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Pilot scale fiber separation from distillers dried grains with solubles (DDGS) using sieving and air classification

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ABSTRACT

Distillers dried grains with solubles (DDGS), the coproduct of fuel ethanol production from cereal grains like corn, is mainly used as cattle feed and is used at low inclusion levels in poultry and swine diets because of high fiber content. Elusieve process, the combination of sieving and air classification (elutriation), was developed in laboratory scale to separate fiber from DDGS to result in a low fiber product which would be more suitable for poultry and swine. In this pilot scale study, DDGS was sieved at a rate of 0.25 kg/s (1 ton/h) into four sieve fractions using a sifter and the three largest sieve fractions were air classified using aspirators to separate fiber on a continuous basis. Results were similar to laboratory scale. Nearly 12.4% by weight of DDGS was separated as Fiber product and resulted in two high protein products that had low fiber contents. Payback period for the Elusieve process in an existing dry grind plant processing corn at the rate of 2030 metric tonnes/day (80,000 bushels/day) would be 1.1 yr.

1. Introduction

Distillers dried grains with solubles (DDGS) is the coproduct of fuel ethanol production from corn and other cereal grains such as wheat and sorghum, using the dry grind process. In the dry grind process, starch in the cereal grains is converted to ethanol and the remaining components (protein, fiber, fat and ash) end up in DDGS. DDGS is a powdery solid that ranges in color from golden yellow to brown. DDGS is mainly used as cattle feed and is used at low inclusion levels in poultry and swine diets because of high fiber content (Noll et al., 2001; Shurson, 2002). The increase in DDGS supply due to the growth in US fuel ethanol production has resulted in a need for opening up of new markets for DDGS (Rosentrater, 2008).

Elusieve process, the combination of sieving and air classification (elutriation), was developed in lab scale to separate fiber from DDGS and produce two valuable products: (1) Enhanced DDGS with lower fiber and higher protein and fat contents that could be more suitable for feeding chicken and pigs, and (2) Fiber (Srinivasan et al., 2005, 2008). In the Elusieve process, DDGS is sieved into four or five different sieve fractions and fiber is separated from the three or four largest sieve fractions by air classification (Srinivasan et al., 2005, 2008). The smallest sieve fraction from DDGS, which comprises 30–40 wt% of the original DDGS, is not subjected to air classification because the sieve fraction contains lower fiber (NDF; neutral detergent fiber), higher protein and higher fat contents. Fiber particles were carried selectively in each sieve fraction, at low air velocities, as they had low terminal velocities due to their flat shape and low mass (Srinivasan and Singh, 2008).

Elusieve process was effective in separating fiber from commercial DDGS samples in laboratory scale. Economics analysis for implementation of the Elusieve process in an existing dry grind plant processing corn at the rate of 2030 metric tonnes/day (80,000 bushels/day) estimated that the total capital investment required would be $1.4 million, based on equipment purchase cost of $0.43 million (Srinivasan et al., 2006). Nutritional studies on poultry have shown increased weight gain for birds fed with DDGS from the Elusieve process (Kim et al., 2007; Loar et al., 2008; Martinez-Amezuca et al., 2007). Low capital investment is needed for the Elusieve process because of its simplicity, non-intrusiveness and use of conventional equipment. A significant portion of US fuel ethanol production comes from farmer owned cooperatives and low capital investment is an important basis for the preference of dry grind process over the wet milling process by these cooperatives (Belyea et al., 2004; RFA, 2008). Elusieve process' value addition to coproducts from fuel ethanol production and its low capital investment requirements have made it a technology of interest for plant scale implementation.

In the laboratory scale apparatus, processing was carried out in batch operation and air classification was carried out in an elutriation column (internal diameter of 63 mm or 155 mm) that was custom built. In industrial scale implementation of the

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Elusieve process, commercial sifters and aspirators would be used. There is a need to evaluate the Elusieve process in pilot scale in order to determine its effectiveness using commercial equipment and to verify its operability in continuous mode. In this study, a pilot plant was assembled to evaluate fiber separation from DDGS on a continuous basis using commercial sifter and aspirators. The sifter and aspirators were not custom made and were procured off-the-shelf from equipment manufacturers. The objective of this study was to evaluate fiber separation from commercial DDGS material in the pilot plant, compare the results with those obtained for laboratory scale and obtain operating experience.

2. Methods

2.1. Pilot plant and nomenclature for fractions and products

A rectangular rotary sifter (Model 484, Gump, Savannah, GA) with a sieving area of 1.8 m^2 (19 ft^2) per deck and consisting of three decks for stack sieving was used to produce four sieve fractions, which are denoted as A (largest size), B, C and D (smallest size) (Figs. 1 and 2). The opening size for screens was chosen such that each of the A, B and C sieve fractions would be 20% by weight of the original DDGS (Srinivasan et al., 2005). The D sieve fraction (smallest size) is also denoted as a product called ''Pan'' DDGS.

The A, B and C sieve fractions were air classified using three multi-aspirators (Model VJ8X6, Kice, Wichita, KS). The multi-aspirator comprises a material feeding section, through which the DDGS sieve fraction is fed, and an air-inlet section through which air is sucked into the aspirator by a fan (Fig. 3). The fan for the multi-aspirator that was used to aspirate the large sieve fraction was operated by a 1.1 kW (1.5 hp) motor and the fans in the other two aspirators were operated by 0.6 kW (0.75 hp) motors. A higher rating fan was used for the large sieve fraction because of the higher air velocities needed to separate fiber from large sieve fraction compared to the other fractions. The air carries the lighter particles in the sieve fraction to the cyclone section. The remaining part of

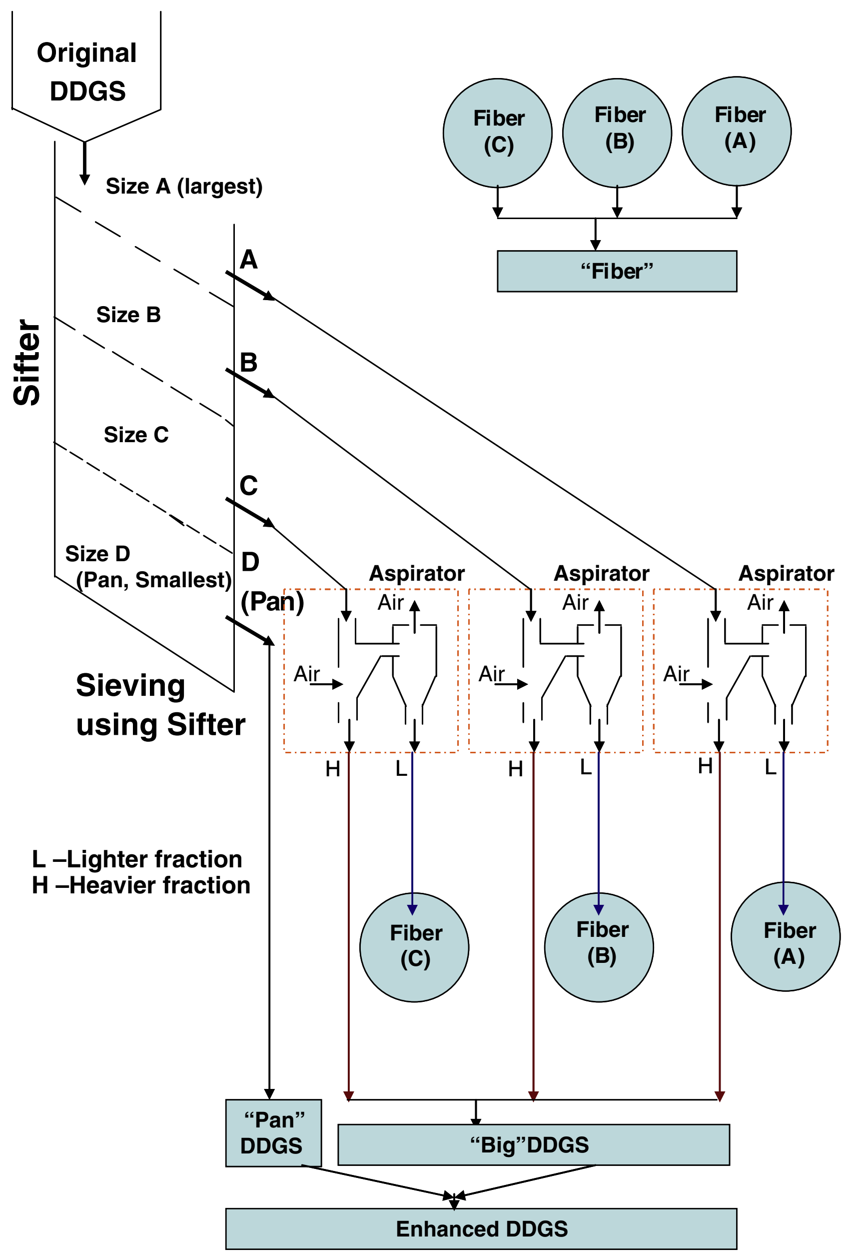

Fig. 1. Schematic of the Elusieve process for fiber separation from DDGS.

Fig. 2. Photograph of pilot plant for the Elusieve process.

the sieve fraction, which are the heavier particles and are not carried by the air, flows straight through the feeding section into a collection drum. The lighter fraction collects at the bottom of the cyclone section and the rotary air-lock valve in the cyclone outlet enables continuous operation by letting the lighter fraction flow into a collection drum. The air from the cyclone flows out through a filter bag, which is used to retain any residual particles. A butterfly type damper is available in the air flow duct to adjust the air flow in the aspirator and thus, control the yield of lighter fraction from the sieve fraction (Fig. 3).

The product obtained by mixing fiber fractions from the three largest sieve fractions, namely the A, B and C fiber fractions, is called the "Fiber" product. The product obtained by mixing the heavier fractions from the three largest sieve fractions, namely the A, B and C heavier fractions, is called "Big" DDGS product because it is the bigger sized portion of the DDGS compared to the other product, Pan DDGS. The product obtained by mixing the Big DDGS and Pan DDGS is called Enhanced DDGS, which is the same as the material referred as Enhanced DDGS in earlier works on the Elusieve process (Srinivasan et al., 2005, 2006, 2008). In this work, we suggest production of three products from the Elusieve process, Pan DDGS, Big DDGS and Fiber, instead of just two products, Enhanced DDGS and Fiber.

2.2. DDGS processing and experimental scheme

Commercial DDGS material was obtained from a local feed mill (Prairie Mills, Prairie, MS). The pilot plant was tested on three different DDGS materials, DDGS-1, DDGS-2 and DDGS-3. The presence of a few wheat kernels along with corn kernels in the DDGS materials suggests that the dry grind plant supplying the DDGS could be processing a mixture of corn and wheat. The moisture contents of DDGS-1, DDGS-2 and DDGS-3 were 12.9%, 11.5% and 12.8%, respectively. The effect of moisture content on fiber separation from DDGS was not studied in this work. DDGS was gravity fed from a hopper to the sifter, through a manual gate valve, at a rate of 0.25 kg/s (1 ton/h).

The quantity of DDGS fed in each processing batch varied depending on the availability of laboratory infrastructure and DDGS material. Within each processing batch, the yields of fractions were fixed. For batch 1 processing of DDGS-1, 312 kg was processed in 25 min at low lighter fraction yields of 6–7% (Table 1). For batch 2 processing of DDGS-1, 53 kg was processed in 5 min at higher lighter fraction yields of 16–29%. DDGS-2 was processed in only one batch; 382 kg was processed in 30 min at lighter fraction yields of 11–15%. For batch 1 processing of DDGS-3, 626 kg was processed in 45 min at lighter fraction yields of 11–15%. For batch 2 processing of DDGS-3, 1096 kg was processed in 75 min at higher lighter fraction yields of 15–25% (Table 1). When referring to the fractions from the processing batches, the terminology used is in the following sequence; DDGS material, batch number, sieve fraction and L or H to refer to the lighter or heavier fractions. For example, 1-1AH refers to DDGS-1, batch 1, A sieve fraction and heavier fraction from the A sieve fraction.

Compositions of fractions were obtained by collecting three samples from each of the collection drums. The samples were ground to a fine powder using a coffee grinder prior to analysis to avoid particle segregation, which has been observed for DDGS by Ileleji et al. (2007). Analyses of samples were carried out at a commercial laboratory (Midwest Labs, Omaha, NE). Neutral detergent fiber (NDF) content was determined using the procedure of Van Soest et al. (1991). Samples were analyzed for total nitrogen (AOAC, 2003, Method 990.03). Crude protein content was calculated as total $N \times 6.25$. Samples were also analyzed for crude fat (AOAC, 2003, Method 920.39) and ash (AOAC, 2003, Method 942.05). Moisture content was determined using the two-stage convection oven method (AACC International, 2000, Method 44-18). The composition of products from Elusieve processing and original DDGS were calculated using the compositions of individual fractions that comprise the products.

2.3. NDF separation factor

NDF separation factor for elutriation is defined as the ratio of the NDF%/non-NDF% of the lighter fraction to the NDF%/non-NDF% of the heavier fraction (Srinivasan et al., 2005). It is calculated as: $[\text{NDF\%}/(100-\text{NDF\%})]_{\text{Lighter fraction}}/[\text{NDF\%}/(100-\text{NDF\%})]_{\text{Heavier fraction}}$. NDF separation factor indicates the selectivity of air in carrying fiber rather than nonfiber. A high NDF separation factor indicates that the selectivity of air in carrying fiber is high.

2.4. Statistical analyses

Analysis of variance (ANOVA) and Tukey's test (SAS Institute, Cary, NC) were used to compare means of compositions of three samples from Elusieve fractions in each processing batch. Within each processing batch, the yields were fixed. There were no replicates for yield of fractions in each processing batch. Statistical significance level was 5% ($p < 0.05$). Coefficients of variation for all compositions were less than 11%.

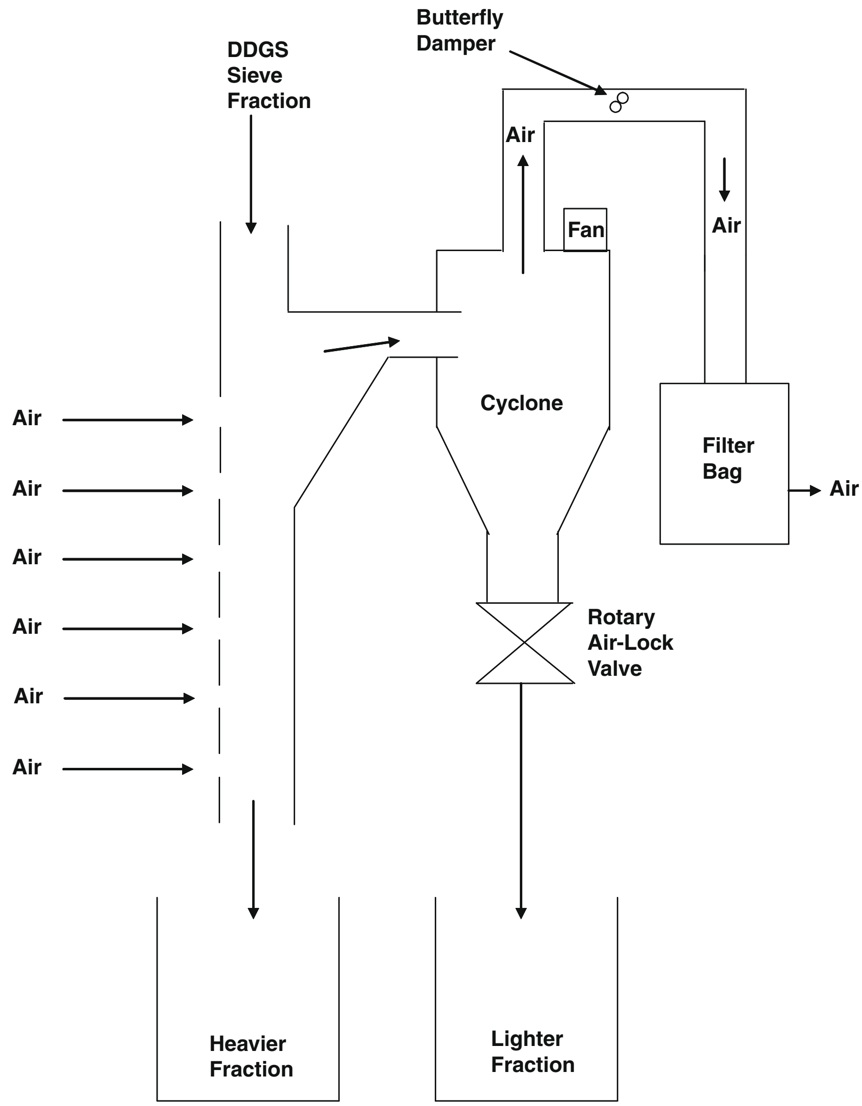

Fig. 3. Schematic of multi-aspirator for air classification of DDGS sieve fractions.

3. Results and discussion

3.1. Elusieve fractions

Lighter fractions from air classification of sieve fractions had higher fiber (NDF) content than corresponding heavier fractions. Heavier fractions had higher protein, fat and ash contents than corresponding lighter fractions (Table 1). NDF separation factors were more than 1.0 indicating fiber separation from sieve fractions. Similar trends were observed in laboratory scale studies also (Srinivasan et al., 2005, 2008). The smallest sieve fraction, D, comprising 32–48% by weight of DDGS, contained lower fiber (NDF) and higher protein contents than the corresponding original DDGS (Table 1). Moisture contents of fractions varied from 11.0% to 13.4%. Coefficients of variation (CV) were less than 11% for sample compositions.

At higher lighter fraction yields from the same sieve fractions, the heavier fractions had higher protein, higher fat, and lower NDF contents than for heavier fractions at lower lighter fraction yields, indicating carry over of higher quantities of fiber from the sieve fractions at higher air velocities (Table 1). Similar trends were observed in laboratory scale studies also (Srinivasan et al., 2005, 2008). For example; for 3-2CH at higher lighter fraction yield of 25.5%, had higher protein content of 37.0%, higher fat content of 8.1%, and lower NDF of 26.0% compared to 3-1CH at lower lighter fraction yield of 15.3%, with protein content of 34.8%, fat content of 7.8% and NDF of 28.9%.

At lower lighter fraction yields from the same sieve fractions, NDF separation factors and NDF of lighter fractions were similar or higher than for higher lighter fraction yields, indicating higher selectivity of air to carry fiber at lower air velocities (Table 1). Similar trends were observed in laboratory scale studies also (Srinivasan et al., 2005, 2008). For example; for 1-1AL at low lighter fraction yield of 7.1%, lighter fraction NDF was 55.1% and separation factor was 3.0, which were higher compared to 1-2AL at higher lighter fraction yield of 15.9%, with lighter fraction NDF of 50.6% and separation factor of 2.5.

At higher lighter fraction yields from the same sieve fractions, protein and fat contents of lighter fractions were similar or higher compared to protein and fat contents of lighter fractions at lower yields, indicating carry over of higher quantity of nonfiber at higher air velocities (Table 1). Similar trends were observed in laboratory scale studies also (Srinivasan et al., 2005, 2008). For example; 1-2CL at higher lighter fraction yield of 22.3%, with protein content of 22.9% and fat content of 7.9%, which were higher compared to 1-1CL at lower lighter fraction yield of 5.6%, with protein content of 17.1% and fat content of 6.0%.

Table 1
Composition (% db) and weights of fractions obtained from pilot scale Elusieve processing of DDGS.

DDGS	Material description	Size (μm)	Weight (kg)		wt% of sieve fraction	Yield (L) (%)	NDF			Protein		Fat		Ash		Moisture (% wb)	
			H	L			H	L	Sep. factor	H	L	H	L	H	L	H	L
DDGS-1 (batch 1, low lighter fraction yields)	1-1A	>1184	48.1	3.7	15.9	7.1	28.7a	55.1b	3.0	28.0a	15.6b	12.4a	5.3b	4.4a	3.9b	11.2a	11.0a
	1-1B	868–1184	64.9	5.1	21.5	7.3	32.0a	52.9b	2.4	28.1a	16.2b	11.4a	5.5b	4.6a	4.0b	11.2a	11.2a
	1-1C	582–868	74.4	4.4	24.2	5.6	30.3a	52.0b	2.5	29.4a	17.1b	10.6a	6.0b	4.6a	4.0b	11.4a	11.4a
	1-1D	<582	124.9		38.4	NA	26.3		NA	33.8		9.2		4.9		12.1	
	DDGS-1	All	312.3		100.0	NA	29.8		NA	30.1		10.3		4.7		11.6	
DDGS-1 (batch 2, high lighter fraction yields)	1-2A	>1184	10.8	2.1	20.4	15.9	28.8a	50.6b	2.5	29.8a	19.2b	12.7a	6.2b	4.5a	3.8b	12.1a	11.9a
	1-2B	868–1184	9.9	4.0	22.1	28.9	29.6a	46.0b	2.0	30.5a	21.8b	11.5a	7.4b	4.4a	4.0b	12.2a	12.1a
	1-2C	582–868	12.5	3.6	25.5	22.3	27.8a	42.5b	1.9	32.2a	22.9b	10.5a	7.9b	4.6a	4.2b	12.3a	12.1a
	1-2D	<582	20.2		32.0	NA	24.0		NA	36.5		9.9		4.8		13.4	
	DDGS-1	All	53.5		100.0	NA	29.8		NA	31.3		10.4		4.5		12.6	
DDGS-2 (batch 1)	2-1A	>1184	42.8	7.7	12.3	15.2	24.1a	42.3b	2.3	27.0a	23.0b	10.6a	5.7b	5.3a	4.1b	12.2a	12.9b
	2-1B	868–1184	59.5	7.3	16.2	10.9	24.7a	48.7b	2.9	28.9a	17.5b	11.0a	5.2b	4.8a	4.1b	12.4a	13.4b
	2-1C	582–868	83.1	14.3	23.7	14.7	27.6a	44.4b	2.1	31.3a	21.3b	8.6a	5.5b	4.8a	4.4b	12.9a	13.1a
	2-1D	<582	196.8		47.8	NA	26.6		NA	35.2		6.8		4.6		12.9	
	DDGS-2	All	382.2		100.0	NA	27.6		NA	31.6		8.1		4.7		12.8	
DDGS-3 (batch 1, low lighter fraction yields)	3-1A	>1041	89.1	12.7	14.9	12.5	27.9a	48.8b	2.5	30.3a	20.6b	10.7a	5.1b	4.3a	3.6b	12.2a	12.4a
	3-1B	680–1041	163.0	19.5	26.7	10.7	29.3a	49.2b	2.3	32.0a	20.0b	9.4a	5.5b	4.2a	3.8b	12.3a	12.5a
	3-1C	470–680	139.3	25.1	24.1	15.3	28.9a	38.6b	1.5	34.8a	28.5b	7.8a	6.1b	4.3a	4.0b	12.4a	12.5a
	3-1D	<470	234.5		34.3	NA	25.5		NA	39.0		6.6		4.7		12.7	
	DDGS-3	All	625.9		100.0	NA	29.0		NA	34.1		7.9		4.4		12.4	
DDGS-3 (batch 2, high lighter fraction yields)	3-2A	>1041	166.4	30.2	15.7	15.4	26.7a	50.6b	2.8	30.5a	16.6b	10.7a	4.8b	4.4a	3.6b	11.9a	12.3b
	3-2B	680–1041	308.6	52.0	28.8	14.4	27.0a	48.5b	2.5	32.3a	19.9b	9.8a	4.9b	4.5a	3.9b	11.9a	12.6b
	3-2C	470–680	211.1	72.2	22.7	25.5	26.0a	37.1b	1.7	37.0a	27.9b	8.1a	6.5b	4.6a	3.9b	12.3a	12.4a
	3-2D	<470	409.7		32.8	NA	26.5		NA	39.6		7.0		4.8		12.6	
	DDGS-3	All	1095.8		100.0	NA	28.7		NA	34.1		8.2		4.5		12.3	

NDF, neutral detergent fiber; H, heavier fraction; L, lighter fraction; NA, not applicable; Sep. factor, separation factor.
Values are reported as means of three samples from each fraction during processing. Values for the same DDGS, same sieve fraction and same composition with the same superscript are not different ($p < 0.05$). Values for original DDGS are calculated from composition of individual fractions. Coefficients of variation (CV) were less than 11%.

The wt% of all DDGS-3 sieve fractions for both processing batches were similar, indicating repeatability of sifter performance (Table 1). The wt% of medium and small fractions for both batches of DDGS-1 were similar, but the wt% of large and pan fractions for the two batches of DDGS-1 were slightly different perhaps because of the low quantity (53.5 kg) of DDGS processed in batch 2 (Table 1).

3.2. Elusieve products

Among the products from the same DDGS, Pan DDGS had the highest protein content and also had the lowest fiber (NDF) content (Table 2). Pan DDGS had slightly lower fat content than the corresponding original DDGS. The difference in protein contents of Pan DDGS and original DDGS was 3.6–5.5%. Difference between protein content of Pan DDGS and original DDGS was higher (4.9–5.5%) for the three cases where the wt% of Pan DDGS was lower (32.0%, 32.8% and 34.3%) compared to the difference in protein contents (3.6–3.7%) for the two cases where the wt% of Pan DDGS was higher (38.4% and 47.8%) (Table 2). The opening of the smallest screen determines the wt% of Pan DDGS and hence, choosing a smaller opening screen for the smallest screen in the sifter would result in Pan DDGS with higher protein contents.

Enhanced DDGS had higher protein and fat contents than corresponding original DDGS and lesser protein and fat contents than corresponding Pan DDGS (Table 2). Difference between protein contents of Enhanced DDGS and original DDGS was higher when wt% of Fiber removed was higher. For example; difference between protein content of Enhanced DDGS and original DDGS was higher (1.6% and 1.7%) for the two cases where the wt% of Fiber was higher (12.4% and 15.3%) compared to the difference in protein contents (0.6–0.9%) for the three cases where the wt% of Fiber was lower (4.1–8.4%) (Table 2).

Big DDGS had slightly lower protein content (difference of −0.4% to −2.1%) compared to corresponding original DDGS, but Big DDGS also had higher fat content (difference of 1.1–1.7%) compared to corresponding original DDGS. Similar to results for Enhanced DDGS, difference between protein contents of Big DDGS and original DDGS was higher when wt% of Fiber removed was higher. For example; difference between protein content of Big DDGS and original DDGS was higher (−0.4% and −0.8%) for the two cases where the wt% of Fiber was higher (12.4% and 15.3%) compared to the difference in protein contents (−1.5% to −2.2%) for the three cases where the wt% of Fiber was lower (4.1–8.4%) (Table 2). Fat contents for Big DDGS were higher when higher wt% of Fiber was removed from the same DDGS. For example; for

Table 2
Composition (% db) and wt% of products obtained by pilot scale Elusieve processing of DDGS.

DDGS	Material description	wt% of original DDGS	Protein	Fat	NDF	Ash	Moisture (% wb)
DDGS-1 (batch 1, low lighter fraction yields)	Original DDGS	100.0	30.1	10.3	29.8	4.7	11.6
	Enhanced DDGS	95.9	30.7	10.5	28.8	4.7	11.6
	Big DDGS	57.6	28.6	11.4	30.5	4.5	11.3
	Pan DDGS	38.4	33.8	9.2	26.3	4.9	12.1
	Fiber	4.1	16.3	5.6	53.2	4.0	11.2
DDGS-1 (batch 2, high lighter fraction yields)	Original DDGS	100.0	31.3	10.4	29.8	4.5	12.6
	Enhanced DDGS	84.7	33.0	10.9	26.9	4.6	12.6
	Big DDGS	52.7	30.9	11.5	28.7	4.5	12.2
	Pan DDGS	32.0	36.5	9.9	24.0	4.8	13.4
	Fiber	15.3	21.6	7.3	45.7	4.0	12.1
DDGS-2 (batch 1)	Original DDGS	100.0	31.6	8.1	27.6	4.7	12.8
	Enhanced DDGS	92.9	32.5	8.3	26.2	4.8	12.8
	Big DDGS	45.1	29.5	9.8	25.9	4.9	12.6
	Pan DDGS	47.8	35.2	6.8	26.6	4.6	12.9
	Fiber	7.1	20.8	5.5	44.9	4.2	13.1
DDGS-3 (batch 1, low lighter fraction yields)	Original DDGS	100.0	34.1	7.9	29.0	4.4	12.4
	Enhanced DDGS	91.6	35.0	8.2	27.6	4.4	12.4
	Big DDGS	57.3	32.6	9.1	28.8	4.3	12.3
	Pan DDGS	34.3	39.0	6.6	25.5	4.7	12.7
	Fiber	8.4	23.9	5.4	44.5	3.8	12.5
DDGS-3 (batch 2, high lighter fraction yields)	Original DDGS	100.0	34.1	8.2	28.7	4.5	12.3
	Enhanced DDGS	87.6	35.7	8.6	26.6	4.6	12.2
	Big DDGS	54.9	33.3	9.5	26.6	4.5	12.0
	Pan DDGS	32.8	39.6	7.0	26.5	4.8	12.6
	Fiber	12.4	23.0	5.6	43.6	3.9	12.5

Values are calculated from compositions of fractions reported in Table 1.

DDGS-3, Big DDGS from batch 2 had higher fat content of 9.5% with high Fiber wt% of 12.4%, compared to lower fat content of 9.1% for Big DDGS from batch 1 with low Fiber wt% of 8.4% (Table 2).

Pan DDGS, Enhanced DDGS and Big DDGS had lower NDF content than their source of original DDGS because of fiber removal (Table 2). For the same DDGS source, Pan DDGS had the lowest NDF, Enhanced DDGS had the next lowest NDF and Big DDGS had the highest NDF. Fiber (NDF) contents for Big DDGS and Enhanced were lower when higher wt% of Fiber was removed from the same DDGS. For example; for DDGS-1, Big DDGS had lower NDF content of 28.7% for batch 2 with high Fiber wt% of 15.3% compared to higher NDF content of 30.5% for Big DDGS from batch 1 with low Fiber wt% of 4.1% (Table 2).

NDF of Fiber from the DDGS varied from 43.6% to 53.2% (Table 2). NDF of pericarp and endosperm fiber from corn wet milling were 79.7% and 27.0%, respectively (Srinivasan, 2006). Thus, Fiber product from the Elusieve process has higher NDF than endosperm fiber from wet milling and lower NDF than pericarp fiber from wet milling. NDF contents for Fiber were higher when lower wt% of Fiber was produced from the same DDGS (Table 2). For example; for DDGS-1, Fiber had NDF content of 53.6% for batch 1 (low Fiber wt% of 4.1%), which was higher compared to NDF content of 45.7% for Fiber from batch 2 (high Fiber wt% of 15.3%) (Table 2).

3.3. Operating experience

It was cumbersome to determine the lighter fraction yields from each sieve fraction by monitoring the weight of the collection drums for the lighter and heavier fractions over a fixed period of time. Installation of solids flow measuring devices to determine and control the yields of fractions would simplify operation and this is envisaged in future operations.

There were a few big chunks of foreign matter in DDGS-3. When DDGS-3 was processed for the first time, these big chunks blocked the feeding section of the multi-aspirator for the A sieve fraction (largest size) and caused an overflow of material out of the multi-aspirator. In subsequent operations, the feeding section of the multi-aspirator for the A sieve fraction was closely monitored and the chunks were removed before any blockage could occur. For industrial scale operation, the feeding section of the multi-aspirator for the A sieve fraction would need to be designed such that even large chunks would flow through.

To maintain the lighter fraction yield at the desired level, the butterfly damper in the air duct of the multi-aspirator that was used to aspirate the C sieve fraction had to be further opened during operation, while processing large quantity of DDGS (1096 kg for DDGS-3 batch 2). This occurred perhaps because of increased resistance to air flow from the filter bag due to accumulation of fine particles in the filter bag. This phenomenon was not observed in the other two multi-aspirators perhaps because of fewer fine particles in the A and B sieve fractions.

3.4. Implementation scenario for the Elusieve process and economics

In the previous works on Elusieve process, it was suggested that two products would be produced: (1) Enhanced DDGS that had 2–3% higher protein content on wet basis than conventional DDGS and (2) Fiber product. As protein content plays a significant role in market value of feeds, we expect that the best implementation scenario for the Elusieve process would be to produce three products: (1) a product (Pan DDGS) that would have 5% higher protein content than the conventional DDGS on wet basis, (2) a product (Big DDGS) that would have nearly same protein content as conventional DDGS, and (3) Fiber product.

In the present market scenario, Elusieve products with higher protein contents are more valuable than products with higher fiber contents because conversion of fiber product into high-value products (cellulosic ethanol, corn fiber gum, polymer composites, etc.) has not reached industrial scale yet. The implementation scenario with highest revenue potential is represented by DDGS-3 batch 2, where Pan DDGS has 4.8% higher protein content than original DDGS and Big DDGS has 0.7% lower protein content, but has higher fat and lower fiber contents, than original DDGS. The other opera-

Table 3
Composition (% wb), wt% and price of products that represents the potential implementation scenario for the Elusieve process; obtained by pilot scale processing of DDGS-3 batch 2.

Product	wt%	Protein	Fat	NDF	Ash	Moisture	Price ($/ton)
Original DDGS	100.0	30.4	7.3	25.6	4.0	12.3	160
Enhanced DDGS	87.6	31.8	7.7	23.7	4.1	12.2	170
Big DDGS	54.9	29.7	8.5	23.8	4.0	12.0	160
Pan DDGS	32.8	35.2	6.2	23.5	4.3	12.6	195
Fiber	12.4	20.4	5.0	38.8	3.5	12.5	114

tions, which result in products with higher fiber contents than higher protein contents, would be more beneficial when fiber value is high. The other operations are not considered the highest revenue scenarios due to the following reasons: (1) DDGS-1 batch 1: Pan DDGS does not have high protein content because the wt% of Pan DDGS is high (38.4%), (2) DDGS-1 batch 2: quantity of DDGS processed (53.5 kg) is low and hence, results may not be statistically suitable, (3) DDGS-2: Pan DDGS does not have high protein content because the wt% of Pan DDGS is high (47.8%), and (4) DDGS-1 batch 1: Big DDGS has low protein content, 1.5% lower than original DDGS, because of low wt% of Fiber removal due to low lighter fraction yields.

Price of Pan DDGS was determined using same method as Srinivasan et al. (2006), which was based on correlation between feed prices and their protein contents. Estimates of prices determined using this method is conservative because of not accounting for opening up of new markets for DDGS. For current prices of feeds obtained from ERS (2008), the increase in price of feed per percent increase in protein content was $7.20. Price of conventional DDGS at current prices was $160/ton and for the increase of 4.8% in protein content, the price of Pan DDGS was $195/ton (Table 3). Big DDGS was valued at the same price of $160/ton as conventional DDGS because Big DDGS has protein content close to conventional DDGS and has higher fat and lower fiber contents. Fiber product has 20.4% protein which is close to protein content of corn gluten feed (21% protein) and hence, Fiber product is valued at the same price of $114/ton as corn gluten feed. The increase in revenue, for a dry grind plant processing corn at 2030 metric tonnes/day (80,000 bu/day), due to Elusieve products would be $1.4 million. Operating costs would be $100,000/yr based on energy consumption of 56 kW (75 hp) and labor requirement of 2 man h/day (Srinivasan et al., 2006). There are no additional drying costs involved for implementation of the Elusieve process for DDGS. Capital investment would be $1.4 million based on $0.43 million as purchase cost of sifters and aspirators for the 2030 metric tonnes/day (80,000 bu/day) plant (Srinivasan et al., 2006).

Payback period (in years) was calculated as total capital investment divided by profit per year (Peters and Timmerhaus, 1980). In calculating payback period, interest and depreciation effects were not accounted for. Net present value (NPV) was calculated by adding together the present values obtained from discounting the projected cash flows at an interest rate of 8% during the lifetime of the plant. The lifetime of the plant was assumed to be 15 yr. Internal rate of return (IRR) is the interest rate at which the NPV of the projected cash flows becomes zero. For a 2030 metric tonnes/day (80,000 bu/day) plant, based on revenue of $1.4 million, operating cost of $100,000/yr and capital investment of $1.4 million, the payback period for the Elusieve process would be 1.1 yr, IRR would be 91% and NPV would be $9.5 million. Financial returns decrease as plant capacity decreases. For a 1520 metric tonnes/day (60,000 bu/day) plant, based on revenue of $1.0 million, operating cost of $75,000/yr and capital investment of $1.2 million, the payback period for the Elusieve process would be 1.2 yr, IRR would be 81% and NPV would be $7.0 million. For a 1020 metric tonnes/day (40,000 bu/day) plant, based on revenue of $0.7 million, operating cost of $50,000/yr and capital investment of $0.9 million, the payback period for the Elusieve process would be 1.4 yr, IRR would be 69% and NPV would be $4.5 million.

4. Conclusions

A pilot plant for the Elusieve process to separate fiber from DDGS was assembled and operated in continuous mode with DDGS processing rate of 0.25 kg/s (1 ton/h). Experiments were conducted on three different commercial DDGS materials. Elusieve process was effective in separating fiber from DDGS in pilot scale in continuous mode. Trends in compositions of fractions were similar to those observed in laboratory scale studies. Valuable operating experience was gained from pilot scale processing.

In the pilot scale operation that best represented the potential implementation scenario, 12.4% by weight of DDGS was separated as Fiber and resulted in two high protein products: (1) a product (Pan DDGS; 32.8% by weight) that had 4.8% higher protein content and lower fiber content than conventional DDGS, on wet basis and (2) a product (Big DDGS; 54.9% by weight) that had nearly same protein content (difference of −0.7%) as conventional DDGS, and had lower fiber (NDF) contents than conventional DDGS. Implementation of the Elusieve process in a dry grind plant processing corn at 2030 metric tonnes/day (80,000 bu/day) would increase revenue by $1.4 million based on conservative estimates, operating cost would be $100,000/yr, capital investment required would be $1.4 million and the payback period would be 1.1 yr. In the context of the need for opening up of new markets and producing valuable products from DDGS, the Elusieve process offers a simple and non-intrusive method to add value to fuel ethanol production. The pilot plant assembled for the Elusieve process was useful in gaining operating experience and data needed for plant scale implementation.

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