EVALUATION OF A PROCESS TO SEPARATE ENSILED CORN GRAIN AND STOVER FOR IMPROVED UTILIZATION AS A BIOMASS FEEDSTOCK

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HIGHLIGHTS

- An experimental machine that combined air classification and mechanical screening was investigated to separate corn grain and stover.
- Important variables included stover:grain ratio, air velocity, and throughput.
- As much as 99.4% of the grain could be separated from the stover with less than 1% foreign matter in the grain.

ABSTRACT. *Corn grain and chopped stover were stored anaerobically at 37% to 50% (w.b.) aggregate moisture content to create a unique biomass feedstock. However, after storage, the two fractions must be separated to accommodate different conversion pathways. In this work, a modified cleaning system from a grain combine harvester was evaluated to investigate its effectiveness in separating the grain from the stover. While this system has been purposefully built for this task, there is no previous literature on separating grain at high material other than grain (MOG) to grain ratios. Using this system, material was separated into four fractions: Grain, Tailings, Heavy MOG, and Light MOG. Subsamples were collected, oven dried, and then hydrodynamically separated to quantify the grain content in the four fractions. Several different configurations of air velocities, mass flow rate, material MOG: grain ratios, and sieve types and openings were investigated. Grain capture was defined as the fraction of the total grain dry mass collected in the grain and tailings fractions. In five experiments, the grain capture effectiveness varied from 89.2% to 99.4% on a dry basis. The dry basis foreign matter (FM) in the clean grain was 0.6% to 10.8%. The use of a modified combine cleaning system has the potential to be one step in a system to fractionate corn grain from stover (i.e., MOG) in a biorefinery that uses both starch and cellulose as biomass feedstocks.*

Keywords. *Air classification, Anatomical fractionation, Cleaning shoe, Corn stover, Mechanical sieving.*

Corn stover offers the largest potential supply of agriculturally based renewable biomaterial in the United States (Langholtz et al., 2016). However, the traditional collection of corn stover using a three-pass, bale-based system is labor-intensive, time-consuming, highly weather-dependent, and too costly (Vadas and Digman, 2013). To overcome these challenges, Cook et al. (2014) investigated using a single-pass system where corn grain and stover were co-harvested with a forage harvester and then anaerobically co-stored. This process varies from traditional whole-plant corn harvested for ruminant animal feed in that harvesting occurs well after plant senescence, when grain yields and whole-plant dry matter (DM) are greater (Shinners and Binversie, 2007). Despite the high DM content, both stover and grain can be well conserved by fermentation, provided anerobic conditions are maintained (Cook et al., 2014; Pike et al., 2023). This biomass feedstock system was shown to be nearly 50% less expensive than a traditional three-pass, bale-based system because it reduced the costs of harvest, transportation, and stover processing (Vadas and Digman, 2013; Hemmelgarn et al., 2023). In the final step of this novel system, the grain and stover would be separated at the biorefinery to accommodate the different conversion pathways for starch and cellulose.

This harvest and storage system was shown to be successful over a wide variety of moisture contents for the aggregate harvested material. Cook et al. (2014) co-harvested and co-stored corn grain and stover from late September to early December, with aggregate moisture content ranging from 65% (w.b.) to 16% (w.b.), respectively. Pike et al. (2023) reported successful co-harvest and co-storage when grain moisture ranged from 29% to 18% (w.b.). These results show that harvest can start earlier than typical grain harvest, and stover harvest can occur in weather conditions that would have prevented dry stover baling.

In a comprehensive investigation of this harvest system, the grain and stover were harvested with a forage harvester that size-reduced the stover fraction to a geometric mean particle size (GMPS) of 25 mm (Pike et al., 2023). Mechanical processes within the harvester shelled the grain from the cob but also resulted in reduced kernel integrity. Between

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13% and 17% of the kernels were split or broken, and the GMPS of these kernels was approximately half of the intact kernels (Pike et al., 2023). These aspects of the system could potentially affect the downstream utilization of grain after separation from the stover.

In addition to grain particle size reduction, the system produces a biomass feedstock with a high material-other-than-grain (MOG) to grain mass ratio, potentially further complicating fractionation. Pike et al. (2023) reported a MOG:grain ratio that varied from 0.38:1 to 0.90:1 as the harvest system was altered to vary the yield, moisture content, and composition of the stover fraction. This is another variable that should be investigated when considering downstream fractionation processes.

The co-storage of grain and stover also changes the chemical properties of the biomass, namely the moisture content, which could affect fractionation. At harvest, the average grain and stover moisture contents were 23% and 48% (w.b.), respectively, and were 34% and 45% (w.b.) at removal from anerobic storage. The fermented corn kernels had larger dimensions, smaller particle and bulk density, and greater friction coefficients than typical dry kernels (Blazer et al., 2023).

The state of technology for separating corn grain and stover is the threshing and cleaning systems employed by the combine harvester (ASABE/ISO Standard 6689, 2022). However, threshing was unnecessary for this feedstock because the grain had already been removed from the cob during harvest (Pike et al., 2023). As such, the research presented here focused on the combine harvester cleaning system. Combine harvester cleaning systems use a combination of mechanical screening and air separation to complete grain separation from MOG. Cleaning systems typically consist of two sieves, one mounted above the other, and a fan delivering air through the sieves (Mui, 2015). Separation of grain from MOG is accomplished by exploiting differences in the physical properties and terminal velocities of the grain and stover fractions.

As the mixture of grain and MOG is deposited on the sieves, the air stream loosens the mat of grain and MOG, allowing grain passage through the matrix of MOG. The air stream also carries away light chaff. Once the grain has passed through the MOG mat, it is screened by the oscillating sieves. The challenge with achieving the desired level of grain cleanliness is that the delivered material composition is not constant. Composition changes depending on the feed rate, MOG content, and moisture content of both the grain and MOG. To adapt to these changes, air velocity, volume, sieve opening size, and oscillation frequency are used to accomplish the desired grain cleanliness.

Johnson (2010) described a system attached to the rear of a combine harvester to separate cobs from other MOGs. Cobs were separated pneumatically from the husks, leaves, and stalks by differences in density and mass. In this work, the moisture content of the cob and other MOG was less than 20% (w.b.), substantially drier than the moisture of the stover in the harvest scenario used to create the material for this research (Pike et al., 2023)

In this research, utilizing a combine harvester cleaning system to separate grain from MOG presents a significant challenge due to the considerably higher MOG content compared to traditional corn grain harvests (fig. 1). During conventional corn harvesting, combine harvesters are typically configured to minimize the entry of MOG into the equipment. The ear snapper header is designed to deliver primarily ears to the feeder house, although some leaf and upper stalk material is inevitably collected. The threshing and separation systems in a typical corn harvesting operation expels most of the Heavy MOG from the rear of the harvester, resulting in only grain, Light MOG, and chaff being conveyed to the cleaning system. Unfortunately, no published literature addressing the MOG distribution over the cleaning system in a combine harvester specifically used for corn harvest has been identified.

This work hypothesizes that, if correctly configured, the cleaning system of a combine harvester can be used to effectively separate grain from MOG, despite the greater than typical MOG to grain ratio. This research will specifically investigate the effectiveness of variable air flow and mechanical sieve settings in the separation effectiveness of grain from MOG at high MOG feed rates. The objectives of this research were to: (a) modify a combine cleaning system to operate independently of the combine harvester, (b) determine the important variables that affect separation effectiveness, and (c) quantify grain separation effectiveness and cleanliness. The goal was to separate at least 95% of the incoming grain from the MOG and achieve no more than 5% foreign matter (FM) in the separated grain. In this work, we defined FM as all non-grain matter in the separated grain.

MATERIALS AND METHODS

This research aimed to determine the optimal parameters for separating and cleaning grain from chopped and ensiled whole-plant corn biomass. To accomplish this goal, a cleaning shoe was removed from a combine harvester (test fixture) and made to run independently. Next, a series of experiments were employed to optimize operating parameters and the physical form of the system. Finally, the performance was quantified in terms of grain capture and purity.

TEST FIXTURE

The test fixture used the grain cleaning system from a John Deere (Moline, IL) 60-series combine harvester. The system allowed air separation and mechanical screening

Figure 1. Typical example of MOG and grain mix that was delivered to cleaning system.

techniques to be tested synchronously. The test fixture was driven by the power-take-off (PTO) of a John Deere model 7R230 tractor.

The functional components of the test fixture are shown schematically in figure 2. The (a) distribution augers metered material onto an (c) oscillating stepped pan, which distributed material to the (d) pre-screener sieve. Airflow from the (b) fan was directed to the pre-screener sieve to begin stratification of the MOG from the grain. Light MOG suspended at the pre-screener would exit the back of the fixture. Grain and remaining MOG that passed through the pre-screener were directed to another (e) stepped pan which distributed material to the front of the (f) top sieve. Material passing over the pre-screener was delivered directly to the top sieve. Material on the top sieve either fell through the openings to the (g) bottom sieve or was conveyed towards the back of the machine. Material passing through the bottom sieve was directed to the (h) grain collection auger, and material passing over this sieve was directed to the (i) tailings collection auger.

The functional elements of the cleaning system had the following dimensions and operational speeds: The outside and inside diameters of the (a) infeed augers were 150 and 25 mm, respectively, the pitch lengths were 150 mm, and they operated at 430 rpm. The width of the (f, g) sieves' working area was approximately 1.25 m. The (c) pre-screener sieve had fixed openings with a 30 mm clearance and an approximate sieve area of 0.5 m2. Sieve clearance was variable on the (f) top and (g) bottom sieves. The approximate working area of the top and bottom sieves was 1.63 and 2.00 m^2, respectively. The top sieve's working area was normally 2.31 m2, but the last 550 mm of the sieve was closed to force more air volume through this sieve.

MATERIAL CLASSIFICATION

The combined MOG and grain delivered to the test fixture was defined as Pre-Separated material. Separated Grain was classified as whole, chipped, or broken corn kernels and foreign matter (FM) collected from the grain collection auger. Tailings were collected from the tailings collection auger and consisted primarily of FM with some grain. In a grain combine harvester, Tailings are typically sent back for reprocessing by the threshing and cleaning systems (Mui, 2015), but in this case, Tailings were collected separately to quantify and characterize this material. Heavy MOG fell off the back of the top sieve and was primarily stalk, cob, and husks. Light MOG (primarily leaves and unidentifiable fines) was suspended by the fan air stream and blown from the pre-screener or top sieve, landing in the Light MOG bins (fig. 2).

TEST PROCEDURE AND MATERIAL COLLECTION

All Pre-Separated material was harvested using a John Deere model 6950 self-propelled forage harvester (Pike et al., 2023). Harvester header height and crop yield impacted the harvested MOG:G ratio and moisture content. Pre-Separated material was conserved by anaerobic storage, either in wrapped bales or a silo bag. Storage duration ranged from 305 to 641 days. The composition of the material at the exposed face of the silo bag dictated the MOG:G ratio used, so this parameter could not be controlled during our experiments. The composition of the material in the wrapped bales was more consistent, so using this material gave some ability to target a MOG:G ratio.

Pre-Separated material was weighed to the nearest 0.1 kg and then spread evenly by hand over an 8 m long belt-type conveyor (fig. 3). The mass placed on the conveyor was determined by the desired target throughput and the duration of a typical experimental replicate (approximately seven seconds). The tractor PTO and the conveyor drive were engaged after the test fixture reached equilibrium speed. To quantify separation performance, the material was collected from five locations (fig. 2): (1) Pre-Separated material; (2) Separated Grain bin; (3) Tailings bin; (4) Heavy MOG bins; and (5) Light MOG bins (fig. 3).

Before each test, three random Pre-Separated samples of approximately 7 L each were collected across the full width and depth of the input conveyor (fig. 3, #1). After each test, the net mass of material in the Separated Grain (fig. 3, #2) and Tailings bins (fig. 3, #3) was determined to the nearest 0.01 kg. Next, the bins were homogenized by hand mixing and three subsamples of approximately 1 L each were collected. The total net mass of the contents of both the Heavy MOG and Light MOG bins was determined to the nearest 0.01 kg. Here, two subsamples of approximately 7 L and 4 L were collected from the Heavy and Light MOG bins, respectively.

To quantify the mass of grain remaining in the Heavy MOG, this material was further processed to separate the grain and fines from the large pieces of MOG by hand-feeding the material into a trommel screen which had a 900 mm diameter, 1,750 mm length, and 12.7 mm square openings operated at a rotational speed of 30 rpm and an angle of 14 degrees. The trommel ejected grain and fines radially,

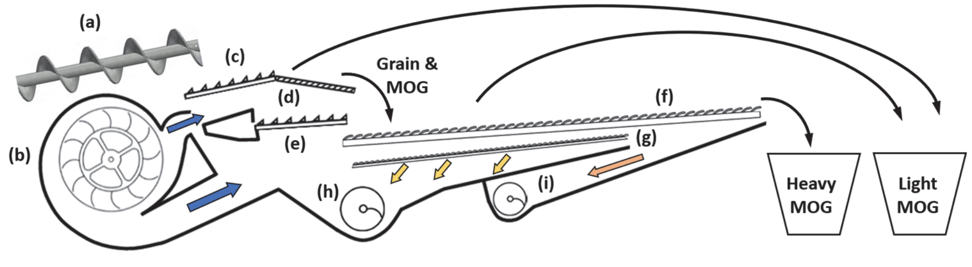

Figure 2. Schematic of the separation test fixture: (a) four-auger distribution bed; (b) fan; (c and d) oscillating pre-screener distribution pan and sieve; (e) oscillating top sieve distribution pan; (f and g) oscillating top and bottom sieves; (h) grain collection auger; and (i) tailing collection auger. Material blown from pre-screener or top sieve collected in Light MOG bins. Material falling off the back of the top sieve collected in Heavy MOG bins.

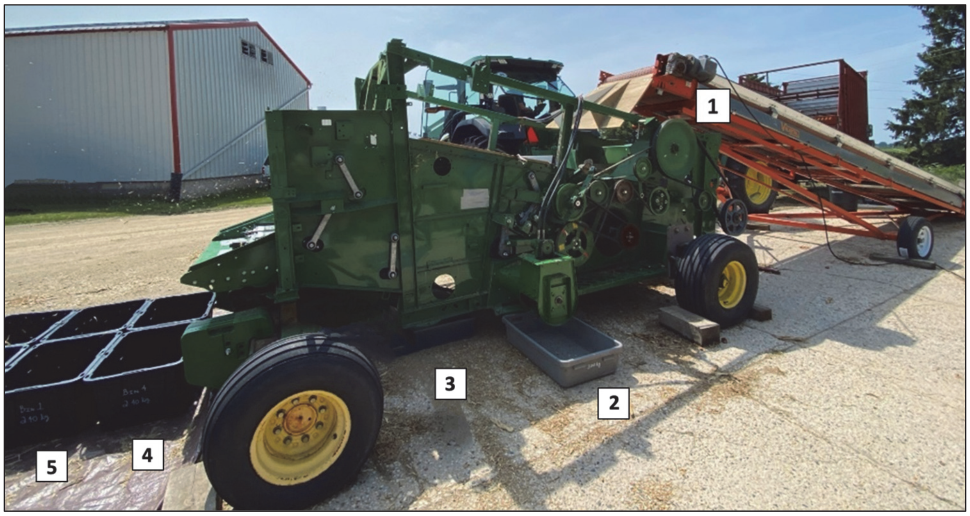

Figure 3. View of test fixture showing locations where samples were collected from (1) Pre-Separated, (2) Separated Grain, (3) Tailings, (4) Heavy MOG, and (5) Light MOG.

while the large pieces of MOG were ejected longitudinally from the downstream side. After screening, the fines and grain were collected and homogenized, and then three 1 L samples were collected. All samples from all locations were oven dried at 55°C for 72 hours to determine dry mass and moisture content following procedures in ASABE Standard S358.2 (ASABE Standards, 2021).

Post Processing

Pre-Separated, Separated Grain, Tailings, and Heavy MOG fractions were separated into MOG and grain fractions using a water separation described by Savoie et al. (2004). After being removed from the oven, the samples were weighed and placed in a 12 L container filled with tap water. Facilitated by hand agitation, the buoyant MOG floated to the top while the dense grain sank. Next, the MOG was removed by hand, the water was drained, and the grain was collected. Any MOG remaining with the grain was removed by hand separation. The grain was then oven-dried at 103°C for 24 hours, and the dry mass was determined. The dry mass fraction of the MOG in each sample was then determined by the difference between the original dry mass and the dry mass of the grain. The dry mass of these two fractions was then used to quantify the performance of the separation process.

Performance Metrics

The dry basis MOG to Grain ratio (MOG:G) of the incoming Pre-Separated material was calculated from:

$$MOG : G = \frac{MOG_{PS}}{G_{PS}} \tag{1}$$

where MOG_{PS} and G_{PS} are the dry mass of the MOG and Grain, respectively, from Pre-Separated material samples collected from the belt conveyor. The total grain mass (G_{TOT}) processed during a replicate test was determined from:

$$G_{TOT} = G_{SG} + G_T + G_{HMOG} \tag{2}$$

where

G_{SG} = the dry mass of grain collected from the Separated Grain bin
G_T = grain collected from the Tailings bin
G_{HMOG} = grain collected from the Heavy MOG bins.

No grain was observed in the Light MOG material in any experiment. The total MOG mass (MOG_{TOT}) processed was determined from:

$$\begin{aligned} &MOG_{TOT} = \\ &MOG_{SG} + MOG_T + MOG_{HMOG} + MOG_{LMOG} \end{aligned} \tag{3}$$

where

MOG_{SG} = dry mass of MOG collected from the Separated Grain bin
MOG_T = MOG collected from the Tailings bin
MOG_{HMOG} = MOG collected from the Heavy MOG bins
MOG_{LMOG} = MOG collected from the Light MOG bins.

The Foreign Matter (FM) in the Separated Grain, expressed as a percent, was determined by:

$$FM = \left[1 - \left(\frac{G_{SG}}{\left(G_{SG} + MOG_{SG}\right)}\right)\right] \cdot 100 \tag{4}$$

The fraction of the total grain (G_{TOT}), which was located in the Separated Grain bin (GF_{SG}), Tailings (GF_T) bin, and Heavy MOG (GF_{HMOG}) bins, expressed as a percent, was determined by:

$$GF_{SG} = \left(\frac{GS_{CG}}{G_{TOT}}\right) \cdot 100 \tag{5}$$

$$GF_{TA} = \left(\frac{G_T}{G_{TOT}}\right) \cdot 100 \tag{6}$$

$$GF_{HMOG} = \left(\frac{G_{HMOG}}{G_{TOT}}\right) \cdot 100 \tag{7}$$

The sum of GF_{SG} and GF_T was considered grain collected during the separation process. The GF_{HMOG} was considered uncollected and would have to be separated in another downstream process or lost to the cellulosic fraction.

EXPERIMENTS CONDUCTED

The variables investigated in this study were cleaning fan speed, material throughput, sieve drive speed, sieve type, and sieve opening size (sieve description discussed below). Five experiments were conducted where two variables were explored during each experiment except Experiment 3, where only the MOG:G ratio (dry basis) was varied (tables 1 and 2).

Experiments 1 and 2 were conducted to investigate the effect of cleaning fan speed and throughput on separation effectiveness. Fan speeds of 800 and 1000 rpm were used, and target throughputs were 32 and 41 Mg $WM \cdot h^{-1}$ (Exp. 1) and 25 and 32 Mg $WM \cdot h^{-1}$ (Exp. 2). Experiment 3 was conducted to explore how material with different MOG:G ratios impacted separation effectiveness. MOG:G ratios of 0.80:1, 0.90:1, 0.99:1, and 1.05:1 were used. Experiment 4 was a factorial experiment where two types of top sieves (General Purpose and Flat Top) and two different sieve drive speeds (280 and 330 rpm) were investigated. Experiment 5 was also a factorial experiment conducted to explore two types of top sieves (Long Finger and Flat Top) and sieve openings (small and large – see table 2) for each type of top sieve. In all experiments, each variable was replicated three times, and the replicated tests were conducted in random order.

Table 1. Material storage duration, MOG:G ratios, and aggregate moisture content for the five experiments conducted.

Experiment No.	Material Storage Duration[a]	MOG:G Dry Basis Ratio[b]	Moisture Content (% w.b.)	Storage Method
1	298	0.85 : 1	45.7	Silo bag
2[c]	307, 640	1.14 : 1	37.3	Silo bag, Wrapped bale
3[d]	305	0.80 : 1	39.7	Silo bag
3[d]	638	0.90 : 1	28.0	Wrapped bale
3[d]	640	0.99 : 1	30.1	Wrapped bale
3[d]	641	1.05 : 1	31.9	Wrapped bale
4	349	1.10 : 1	49.6	Silo bag
5	357	0.70 : 1	44.3	Silo bag

[a] Duration material was anaerobically stored before separation experiments occurred.

[b] Dry basis mass ratio of material-other-than-grain (MOG) to grain.

[c] Material used in experiment 2 was a blend of two materials from different storage methods.

[d] Material from several harvests were used in experiment 3 to achieve different MOG:G ratios.

General Purpose top sieves were used in Experiments 1 – 4 (table 2, fig. 4). Two different top sieves were used in Experiment 4 (General Purpose and Flat Top) and Experiment 5 (Flat Top and Long Finger). The Flat Top and Long Finger sieves had different louver shapes that were intended to reduce the tendency for long, slender MOG from sliding between the louvers and dropping onto the bottom sieve (fig. 4). With the General Purpose and Long Finger louvers, the material could fall to the bottom sieve either between adjacent fingers of the louvers or between the adjacent rows of louvers (fig. 5). The material could only fall to the bottom sieve between the adjacent rows of louvers with the Flat Top sieve. Clearance between the adjacent rows of louvers was determined using a tapered wedge scale illustrated in figure 5.

STATISTICAL ANALYSIS

Factorial analysis using the Standard Least Squares option in the Fit Model platform of JMP Pro (ver. 15, SAS Institute Inc., Cary, NC, USA) was used to conduct the statistical analysis using full-factorial analysis. All least square means were compared using Tukey's test. In the full factorial analysis for all five experiments, the interaction effects were found to have $p > 0.25$, so the results were also reported

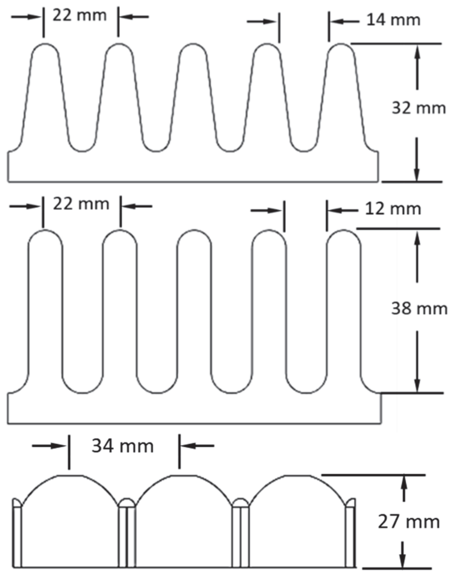

Figure 4. Schematic of top sieve louvers used – General Purpose (top); Long Finger (middle); Flat Top (bottom). Not to scale.

Table 2. Variables considered in the five experiments conducted.

Experiment No.	Fan Speed[a] (rpm)	Target Throughput (Mg WM/h)	Sieve[b] Frequency (cycles/min)	Top Sieve	
				Type[c]	Opening[d] (mm)
1	800, 1000	32, 41	300	General Purpose	10
2	800, 1000	23, 32	300	General Purpose	10
3[e]	800	32	300	General Purpose	10
4	900	36	280, 330	Flat Tooth	12
4	900	36	280, 330	General Purpose	10
5	1000	36	300	Flat Tooth	16, 21
5	1200	36	300	Long Finger	10, 15

[a] Air velocity at rear of top sieve when no material was present was 5.5, 6.0, 6.5, and 7.5 m/s at fan speeds of 800, 900, 1000, and 1200 rpm.

[b] Frequency of pre-screener, top and bottom sieves.

[c] See figure 4.

[d] Bottom sieve opening was 12 mm for all experiments.

[e] Four MOG:G ratios were used while all other variables remained constant.

Figure 5. Measuring sieve clearance between adjacent rows of sieve louvers using a tapered wedge scale.

based on single-factor analysis. Significant differences were declared at $p \leq 0.05$, and tendencies were considered at $0.05 < p \leq 0.10$.

RESULTS AND DISCUSSION

Craessaerts et al. (2007) investigated combine cleaning system effectiveness when processing corn. They reported that the factors that had the greatest influence on machine performance were air velocity (fan speed), sieve openings, and material throughput. However, their work used grain without MOG, while in this research, the MOG mass was almost equal to or greater than that of the grain mass, so additional variables were considered that might impact grain separation at high MOG:G ratios.

MATERIAL COMPOSITION

Separated Grain was largely whole and broken kernels in addition to some FM. Initial investigation had shown that intact, chipped, and broken kernels could be fractionated together at the same air speed (Blazer, 2022), and that was the case in this research. The FM was primarily broken pieces of cob or flat sections of stalk rind and pith that had slipped between the fingers of the sieves (fig. 6). Tailings were mainly broken kernels and FM. The FM in the Tailings consisted of broken cob, stalk rind, and unidentifiable fines. The Heavy MOG was largely stalks, husks, and cobs, and the Light MOG was primarily leaves and unidentifiable fines (fig. 7).

Figure 7. Heavy MOG (top bins), which was mainly stalks, cobs, and husks; and Light MOG (bottom bins), which was primarily leaves and unidentifiable fines.

MATERIAL MOISTURE CONTENT

The average moisture content of the Pre-Separated, Separated Grain, Tailings, Heavy MOG, and Light MOG was determined (table 3). Moisture content varied significantly between these materials, with the Separated Grain and the Heavy MOG having the least and greatest moisture content, respectively. These results indicate that despite being anaerobically co-stored for many months, there was migration, but no equalization, of moisture between fractions. Differences in moisture may affect the separation properties of each fraction. Shinners and Binversie (2007) reported that when grain moisture content was 20% to 30%, (w.b.) leaves were less than 20%, husks were 27% to 43%; cobs were 40% to 50%, top stalks were less than 20%, mid stalks were 45% to 60%, and bottom stalks were 65% to 75% moisture content (w.b.). The material in the Heavy MOG fraction consisted mostly of stalk and cob, so this material had the greatest moisture. The Light MOG consistently had lower moisture content than the Heavy MOG because the former material had more dry leaves. For most experiments, the Tailings had greater moisture content than the Separated Grain because the former material contained greater FM than the latter.

FAN SPEED AND THROUGHPUT

The two independent variables investigated in Experiment 1 were fan speed and material throughput (table 4).

Figure 6. Typical material located in the Separated Grain. From left to right, cob pieces, stalk rind and pith, whole grain, and broken grain. All material to the same scale. The two left hand materials were typical examples of Foreign Matter (FM) found in the Separated Grain.

Table 3. Average moisture content of material collected at five locations for all five experiments.

Material Collection Location[a]	Moisture Content (% w.b.)				
	Experiment Number[b]				
	1	2	3	4	5
Pre-Separated	45.7bc	37.3b	34.5b	49.6c	44.3b
Separated Grain	34.6d	28.1d	27.9c	36.6d	32.7c
Tailings	43.2bc	32.1c	33.2bc	48.6c	44.0b
Heavy MOG	52.7a	41.9a	45.9a	55.8a	53.4a
Light MOG	47.4b	32.6c	35.2b	53.3b	46.0b
SEM[c]	0.73	0.62	1.44	0.61	0.82
p-value[c]	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
LSD (p = 0.05)[c]	2.9	2.5	5.8	2.5	3.3

[a] Location where material was collected – see figure 3.

[b] See table 1 for input material details. See table 2 for experimental conditions.

[c] Standard error of the mean (SEM) n = 12. Within each column, lower case markers indicate significant differences at $p < 0.05$ using Tukey's comparisons. Least square difference (LSD) for $p = 0.05$.

Variation in fan speed between 800 and 1000 rpm did not result in significant changes in foreign matter (FM) in the Separated Grain, nor in which fraction the grain was located. Throughput, however, was a significant variable. At lower throughputs, significantly more grain was located in the Separated Grain with an increase from 88.4% to 93.5%, and more grain was captured overall, from 92.4% to 95.8%, corresponding to a decrease in mass flow rate from 18.8 to 14.3 Mg DM·h^{-1}. Additionally, this decrease in mass flow rate resulted in 45% less grain being located in the Heavy MOG. At the lower throughput, the goal of separating at least 95% of the grain was achieved, but the average FM in the grain was 6.1%, which was slightly more than the goal of less than 5%.

In a second experiment (Experiment 2), the same fan speeds were investigated but at lower target throughputs (table 5). Here, the MOG:G ratio was greater (1.14:1) than for the previous experiment (0.85:1). There was more FM in the Separated Grain in Experiment 2 than in Experiment 1 (13.9% vs. 6.1%), which might be attributed to the differences in MOG:G ratio. The 13.9% FM in the Separated Grain exceeded the 5% goal. Fan speed variation between 800 and 1000 rpm had a significant impact on the amount of collected grain and where it was located. Overall, the 800 rpm treatment resulted in a 6.5 percentage point increase in collected grain, with a similar decrease in grain remaining in the Heavy MOG. There was no significant difference in FM in the Separated Grain between fan speeds. More grain was separated from the MOG, and less grain remained in the MOG at the lower throughput. In Experiment 1, where throughput was greater, fan speed did not result in significant results, while throughput did.

MOG:G RATIO

In a third experiment (Experiment 3), the impact of the MOG:G ratio of the Pre-Separated material on FM and grain recovery was explored (table 6). A greater MOG:G ratio was achieved by using material that had been harvested at lower header heights, which resulted in more MOG harvested (Pike et al., 2023). Although achieving similar dry basis throughput for all treatments was desired, the throughputs were greater for the higher two MOG:G ratio treatments. Additionally, there was a tendency for greater collected grain and improved grain cleanliness as the MOG:G ratio decreased. The differences were small. The smallest MOG:G ratio had the greatest quantity of total grain in the Separated Grain, the least Tailings, and the least amount of grain in the Heavy MOG. At this MOG:G ratio, the collected grain goal of 95% was met, but the FM in the grain (15.0%) was much greater than the 5% goal. The overall average of FM at 15.4% was well above the goal of less than 5%. Similarly, the overall average of 6.9% of the grain in the Heavy MOG was greater than the goal of less than 5%.

SIEVE TYPE AND SIEVE DRIVE SPEED

In a fourth experiment (Experiment 4), variations in sieve oscillation frequency and type of top sieve were investigated (table 7). An 18% greater sieve drive speed resulted in significantly less FM in the Separated Grain (8.6% vs. 12.2%).

Table 4. Separation system effectiveness as impacted by fan speed and material throughput – Experiment 1.

	Fan Speed (rpm)	Target Throughput (Mg WM·h^{-1})	Dry Basis Mass Flow (Mg DM·h^{-1})	MOG:G Mass Ratio	Grain				
					FM[a] (%)	Fraction (%) of Total Grain Located In:			
						Separated Grain	Tailings	Collected[b]	MOG[c]
	800	32	14.2b	0.80	6.5	92.9	3.0	95.9	4.1
	1000	32	14.5b	0.86	6.6	91.7	4.1	95.7	4.3
	800	41	18.4a	0.86	6.2	88.4	4.0	92.4	7.6
	1000	41	19.1a	0.88	5.2	88.3	4.1	92.4	7.6
SEM[d]			0.43	0.048	1.08	1.47	0.65	1.17	1.17
p-value[d]			0.701	0.977	0.621	0.717	0.496	0.943	0.943
LSD (p=0.05)[d]			2.0	0.41	5.0	6.8	3.0	5.4	5.4
	800		16.3	0.83	6.3	90.7	3.5	94.1	5.9
	1000		16.8	0.87	5.9	90.0	4.1	94.1	5.9
SEM[d]			0.31	0.034	0.76	1.04	0.46	0.83	0.83
p-value[d]			0.261	0.389	0.713	0.660	0.374	0.962	0.962
LSD (p=0.05)[d]			1.4	0.16	3.5	4.8	2.1	3.8	3.8
		32	14.3b	0.83	6.5	92.3a	3.5	95.8a	4.2b
		41	18.8a	0.87	5.7	88.4b	4.0	92.4b	7.6a
SEM[d]			0.31	0.034	0.76	1.04	0.46	0.83	0.83
p-value[d]			< 0.001	0.419	0.473	0.028	0.440	0.020	0.020
LSD (p=0.05)[d]			1.4	0.16	3.5	4.8	2.1	3.8	3.8

[a] Fraction of the Separated Grain (dry basis) as foreign matter (FM). See equation 4.

[b] Sum of Separated Grain and Tailings grain (dry basis).

[c] Grain found in Heavy MOG. No grain was observed in the Light MOG.

[d] Standard error of the mean (SEM) n = 3. Within each column, lower case markers indicate significant differences at $p < 0.05$ using Tukey's comparisons or Students t-test. Least square difference (LSD) for $p = 0.05$.

Table 5. Separation system effectiveness as impacted by fan speed and material throughput – Experiment 2.

	Fan Speed (rpm)	Target Throughput (Mg WM·h^{-1})	Dry Basis Mass Flow (Mg DM·h^{-1})	MOG:G Mass Ratio	Grain				
					FM[a] (%)	Fraction (%) of Total Grain Located In:			
						Separated Grain	Tailings	Collected[b]	MOG[c]
	800	25	13.8b	1.14	14.4	92.6a	3.9b	96.5a	3.5b
	1000	25	13.9b	1.12	13.2	81.9b	8.5a	90.5b	9.5a
	800	35	19.9a	1.13	15.7	91.1a	3.8b	94.9a	5.1b
	1000	35	19.8a	1.15	12.3	80.1b	7.8a	87.9b	12.1a
SEM[d]			0.15	0.076	0.11	0.78	0.33	0.89	0.89
p-value[d]			0.665	0.796	0.350	0.831	0.368	0.598	0.598
LSD ($p = 0.05$)[d]			0.7	0.36	5.1	3.6	1.5	4.1	4.1
	800		16.9	1.13	15.0	91.9a	3.8b	95.7a	4.3b
	1000		16.9	1.14	12.7	81.0b	8.1a	89.2b	10.8a
SEM[d]			0.10	0.054	0.759	0.5508	0.23	0.63	0.63
p-value[d]			0.957	0.977	0.066	< 0.001	< 0.001	< 0.001	< 0.001
LSD ($p = 0.05$)[d]			0.5	0.25	3.5	2.5	1.1	2.9	2.9
		25	13.9b	1.13	13.8	87.3	6.2	93.5a	6.5b
		35	19.9a	1.14	14.0	85.6	5.8	91.4b	8.6a
SEM[d]			0.10	0.054	0.759	0.5508	0.23	0.63	0.63
p-value[d]			< 0.001	0.881	0.845	0.068	0.203	0.045	0.045
LSD ($p = 0.05$)[d]			0.5	0.25	3.5	2.5	1.1	2.9	2.9

[a] Fraction of the Separated Grain (dry basis) as foreign matter (FM). See equation 4.

[b] Sum of Separated Grain and Tailings grain (dry basis).

[c] Grain found in Heavy MOG. No grain was observed in the Light MOG.

[d] Standard error of the mean (SEM) $n = 3$. Within each column, lower case markers indicate significant differences at $p < 0.05$ using Tukey's comparisons or Students t-test. Least square difference (LSD) for $p = 0.05$.

Table 6. Separation system effectiveness as impacted MOG:G ratio of Pre-Separated material – Experiment 3.

	MOG:G Mass Ratio	Dry Basis Mass Flow (Mg DM·h^{-1})	Grain				
			FM[a] (%)	Fraction (%) of Total Grain Located In:			
				Separated Grain	Tailings	Collected[b]	MOG[c]
	0.80c	18.3b	15.0bc	92.7a	2.9b	95.6a	4.4b
	0.90b	18.0b	13.6c	87.8b	5.2a	93.0ab	7.0ab
	0.99ab	21.4a	15.3b	87.1b	4.7a	91.8b	8.2a
	1.05a	21.3a	17.8a	87.6b	4.4a	92.0ab	8.0ab
SEM[d]	0.031	0.28	0.35	1.01	0.25	0.84	0.84
p-value[d]	0.003	< 0.001	< 0.001	0.014	0.001	0.043	0.043
LSD ($p = 0.05$)[d]	0.14	1.3	1.6	4.7	1.2	3.9	3.9

[a] Fraction of the Separated Grain (dry basis) as foreign matter (FM). See equation 4.

[b] Sum of Separated Grain and Tailings grain (dry basis).

[c] Grain found in Heavy MOG. No grain was observed in the Light MOG.

[d] Standard error of the mean (SEM) $n = 3$. Within each column, lower case markers indicate significant differences at $p < 0.05$ using Tukey's comparisons. Least square difference (LSD) for $p = 0.05$.

Table 7. Separation system effectiveness as impacted by sieve drive speed and type of top sieve – Experiment 4.

	Sieve Oscillation Frequency (cycles/min)	Type of Top Sieve	Dry Basis Mass Flow (Mg DM·h^{-1})	MOG:G Mass Ratio	Grain				
					FM[a] (%)	Fraction (%) of Total Grain Located In:			
						Separated Grain	Tailings	Collected[b]	MOG[c]
	330	Flat Top	18.0	1.07	7.2c	87.7	4.7a	92.4	7.6
	280	Flat Top	17.9	1.11	10.3ab	92.8	3.2b	96.1	3.9
	330	General Purpose	18.4	1.12	9.9b	89.1	5.0a	94.1	5.8
	280	General Purpose	18.5	1.08	14.2a	92.8	2.6b	95.4	4.6
SEM[d]			0.16	0.056	0.65	1.25	0.29	1.04	1.04
p-value[d]			0.749	0.459	0.403	0.570	0.143	0.275	0.275
LSD ($p = 0.05$)[d]			0.7	0.26	3.2	5.8	1.4	4.8	4.8
	330		18.2	1.10	8.6b	88.4b	4.9a	93.3b	6.7a
	280		18.2	1.09	12.2a	92.8a	2.9b	95.7a	4.3b
SEM[d]			0.11	0.039	0.46	0.89	0.21	0.74	0.74
p-value[d]			0.986	0.976	< 0.001	0.008	< 0.001	0.047	0.047
LSD ($p = 0.05$)[d]			0.5	0.10	2.1	4.1	1.0	3.4	3.4
		Flat Top	18.0b	1.09	8.8b	90.3	4.0	94.2	5.8
		General Purpose	18.4a	1.10	12.1a	91.0	3.8	94.8	5.2
SEM[d]			0.11	0.039	0.46	0.89	0.21	0.74	0.74
p-value[d]			0.017	0.875	0.001	0.582	0.567	0.617	0.617
LSD ($p = 0.05$)[d]			0.5	0.10	2.1	4.1	1.0	3.4	3.4

[a] Fraction of the Separated Grain (dry basis) as foreign matter (FM). See equation 4.

[b] Sum of Separated Grain and Tailings grain (dry basis).

[c] Grain found in Heavy MOG. No grain was observed in the Light MOG.

[d] Standard error of the mean (SEM) $n = 3$. Within each column, lower case markers indicate significant differences at $p < 0.05$ using Tukey's comparisons or Students t-test. Least square difference (LSD) for $p = 0.05$.

However, the greater drive speed resulted in statistically greater grain in the Heavy MOG (6.7% vs. 4.3%). The greater oscillation frequency at higher drive speeds passed material more quickly over the top sieve, which resulted in less FM in the Separated Grain, but greater grain leaving with the Heavy MOG. The Flat Top sieve resulted in less FM in the in the Separated Grain (8.8% vs. 12.1%) than the General Purpose sieve. When operated at the slower sieve drive speed, both the General Purpose and Flat Top sieves met the goal of greater than 95% grain capture, but the average FM in the Separated Grain of 12.2% was above the 5% goal.

SIEVE TYPE AND SIEVE CLEARANCE

The type of top sieve and the sieve openings were investigated in a fifth experiment (Experiment 5, table 8). Small sieve openings were 16 and 10 mm, while large sieve openings were 21 and 15 mm for the Long Finger and Flat Top sieves, respectively. Smaller sieve openings resulted in less FM in the Separated Grain (3.9% vs. 5.7%) but also produced greater grain in the Heavy MOG (1.4% vs. 0.6%). The Flat Top sieve resulted in less FM in the Separated Grain than the Long Finger sieve (4.4% vs. 5.1%). Total grain collected and grain in the Heavy MOG were not statistically different between the two sieve types. At the smaller sieve clearance, the goals of greater than 95% grain capture and less than 5% FM in the Separated Grain were met for both sieve types. Both of these performance metrics were considerably better than in most of the previous experiments, which might have been partially due to the low MOG:G ratio of the Pre-Separated material in this experiment (table 1). The average MOG:G ratio of 0.70:1 was less than any other material used in this research.

Successful separation of corn grain from MOG during the typical operation of a combine harvester cleaning system is primarily influenced by mechanical effects rather than aerodynamic considerations because the MOG:G ratio would be significantly smaller for corn than for small grains (Mailander, 1984). Typical MOG:G ratios of material entering the combine harvester during corn harvest range from 0.15 to 0.22 (Shinners et al., 2012; Keene et al., 2013; Bergonzoli et al., 2020). When the average MOG:G ratio was 0.16, combine dry basis throughput was 10.5 and 67.6 Mg·h^{-1} for the stover and grain fractions, respectively (Walters et al., 2020). How much of the ingested MOG passes through to the cleaning system versus that which is ejected from the rear of the separator has not been found in the literature. That said, even if the majority of the MOG was delivered to the cleaning system, the MOG:G ratio of a typical combine harvesting corn would be much less than used in this research, where the MOG:G ratio was close to unity.

Combine harvester losses are typically quantified as those associated with gathering (i.e., header losses), threshing, separation, and cleaning. Due to difficulty identifying separation and cleaning losses, these losses are often categorized simply as losses associated with separating threshed grain from the MOG. From field measurements, separation and total losses averaged 0.4% and 1.2% of DM (Turner et al., 2021), 0.9% and 1.3% of DM (Paulsen et al., 2014), respectively. In this research, grain not separated from the MOG ranged from 0.5% to 12.1% of DM. In our most successful experiment (No. 5, table 8), grain lost to the MOG averaged 1.0% of DM, which would have been similar to losses experienced when grain and MOG are separated during field harvest.

Foreign matter and impurities averaged 2.1% during field experiments (Rodrigues et al., 2014). Corn delivered to commercial storage over five years (2011–2015) averaged 0.2% foreign matter (Paulsen et al., 2019). In this research, foreign matter ranged from 5.3% to 17.8% of DM. In our most successful experiment (No. 5, table 8), FM in the Separated Grain averaged 4.8% of DM, which would have been much greater than reported when grain and MOG are separated during field harvest.

Kutzbach and Quick (1999) describe three phases of cleaning system performance. In the first phase, MOG and

Table 8. Separation system effectiveness as impacted by type of top sieve and top sieve clearance – Experiment 5.

	Type of Top Sieve	Sieve Clearance (mm)	Dry Basis Mass Flow (Mg DM·h^{-1})	MOG:G Mass Ratio	Grain				
					FM[a] (%)	Fraction (%) of Total Grain Located In:			
						Separated Grain	Tailings	Collected[b]	MOG[c]
	Long Finger	16	20.2	0.69b	4.5ab	95.0a	3.4b	98.3	1.7
	Long Finger	21	20.2	0.77a	5.8a	97.5a	1.7b	99.2	0.8
	Flat Top	10	20.0	0.68b	3.3b	91.3b	7.6a	98.9	1.1
	Flat Top	15	20.1	0.66b	5.6a	96.0a	3.5b	99.5	0.5
SEM[d]			0.15	0.015	0.3	0.70	0.47	0.38	0.38
p-value[d]			0.687	0.014	0.135	0.152	0.033	0.809	0.809
LSD ($p = 0.05$)[d]			0.7	0.07	1.4	3.2	2.2	1.8	1.8
		Small	20.1	0.69	3.9b	93.1b	5.5a	98.6	1.4
		Large	20.2	0.72	5.7a	96.7a	2.6b	99.4	0.6
SEM[d]			0.11	0.010	0.21	0.5	0.33	0.27	0.27
p-value[d]			0.799	0.082	< 0.001	< 0.001	< 0.001	0.076	0.076
LSD ($p = 0.05$)[d]			0.5	0.05	1.0	2.3	1.5	1.3	1.3
	Long Finger		20.2	0.73a	5.1a	96.2a	2.6b	98.8	1.2
	Flat Top		20.0	0.67b	4.4b	93.6b	5.6a	99.2	0.8
SEM[d]			0.11	0.010	0.21	0.5	0.33	0.27	0.27
p-value[d]			0.304	0.005	0.046	0.006	< 0.001	0.310	0.310
LSD ($p = 0.05$)[d]			0.5	0.05	1.0	2.3	1.5	1.3	1.3

[a] Fraction of the Separated Grain (dry basis) as foreign matter (FM). See equation 4.

[b] Sum of Separated Grain and Tailings grain (dry basis).

[c] Grain found in Heavy MOG. No grain was observed in the Light MOG.

[d] Standard error of the mean (SEM) n = 3. Within each column, lower case markers indicate significant differences at $p < 0.05$ using Tukey's comparisons or Students t-test. Least square difference (LSD) for $p = 0.05$.

grain throughput are low, and excess air flow can cause high grain loss because grain is suspended and conveyed over the top sieve. In the fluidization phase, the MOG and grain throughput allow the airflow to create conditions where the grain can fall through the MOG layer and land on the top sieve, preferably near the front of the sieve. At high MOG and grain throughputs (bulk phase) the material layer cannot be loosened by the air flow and grain penetration through the MOG layer is hampered. Kutzbach and Quick (1999) suggest that fan speed should be increased at high throughputs to produce acceptable grain loss. In our research, the best grain capture and lowest grain loss results were achieved when fan speed was greatest and MOG:G ratio was the least (Experiment 5, table 8).

Improved grain capture and cleanliness were observed at lower feed rates, which relates to reduced mass of material per unit area of the top sieve. Mui (2015) reported that at high feed rates, separation of grain from chaff improved with longer top sieves. This suggests that separating and cleaning grain from corn stover MOG could be improved at high feed rates by using sieves with a greater surface area than was used in this research. Due to material availability, the replicate tests had a relatively short duration. Transient conditions may have led to inconsistent air flow through the mat of material at the beginning and end of each test. Future research should focus on longer duration tests that would better mimic the continuous flow process that would be expected in a processing plant.

Based on published literature and our results, reducing the MOG:G ratio would improve both grain separation and reduce FM in the separated grain. In our proposed harvest system, the MOG:G ratio will be an uncontrolled variable that is dictated by an economical and sustainable stover yield. Therefore, adding a component to the separation system that pre-separates some stover, for instance, the stalks, cobs, and husk, may improve both grain separation and cleanliness at the cleaning system by reducing the MOG:G ratio. This pre-separation could be the first step in a system that further separates the stover into preferred anatomical fractions. We observed that the most prevalent FM in the Separated Grain was the slender section of the rind of the stalk that had slipped between the fingers of the sieves (fig. 6). The terminal velocity of moist grain (i.e., > 25% w.b.) was slightly greater than 12 $m \cdot s^{-1}$ (Ahmadi Chenarbon and Movahhed, 2021), while the terminal velocity of rind sections of the moist stalk (i.e., > 40% w.b.) was slightly less than 8 $m \cdot s^{-1}$ (Womac et al., 2023). So, the air classification of these two fractions should be possible. However, it was impossible to assess the air velocity passing through the deep mat of MOG, but given that many of these slender rind sections were observed in both the Heavy and Light MOG fractions, it is likely that the terminal velocity of this material was achieved. We also observed in separate wind tunnel tests (Blazer, 2022) that when these rind sections would orientate with the thickness in the direction of the air, the sections would rapidly fall until they reoriented with the large surface area perpendicular to the airflow. If this orientation change occurred in the MOG mat, some of these rind sections would have likely landed on the top sieve. These rind sections could then easily pass through the finger-type louvers of the sieves. Sieves that feature a round hole or countersunk round hole may improve grain capture and grain cleanliness by reducing the tendency for slender rind sections to slip through the louvered fingers (Wang et al., 2021).

CONCLUSIONS

The utilization of a combine cleaning system to separate grain from high dry-matter whole-plant corn stover was affected by several machine settings. Fan speed, mass flow rate, sieve type, and sieve clearance resulted in significant differences in grain cleanliness, capture rate, and losses. The system could be optimized to achieve state of technology performance in terms of grain capture and cleanliness. However, the system was sensitive to MOG:G ratio. Methods of quantifying input material MOG:G or initial fractionation approaches that remove large stover fractions before the cleaning system could improve system throughput and effectiveness.

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