varieties. The selected wheat varieties should be milled and processed for ethanol production.

Table 1 Canadian wheat varieties and their protein content[14]

Wheat varieties	Typical protein level/% (dry basis)
Canadian Western Red Spring	13.2
Canadian Western Extra Strong	12.2
Canadian Prairie Spring Red	11.5
Canadian Western Red Winter	11.3
Canadian Prairie Spring White	11.2
Canadian Western Soft White	10.5
Canadian Western Amber Durum	12.8

Milling of grains, prior to fermentation, improves ethanol yield[16]. Pearling (debranning) was incorporated in commercial production of ethanol by Wang et al.[17]. Debranning uses friction and abrasion to partially remove the outer layers of the wheat kernel[18] to further improve ethanol production. Debranning increases the starch content of the grains by removing the fiber and protein[17], thereby increasing the efficiency and yield of ethanol plants[13]. Wang et al.[17] showed that dehulling increased the starch content of the debranned kernels by 12.2%. The ethanol yield per tonne of grain also increased by 6.5%-22.5%[19], thus increasing the production rate. Sosulski and Sosulski[13] used the Allis-Chalmers mill for partial debranning of wheat. Complete debranning could not be done due to the presence of the crease on the ventral side of the kernel. The starch content of the whole grains was reported to be 54%-57% and it was 64%-68% in the debranned flour[13].

Debranning using the Satake mill is highly beneficial. The mill is compact having characteristics such as good flowability and controlled processing[20]. Another advantage of the Satake mill is its flexibility[21]. A flexible system adjusts the amount of bran removal, producing different products. Wang et al.[22] studied dry oat dehulling using the Satake TM-05 abrasive mill. The results concluded that debranning removed the trichomes from the oats. In addition, high amount of pearled oat fractions, rich in aleurone cells was produced.

The tangential abrasive dehulling device (TADD) is another debranning equipment which works on the principle of abrasion. The TADD uses tangential abrasion to remove the bran layer([23,24]) from grain kernels. The mill has been successfully used to debran different grains by Normand et al.[25]. Upon usage, it was seen that at higher retention times, the bran fraction versus retention time plot in TADD was nonlinear[26]. Since the Satake and the TADD mills have been used successfully for dehulling grains, it is essential to optimize the mill operations during debranning of wheat when it is considered as a feedstock preparation process prior to ethanol fermentation. Optimal conditions of debranning will lead to improvement in the quality of the feedstock and the final product. Since lab-scale evaluations are logistically manageable and economically feasible, these mills were selected for successfully predicting industrial scale performance.

The objective of this study was to optimize the laboratory debranning process of wheat using the two milling equipments, the Satake mill and the tangential abrasive dehulling device (TADD), before using it as feedstock for ethanol production.

2 Materials and methods

2.1 Materials

The wheat grain (AC Andrew, a soft white spring variety) used in this study was obtained from an ethanol plant located in southern Saskatchewan, Canada. The samples were stored in large plastic bins to protect the grain from rodent infestation. A dockage tester (Model: C-XT3, Cea-Simon-Day Ltd., Winnipeg, MB) was used to mechanically separate the various components, i.e. broken kernels, stones, and other grains present along with the wheat grain sample, according to particle size and weight[27]. The machine was turned on and the sample was discharged into the hopper. The materials were collected after they passed the hopper and the sieves. The sieves were tapped for this purpose. When the samples passed through all the sieves completely, the machine was turned off. The materials of different particle size were poured into separate pans. Only clean whole wheat grains were used for dehulling.

2.2 Experimental methods

Two types of abrasive mills, the Satake mill and the TADD, were used to conduct optimization studies for bran production. Previous studies done using abrasive mills have shown that debranning efficiency can be optimized by adjusting factors such as sample size, rotational speed, diameter, clearance, grit size, and the retention time for each run. The levels of rotational speed and grit size for the Satake mill were based upon the range (minimum and maximum) of the equipment and the retention times were based upon initial testing results. The grit sizes for the TADD were based on the available grit size for this equipment. The rotational speed was fixed at 900 r/min based upon experience in the lab for cereal grain, and retention time levels were based upon initial testing results. For the optimization process in this study, the sample size, the rotational speed, the retention time, and the grit size (nominal size of abrasive particles corresponding to the number of openings per inch in a screen through which the particles can pass) were varied in the two mills. Each test was conducted with three replicates for reproducibility of results.

2.2.1 Experimental plan

Wheat samples (30 and 200 g) were debranned in the Satake mill at rotational speeds of 1 215, 1 412, and 1 515 r/min, grit sizes of 30, 36, and 40, and retention times of 30, 60, and 90 s and in the TADD mill at rotational speed of 900 r/min, grit sizes of 30, 36, 50, and 80, and retention times of 120, 180, 240, and 300 s. The starch content of the debranned kernels was used to calculate the starch separation efficiency of the debranning equipment.

2.2.2 Dehulling procedure

Dehulling in Satake mill-The dehulling experiment was done in the Satake mill (Satake Grain Testing Mill, Model: TM-05, Satake Engineering Co., Ltd, Japan; Figure 1). The cleaned wheat from the dockage tester was poured into the mill through the feed hopper. On entering the abrasion chamber, the roller and the metallic casting dehulled the grains[28]. The abraded grains moved to the discharge end. There was a friction between the kernels and the screen, completing the debranning process. At the end of milling, the husk and bran were collected in the wooden box attached to the milling chamber[28]. The grains were collected separately. The degree of debranning was controlled by various factors. For this research, 30 and 200 g of wheat was used for each test, and the sample size, rotational speed, grit size, and retention time were the factors to be optimized.

Figure 1 The Satake mill

Dehulling in the tangential abrasive dehulling device (TADD)- Dehulling of wheat was also done in theTADD mill (Model: 4E-230, Venables Machine Works, Saskatoon, SK; Figure 2). The mill had a horizontally placed roller and a stationary aluminum head plate holding eight stainless steel open-bottomed sample cups[29]. The grains were placed in the sample cups located opposite to each other. A digital electronic timer (Model: 8683-10, ColeParmer Instrument Company, Chicago, IL) was used to adjust the residence time during each test[29]. After debranning, the debranned grains were collected using a vacuum aspirator[24], and the husk and bran were collected through a cyclone separator device, connected to the TADD[28]. Sample sizes of 30 and 200 g were used for each test in this research, and the sample size, grit size, and retention time were the factors to be optimized. Rotational speed had been optimized earlier and the optimal value (900 r/min) was used throughout the experiments.

2.2.3 Moisture content determination

Moisture content (wet basis) of whole wheat and wheat bran samples obtained after debranning was determined using the air-oven method (AOAC method 930.15[30]). Two to three grams of the samples (ground) were dried at 135℃ for 2 h. The moisture content was expressed as the percentage of the total mass i.e. mass of water per original mass of the sample. Three runs were conducted for the samples from the two abrasive devices.


Figure 2 The tangential abrasive dehulling device

2.2.4 Starch content and starch separation efficiency

The data obtained for the percent bran fraction from the Satake and the TADD mills were compared and the combinations (speed, grit size, and retention time) leading to optimal bran production was further analyzed for starch content. The AOAC (Method 996.11[31]) and AACC (Method 76.13[32]) methods are simple and reliable procedures for the measurement of total starch.

The starch separation efficiencies for the two abrasive devices, the Satake mill and the TADD were calculated by analyzing the debranned wheat obtained from the devices for the starch content. Starch analysis was carried out by following the procedure as stated in AOAC Method 996.11 and AACC Method 76.13 for total starch assay (Amyloglucosidase/α-Amylase method[33]). Each sample was replicated thrice. The percentage of the total starch retained in the debranned kernel that was recovered is a measure of the starch separation efficiency of the debranning equipment. The starch separation efficiency for the two mills was calculated according to the formula used by Tyler et al.[34] which is given below.

Starch separation efficiency=

$$\left(\frac{\text{wt. of debranned wheat} \times \text{total starch in debranned kernels}}{\text{wt. of whole wheat} \times \text{total starch in whole wheat}}\right) \times 100$$

2.2.5 Data analysis

Statistical analysis of the results obtained for debranning and starch analysis were done using SAS Version 9.2 software[35]. The GLM and ANOVA procedures were used in the Student-Newman-Keuls test. Analysis of variance was used to determine if differences between treatments were significant at 5% significance level and to determine the relationship between the parameters of debranning (rotational speed, grit size, and retention time) in the Satake mill and the TADD.

3 Results and discussion

Experiments were conducted to determine the effects of variation in sample size, rotational speed, grit size, and retention time on the debranning of wheat and starch separation efficiencies of the Satake and the TADD mills. The comparison in the debranning efficiencies of the Satake and the TADD mills are based on the mechanisms of abrasion.

3.1 Debranning

3.1.1 Debranning in the Satake mill (30 g sample size)

Debranning efficiency of a mill is an important machine characteristic. The study by Wang[36] reported that dehulling of grains in the Satake mill is affected by the process variables such as rotational speed and dehulling time. The results for debranning with different sample sizes (30 and 200 g) for the Satake mill are given in Table 2 and Table 3, respectively. The amount of bran fraction obtained is an indicator of debranning efficiency of the abrasive mill.

Table 2 Debranning of wheat (AC Andrew) using Satake mill (30 g)

Sample size /g	Rotation speed /r min^{-1}	Grit size	Retention time /s	Bran/%*
30	1215	30	30	2.83(0.05)i(1)
30	1215	30	60	6.81(0.41)gh
30	1215	30	90	10.82(0.75)f
30	1215	36	30	2.73(0.22)i
30	1215	36	60	6.17(0.26)gh
30	1215	36	90	11.02(0.53)f
30	1215	40	30	2.51(0.11)i
30	1215	40	60	6.53(0.08)gh
30	1215	40	90	10.89(0.75)f
30	1412	30	30	5.39(0.44)h
30	1412	30	60	12.65(0.15)f
30	1412	30	90	20.29(0.37)c
30	1412	36	30	5.19(0.42)h
30	1412	36	60	12.01(0.46)f
30	1412	36	90	19.21(0.30)c
30	1412	40	30	5.37(0.38)h
30	1412	40	60	11.72(0.16)f
30	1412	40	90	18.78(0.21)c
30	1515	30	30	7.78(0.15)g
30	1515	30	60	17.31(0.46)d
30	1515	30	90	26.30(0.67)a
30	1515	36	30	7.37(0.34)g
30	1515	36	60	15.19(0.52)e
30	1515	36	90	23.07(0.49)b
30	1515	40	30	5.86(0.33)g
30	1515	40	60	14.47(0.62)f
30	1515	40	90	23.59(0.38)b

Note: Number in parenthesis is standard deviation, *n = 3; (1) Mean values with at least one common letter are not significantly different at P = 0.05.

Table 3 Debranning of wheat using Satake mill (200 g)

Sample size /g	Rotation speed / r min^{-1}	Grit size	Retention time /s	Bran/%*
200	1215	30	30	3.63(0.09)g(1)
200	1215	30	60	17.11(0.56)efg
200	1215	30	90	31.94(0.23)bc
200	1215	36	30	4.44(0.83)fg
200	1215	36	60	18.06(0.12)de
200	1215	36	90	33.05(0.53)ab
200	1215	40	30	6.69(0.05)fg
200	1215	40	60	18.19(0.26)de
200	1215	40	90	30.64(0.06)ab
200	1412	30	30	5.65(0.39)fg
200	1412	30	60	20.03(1.16)cd
200	1412	30	90	35.73(0.86)ab
200	1412	36	30	6.52(0.11)fg
200	1412	36	60	21.65(1.13)cd
200	1412	36	90	36.01(0.19)ab
200	1412	40	30	5.65(0.31)fg
200	1412	40	60	18.52(0.76)de
200	1412	40	90	33.21(0.32)ab
200	1515	30	30	6.08(0.98)fg
200	1515	30	30	14.03(0.26)def
200	1515	30	90	31.83(0.29)ab
200	1515	36	30	6.75(0.11)fg
200	1515	36	60	20.82(0.32)cd
200	1515	36	90	37.85(0.69)a
200	1515	40	30	4.17(0.10)efg
200	1515	40	60	22.90(0.02)bc
200	1515	40	90	36.60(0.34)ab

Note: Number in parenthesis is standard deviation, *n = 3; (1) Mean values with at least one common letter are not significantly different at P = 0.05.

The results from Table 2 (and trends indicated in Figure 3) indicate that for a sample size of 30 g and 1 215 r/min rotational speed, the highest amount of bran fraction produced was 11.02% (grit size-36, retention time-90 s). The bran fractions for all the three grit sizes with a lower retention time (30 and 60 s) were less than 7%. The study by Oomah et al.[24] and Mbengue[37] as cited in Bassey and Schmidt[38] emphasized that factors such as grit size of the grinding surface affect the dehuller performance. Results of the experiments of this study also lead to similar conclusions. Higher rotational speeds (1 412 and 1 515 r/min) and different combinations of grit size and retention time were able to cause extensive bran removal. For the rotational speed of 1 515 r/min, the three grit sizes (30, 36, and 40) and a 90 s retention time lead to removal of a very high bran fraction (26.30%, 23.07%, and 23.59% respectively, Figure 3), which was beyond the desired optimal value. The combination for 30 g sample size which lead to optimal bran removal were 1 412 r/min and 1 515 r/min, all grit sizes (30, 36, and 40), and 60 s retention time. For the wheat grain, there was an increase in bran fraction with increasing rotational speed. This was similar to the trend followed by oat grains dehulled in an impact dehuller[39]. Statistical analysis for Satake mill showed that the three variables (rotational speed, grit size, and retention time) had positively significant effect on debranning (P<0.01 for each). Also, the interaction between speed and grit size as well as speed and retention time was also positively significant (P<0.01 for each).

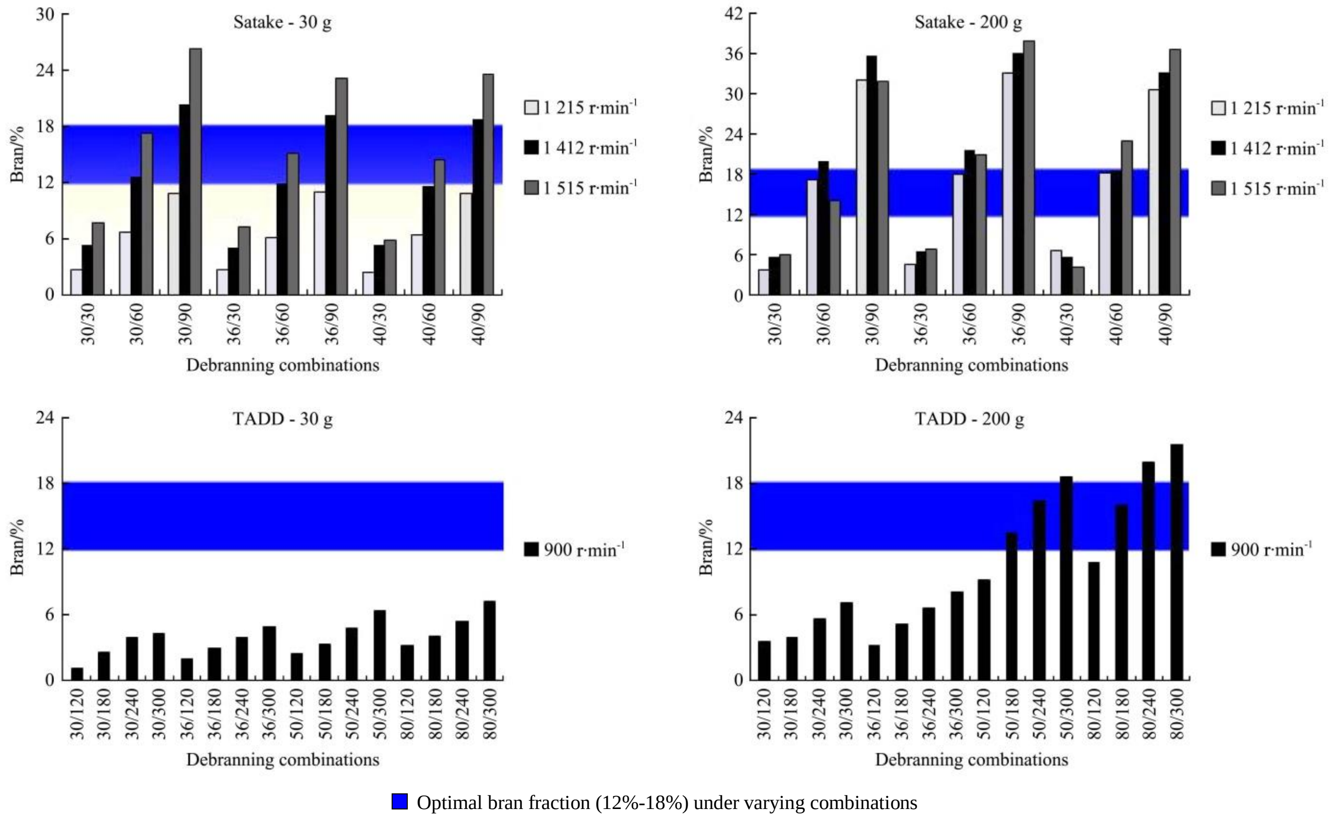

Figure 3 Debranning efficiency of the Satake and the TADD mills. Debranning combinations are designated as xx/yyy, where xx is grit size and yyy is retention time in seconds

3.1.2 Debranning in the Satake mill (200 g sample size)

Using the 200 g sample size, the rotational speed of 1 215 r/min was optimal for 12%-18% bran fraction production (Table 3). The results were consistent with the findings of McCluggage[40] as cited in Liu[41], who stated that the degree of dehulling increased as mass of the grain in the dehuller increased. The debranning results for the Satake mill for 200 g sample size (30, 36, and 40 grit size) also indicated that using higher retention time (90 s) resulted in removal of very high amount of bran from the wheat grains (30%-38%). For 200 g sample size, the three rotational speeds (1 215, 1 412, and 1 515 r/min) and 60 s retention time provided optimal results (Figure 3).

Similar to the 30 g sample size, with a constant retention time and increasing rotational speed of the mill, there was increased bran removal as the grit size increased. Statistical analysis for the Satake mill (200 g sample size) showed that the three variables (rotational speed, grit size, and retention time) had positively significant effect on debranning (P<0.01 for each). Although all the three variables were significant, retention time had the highest effect on debranning efficiency. Also, the interaction among the three variables was positively significant (P=0.02).

The debranning results from the Satake mill (30 g and 200 g) showed that optimal bran fraction values could be obtained with both sample sizes, but with varying speed, grit size, and retention time. For both sample sizes, 90 s retention time led to removal of more than 20% bran (Figure 3). This indicates that along with the bran, outer endosperm layers were also being removed during the debranning process. This would lead to an undesirable loss of starch from the debranned kernels. As a result, the starch content of the debranned wheat kernels being used as feedstock for ethanol production would be reduced, lowering the quality of the final product.

3.1.3 Debranning in the TADD mill (30 g sample size)

The debranning results for the TADD mill for the two sample sizes (30 g and 200 g), rotational speed (900 r/min), grit sizes (30, 36, 50, and 80), and retention times (120, 180, 240, and 300 s) are given in Tables 4 and 5. The results showed that the degree of debranning was regulated by grit size, retention time, and other factors. The results of the experiments had conclusions similar to the results reported by Posner and Hibbs[42] on wheat flour milling. Their study revealed that grit roughness and roller speed affected debranning efficiency. With 30 g as the sample size and at 900 r/min rotational speed, on varying the grit size and increasing the retention time, the percent bran fraction obtained increased. This implies that under each combination of rotational speed and grit size, on increasing the retention time, there was a slight increase in the bran fraction removal. Similar conclusions were drawn by Mwasaru et al.[43] who stated that abrasive surface of the TADD mill affected dehulling efficiency. Furthermore, under each combination, the bran fraction removal was much lower than the optimal value (Figure 3). The highest bran fraction percentage achieved with 30 g sample size was 7.28%, which was attained by using 900 r/minspeed, 80 grit size, and 300 s retention time.

The statistical analysis results for 30 g sample size showed that both grit size and retention time had positive significant effect on the debranning efficiency of the mill (P<0.01 for both). Variable interaction was insignificant.

Table 4 Debranning of wheat using tangential abrasive dehulling device (TADD, 30 g)

Sample size /g	Rotation speed /r min^{-1}	Grit size	Retention time /s	Bran/%*
30	900	30	120	1.09 (0.09)j[(1)]
30	900	30	180	2.54 (0.36)h
30	900	30	240	3.89 (0.28)e
30	900	30	300	4.35 (0.13)c
30	900	36	120	2.00 (0.08)i
30	900	36	180	2.94 (0.04)g
30	900	36	240	3.89 (0.21)e
30	900	36	300	4.93 (0.03)d
30	900	50	120	2.47 (0.03)h
30	900	50	180	3.35 (0.08)f
30	900	50	240	4.80 (0.22)d
30	900	50	300	6.36 (0.01)b
30	900	80	120	3.22 (0.20)fg
30	900	80	180	4.01 (0.06)e
30	900	80	240	5.40 (0.08)c
30	900	80	300	7.28 (0.12)a

Note: Number in parenthesis is standard deviation, *n = 3; [(1)] Mean values with at least one common letter are not significantly different at P = 0.05.

Table 5 Debranning of wheat using the tangential abrasive dehulling device (TADD, 200 g)

Sample size /g	Rotation speed /r min^{-1}	Grit size	Retention time /s	Bran/%*
200	900	30	120	3.53 (0.30)k[(1)]
200	900	30	180	3.99 (0.37)k
200	900	30	240	5.63 (0.74)j
200	900	30	300	7.10 (0.15)i
200	900	36	120	3.19 (0.13)k
200	900	36	180	5.18 (0.21)j
200	900	36	240	6.61 (0.01)i
200	900	36	300	8.13 (0.36)h
200	900	50	120	9.17 (0.40)g
200	900	50	180	13.43 (0.53)e
200	900	50	240	16.38 (0.64)d
200	900	50	300	18.61 (0.57)c
200	900	80	120	10.78 (0.37)f
200	900	80	180	16.01 (0.07)d
200	900	80	240	19.94 (0.09)b
200	900	80	300	21.51 (0.09)a

Note: Number in parenthesis is standard deviation, *n = 3; [(1)] Mean values with at least one common letter are not significantly different at P = 0.05.

3.1.4 Debranning in the TADD mill (200 g sample size)

McCluggage[40] as cited in Lawton and Faubion[26] stated that the quantity of sample per run and the dimensions of the grains influenced milling. According to the experiments done in this study, increasing the sample size to 200 g gave better debranning results. The results showed that with a constant rotational speed, usage of higher grit size was preferable. With 50 and 80 grit size and 180, 240, and 300 s retention time, the bran fraction obtained ranged from 13%-21% (Figure 3). Upon using 50 and 80 grit size, and 180 and 240 s retention time, optimal debranning could be attained. The statistical analysis results for 200 g samples size suggested that retention time and grit size were significant factors affecting debranning efficiency positively (P<0.01 for both). In contrast to the results for 30 g sample size, grit size and retention time interaction had positively significant effect on the bran fraction (P=0.03).

Debranning in the TADD resulted in lower yield of bran fraction under the above conditions as compared to the Satake mill. The debranning results for 30 g sample size were lower than the optimal range (12%-18% bran fraction) which is unacceptable. In the case of 200 g sample size, the optimal range for bran fraction was attained at 50 and 80 grit size and 180 and 240 s retention time, providing values comparable to the Satake mill results. In their evaluation of the application of the TADD mill, Reichert et al.[44] observed a linear relationship between disc speed and dehulling efficiency. Since the rotational speed was kept constant for both sample sizes in this study, this aspect could not be analyzed.

Figure 3 shows that most of the combinations used in the Satake mill (200 g) produced optimal bran fractions. Overall, the Satake mill indicated maximized dehulling efficiency. Although the TADD mill at 200 g sample size was able to provide results of debranning comparable to the Satake mill results, it was also noted that the time for debranning in the TADD mill was much longer than the Satake mill. While the Satake mill reached optimal debranning values at 60 s, it took 240-300 s in the TADD mill. Moreover, the Satake mill and TADD differ in the mechanics of abrasion. The Satake mill has a vertically rotating abrasive roller which provides more abrasive surface for debranning. As the materials entered the abrasion chamber, they were continuously mixed, improving the rate of debranning and reducing the retention time. In the TADD, the horizontally placed disc and the sample cups provided lesser abrasive surface. The sample size per sample cup was also a limiting factor. Abrasion in the TADD mill took longer, decreasing the production rates. On comparing the Satake mill and the TADD, the abrasion mechanism used in the Satake mill is preferable for industrial processes. Debranning equipment with similar mode of action as the Satake mill would increase the production rates.

For similar reasons, the Satake mill was used by Wang[36] to dehull red lentils and by Black et al.[45] (1998) to dehull field peas. The results from the TADD and the Satake mills demonstrated that the milling conditions impact the dehulling characteristics of the grains, which was also the conclusion drawn by Wang[36].

3.2 Starch content

Sosulski and Sosulski[13] used partial debranning method to improve the ethanol yield from barley, rye, and triticale. In their experiment, the starch content increased from 54%-57% in the whole grains to 64%-68% in the flours by debranning. This study also aimed at similar results. Moisture content of grains is an important factor which affects the physical properties of grains in various ways. Previous studies have reported that moisture content is required for starch gelatinization[46]. Dziki[47] reported that the rupture point on the application of force in the wheat grains varied with the moisture content. Furthermore, in the case of soft white spring wheat varieties, increased grain moisture reduced grain hardness[48] which in turn aided in the debranning. Studies have shown that water diffuses into the kernels, causing swelling which weakens the cohesion forces, reducing grain hardness. Optimal debranning also implies good starch separation efficiency of abrasive mills. Considering these aspects, the starch analysis of the debranned kernels was done to evaluate the separation efficiency of the debranning equipment.

3.2.1 Starch content of the debranned kernels from the Satake and the TADD mills (30 g sample size)

The samples from the debranning test which provided optimal bran fraction were selected for starch analysis. The starch content of the debranned kernels from the Satake mill and the TADD (30 g sample size) are shown in Table 6. For the Satake mill samples, the starch content of the kernels increased on debranning by almost 8.0% (from 70.4% to 76.0%). According to Wang[49], the starch content of grains and the debranning efficiency were directly proportional. El Hag et al.[50] also stated that dehulling significantly increased the starch content in the grains. Since the bran contains very little starch, its removal means that there is proportionally more starch in the dehulled grains. Rios et al.[51] concluded that dehulling isolated the starchy endosperm and reduced fungal contaminations in wheat flours. Therefore, optimal debranning results were an indicator of less starch loss from the grains.

Table 6 Starch content of the debranned kernels from the Satake mill and the TADD mill (30 g)

Sample	Sample size/g	Speed/r min^{-1}	Grit size	Retention time/s	Moisture content/%w.b*	Starch content/%* (kernel)	Starch separation efficiency/%
Initial wheat grains	-	-	-	-	11.87	70.4 (3.1)	-
Satake	30	1412	30	90	9.28	72.6 (3.0)a(1)	70.0c
Satake	30	1412	36	60	9.48	76.2 (0.9)a	69.7c
Satake	30	1412	40	90	9.83	75.5 (1.4)a	67.5c
Satake	30	1515	30	60	10.19	60.3 (4.9)b	71.4c
Satake	30	1515	30	90	9.74	68.6 (0.9)a	71.6c
Satake	30	1515	36	60	10.21	71.7 (2.1)a	88.1a
Satake	30	1515	36	90	10.36	75.5 (2.0)a	83.4b
Satake	30	1515	40	60	9.92	74.4 (1.0)a	91.7a
Satake	30	1515	40	90	9.81	76.2 (1.0)a	84.5b
TADD	30	900	80	300	8.24	78.8 (1.0)	101.2

Note: Number in parenthesis is standard deviation, *n = 3; (1) Mean values with at least one common letter are not significantly different at P = 0.05.

Starch separation efficiency of the Satake mill varied from 67% to 91%, depending upon the starch content of the debranned wheat samples (Figure 4). The TADD mill sample (bran fraction 7.28%) used for starch analysis was obtained with the rotational speed of 900 r/min, 80 mm grit size, and 300 s retention time. The starch content of the sample (78.8%) was higher than the Satake mill samples (Table 6), owing to partial or incomplete debranning. Wang et al.[17] demonstrated that the starch content of the dehulled grains increased as the bran layers were removed progressively. The grains might have undergone partial debranning in the TADD mill and some of the starch from the inner bran layers might be retained with the grain kernels. According to the equation formulated by Tyler et al.[34], the starch separation efficiency was positively correlated to the starch content of debranned grains. For starch content, the process variables had a positively significant effect. The grit size had the highest effect (P<0.01), whereas rotational speed and retention time had a lower effect (P=0.02 and 0.01, respectively). The interaction between the variables was low or insignificant (P>0.05). In case of starch separation efficiency of the Satake mill, rotational speed, grit size, and the interaction between them was positively significant (P=0.02, 0.02, and 0.03 respectively). Since only one TADD mill sample was acceptable for starch analysis, no statistical analysis could be done.

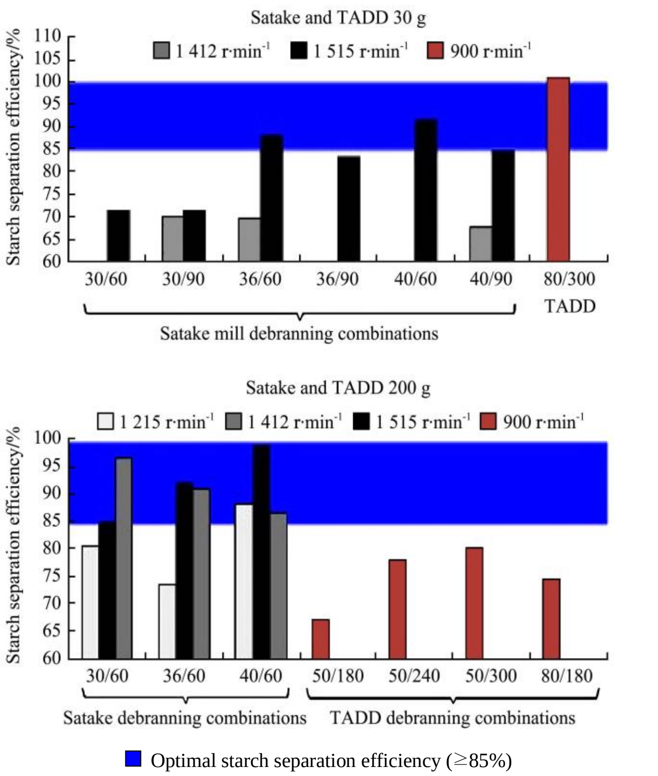

Figure 4 Starch separation efficiency of the Satake and the TADD mills combinations (optimal bran fraction production). Debranning combinations are designated as xx/yyy, where xx is grit size and yyy is retention time in seconds

From the results obtained for 30 g sample size, the optimal condition for debranning in the Satake mill was determined to be 1 515 r/min rotational speed, 40 grit size, and 60 s retention time. The TADD mill results were poor compared to the Satake mill, with lower debranning and starch separation efficiency.

3.2.2 Starch content of the debranned kernels from the Satake mill (200 g sample size)

Debranned kernel samples from the Satake mill were tested for starch content and the results of starch analysis are given in Table 7. The results indicated that sample size of 200 g could be highly recommended because the starch separation efficiency achieved under varying conditions went up to 98%. The data for starch content of the debranned kernels showed that rotational speeds 1 412 and 1 515 r/min, grit sizes 30, 36, and 40, and retention time 90 s gave the highest values (more than 85%). From the starch separation efficiency formula, it is understood that separation efficiency is directly proportional to the debranned kernel weight and the starch content of the debranned kernels. Also, starch content is inversely proportional to kernel weight i.e. as complete debranning occurs, kernel weight reduces and the overall starch content in the kernel increases. Thus, with a decrease in kernel weight and an increase in starch content of kernels, the separation efficiency is affected both ways. The general trend in the data obtained was that, as grain kernel weight decreased (higher retention time in debranning), the starch content increased while the separation efficiency decreased.

Table 7 Starch content of the debranned kernels from the Satake mill (200 g)

Speed/r min^{-1}	Grit size/mm	Retention time/s	Moisture content*/%	Starch content*/%	Starch separation efficiency**/%
1215	30	30	9.29a(1)	64.3(1.0)i	89.3(1.3)abcde
1215	30	60	9.46a	68.8(0.6)i	80.6(0.8)bcdefg
1215	30	90	9.81a	71.6(1.5)i	68.7(1.5)efgh
1215	36	30	9.28a	52.1(2.5)j	71.8(3.5)gh
1215	36	60	9.48a	63.4(0.6)i	73.5(0.7)fgh
1215	36	90	9.80a	71.8(0.1)gh	67.8(0.1)h
1215	40	30	9.30a	65.3(1.7)i	87.0(2.2)bcdef
1215	40	60	9.47a	75.4(0.2)fg	88.1(0.3)bcde
1215	40	90	9.85a	85.0(1.7)bcd	83.1(1.7)cdefg
1412	30	30	9.26a	69.0(0.6)hi	94.4(0.8)abcd
1412	30	60	9.52a	75.2(3.6)fg	85.0(4.1)bcdefg
1412	30	90	10.10a	87.7(0.1)abc	79.4(0.1)efgh
1412	36	30	9.19a	75.3(0.9)fg	99.0(1.2)a
1412	36	60	9.51a	83.0(1.7)cde	92.0(1.8)abcde
1412	36	90	9.81a	90.1(0.6)ab	80.6(0.5)defg
1412	40	30	9.28a	65.8(0.2)i	89.9(0.2)abcde
1412	40	60	9.43a	85.4(0.96)bcd	98.88(1.1)ab
1412	40	90	9.84a	93.6(0.8)a	87.6(0.7)bcde
1515	30	30	9.84a	63.9(2.0)i	86.2(2.8)bcdef
1515	30	60	10.19a	78.8(1.1)ef	96.6(1.4)abc
1515	30	90	9.74a	89.8(1.2)ab	86.5(1.2)bcdef
1515	36	30	10.78a	67.9(0.9)hi	91.6(1.3)abcde
1515	36	60	10.21a	80.6(1.8)def	91.0(2.0)abcde
1515	36	90	10.36a	89.4(0.2)ab	77.3(0.2)efgh
1515	40	30	9.66a	64.1(0.7)i	88.4(0.9)bcdefg
1515	40	60	9.92a	78.3(0.3)fg	86.6(0.4)efgh
1515	40	90	9.81a	93.0(0.8)a	84.7(0.7)bcdefg

Note: Number in parenthesis is standard deviation, *n = 3, **initial whole wheat starch content = 69.0%; (1) Mean values with at least one common letter are not significantly different at P = 0.05.

The results from the starch analysis showed that rotational speeds 1 412 and 1 515 r/min, 40 grit size, and 90 s retention time lead to higher starch content in debranned kernels (~93%). Also, with the same rotational speeds, all the grit sizes of the Satake mill caused high starch separation with 60 s retention time (more than 85%, Figure 4). For the starch content, retention time had the highest positively significant effect (P<0.01). The effect of rotational speed on the starch content was also positively significant (P<0.01) whereas interaction between the two and grit size had a lower significance (P=0.03 for both).

In the case of starch separation efficiency of the Satake mill, rotational speed and retention time held high positive significance (P<0.01). The interaction between the variables and the effect of grit size were insignificant

(P>0.05).

3.2.3 Starch content of the debranned kernels from the TADD mill (200 g sample size)

Four of the samples from the TADD mill gave optimal debranning values and were selected for starch analysis. From the results obtained (Table 8), it was seen that the starch content of the debranned kernels increased up to 68% owing to incomplete debranning. Similarly, starch separation efficiency of the TADD mill was only as high as 80% under 900 r/min rotational speed, 50 grit size, and 300 s retention time (Figure 4). This indicated that the TADD mill had lower efficiency of debranning and starch separation as compared to the Satake mill. The statistical analysis results revealed that both grit size and retention time (process variables) positively affected starch content of the debranned kernels and the separation efficiency of the TADD mill. The P-values for both were higher than 0.05.

Table 8 Starch content of the debranned kernels from the TADD mill (200 g)

Speed/r min^{-1}	Grit size/mm	Retention time/s	Moisture content*/%	Starch content*/%	Starch separation efficiency**/%
900	50	180	10.12	53.6(0.3)c[(1)]	67.2(0.3)b
900	50	240	10.05	64.4(0.3)ab	78.0(0.3)a
900	50	300	9.86	68.0(2.9)a	80.2(3.4)a
900	80	180	9.98	61.2(1.8)b	74.4(2.2)a

Note: Number in parenthesis is standard deviation,*n = 3, **initial whole wheat starch content = 69.0%; [(1)] Mean values with at least one common letter are not significantly different at P = 0.05.

Figure 4 shows the starch separation efficiency of the different combinations in the Satake and the TADD mills that produced optimal bran fractions. It can be understood that for 200 g sample size, 60 s retention time and 1 412 and 1 515 r/min rotational speed improved the starch separation efficiency (≥ 85%) for all grit sizes.

4 Conclusions

The experiments conducted helped in optimizing the two laboratory abrasive mills, the Satake and the TADD mills. The first sample size used for the debranning experiments was 30 g. The results showed that using 30 g of sample size, the debranning efficiency of both the mills was low. A lower debranning efficiency would reduce the productivity of the mills. Studies have shown that larger sample sizes improve abrasion accuracy. Two hundred grams was the maximum applicable sample size suggested in previous studies. Due to this reason, 200 g was the second sample size used in this study to improve the debranning efficiency. The optimal conditions of debranning in the Satake mill were found to be 200 g sample size, 1 412 and 1 515 r/min rotational speeds, all grit sizes, and 60 s retention time. In the case of TADD, 200 g sample size, 900 r/min rotational speed, 50 and 80 grit sizes, and 180 and 240 s retention times provided results slightly comparable to the Satake results. The experimental results concluded that the Satake mill provided better debranning results as compared to the TADD. This is because, on using the Satake mill, optimum bran production could be done in 60 s whereas in case of the TADD mill, it took at least 240 s. This indicated that the Satake mill had higher productivity. The results of starch separation efficiency showed that the Satake mill was more preferable compared to the TADD. The results concluded that sample size of 200 g, rotational speed of 1 515 r/min, 30 grit size, and 60 s retention time are the optimum condition for bran production for the Satake mill. Similarly, 200 g sample size, 900 r/min rotational speed, 50 grit size, and 240 s retention time are the optimum conditions for the TADD mill. Previous studies have provided evidence that laboratory mills are constructed to simulate the operations of commercial mills and they adequately represent commercial milling processes. Therefore, the results of this study suggest that debranning of wheat using the abrasive mechanism similar to the Satake can be used to debran wheat in a commercial mill for an ethanol plant. Moreover, the statistical analysis shows that retention time was the parameter which affected debranning efficiency and starch separation efficiency the most. Therefore, in a commercial set-up, retention time adequately replicating the 60 s retention time of the lab-scale should be used for achieving higher productivity.

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