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An Apparatus and Method for Evaluating Particle-Size Distribution of Small Grain Crop Residues

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Abstract: Size-reduction of small grain residue is required on the combine harvester to promote uniform distribution of residue across the full harvested width. However, unnecessary size reduction increases energy expenditures that can reduce harvester capacity. To objectively quantify the degree of residue processing, an apparatus and method was developed for evaluating particle-size distribution of small grain crop residue. The apparatus consisted of a pre-screener to sort long particles and an oscillating cascade of three screens which separated material into four additional fractions. The separation process was continuous, so large volume samples could be separated more quickly than batch systems. The developed system was used to evaluate wheat residue which was processed to various extents by a combine residue chopper in two experiments. Statistically significant ($p < 0.05$) differences between variably processed wheat residues were found using the developed apparatus and methodology. The separated wheat residue was partitioned into three particle-size ranges of less than 50 mm, 50 to 125 mm, and greater than 125 mm. Samples of 3 to 4 kg could be completely analyzed in less than 10 min.

Keywords: apparatus; chaff; chopper; method; particle-size; residue; straw

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1. Introduction

Improving how the combine harvester size-reduces and redistributes small grain residue is increasingly important as headers become wider, crops yields increase, and reduced tillage becomes more commonplace. The first step in a successful low- or no-tillage systems is uniform residue distribution. Inadequate spatial distribution and poor nutrient availability due to slow residue break down are often indications of poor harvest residue management. To produce small grain crops more sustainably, producers are adopting conservation tillage and no-tillage practices that leave more residue on the soil surface [1,2]. However, residue which is not incorporated into the soil decomposes at a slower rate than buried residue [3,4]. Small grain crops have been bred to resist lodging through thicker stems which contain greater lignin, making them more resistant to microbial decomposition [5,6]. The rate of residue decomposition is proportional to the mass per unit area [7], so uneven distribution has a spatial impact on soil organic matter.

The dynamics of residue decomposition is controlled by many factors, but residue distribution and particle size influence soil incorporation and decomposition [4]. Flower et al. [8] noted that across five years of study, the distribution of wheat and barley residue behind the harvester was always uneven, with up to twice as much residue directly behind the harvester compared with mid and outer locations [8]. The effect on subsequent crop yield was inconsistent, but soil nutrient content was consistently greater in high residue locations. They note that research to improve uniformity of residue spread behind harvesters is crucial and unless uniformity is improved variation in crop performance will increase as harvesters get larger. As combine headers become wider, it becomes challenging to uniformly redistribute residue across the full harvested strip when the combine body may be less than 10% of header width. For all these reasons, combines have extensive mechanical systems to size-reduce and redistribute small grain residue exiting the rear of the harvester.

Residue size-reduction helps with redistribution of straw from the harvester, but excess size-reduction increases combine fuel consumption and may actually impair uniform distribution because fine, lightweight particles are easily deflected by wind. When the residue chopper of the combine harvester was configured to do minimal residue processing, the energy consumption for harvesting wheat was reduced by 17% [9]. Germination of the next crop can be hindered, and subsequent crop yield can suffer if residue size-reduction and redistribution are inadequate [10,11]. Long residue particles may not fall through the standing crop stubble and will decompose too slowly and can hairpin and plug tillage and planting elements [3,4,12]. Non-uniformly distributed residue may impair good seed-soil contact and have differential spatial impact on soil moisture, soil temperature, nutrient availability, and water infiltration [10,13].

Small grain residue is typically a mix of fine particles and long straw. The mass fractions of wheat residue were 56% less than 50 mm, 32% between 50 and 180 mm, and 12% greater than 180 mm [14]. Particle size analysis of agricultural material is usually conducted on either fine ground material or on precision cut forages [15]. Although fractionation by sieving is common, these materials would rarely include substantial amount of long material typical of small grain residue. What is needed is a system that can partition small grain residue that is a mix of small particles and long straw.

Because there has not been a good methodology to quantify small grain residue size distribution, there is little published research to suggest a desirable size range. Schwarz and von Chappuis [16] suggested that small grain residue less than 175 mm would limit interference with tillage and seeding. Vosshenrich [17] reported good residue distribution of wheat straw particles that passed through a 67 mm screen, but particles less than 20 mm were more concentrated in the center of the residue distribution pattern [18]. In this research, residue particles of 50 to 125 mm were proposed as a desirable size range. The upper limit was chosen because 125 mm is typically the narrowest row spacing that many small grains are planted, so residue less than this dimension would reduce issues with row plugging during no-till planting. The minimum spacing between stationary knives on residue choppers is varied, but is typically about 50 mm [19], so this was chosen as the lower limit. Creating particles smaller than 50 mm would waste energy and these particles were considered too small to be adequately distributed across wide harvest widths.

Research on methods to quantify small grain residue size distribution is very limited and techniques often poorly described. Mechanical screening is most often mentioned, but few details have been provided on the mechanisms or procedures used [10,14,17]. Image analysis has been applied to determine some physical properties of forages and residues, but these approaches have limitations for assessing small grain residue distribution systems [20–23].

Consistent and uniform chop length is noted as a first requirement for uniform distribution of crop residues exiting the combine harvester [19]. Residue size, as impacted by harvester throughput and residue chopper settings, was noted as a key factor in field evaluation of distribution uniformity [24]. Given its impact on combine performance, residue distribution, and subsequent field operations, quantitative assessment of residue particle size distribution is vital for improving combine harvester residue management systems. Therefore, the first objective of this research was to develop an apparatus and process methodology for separating small grain residue by size. The second objective was to develop a numerical index to summarize the size distribution of the fractionated residue. Specifically, we sought to separate small grain residue into three size categories of less than 50 mm, 50 to 125 mm, and greater than 125 mm. The final objective was to demonstrate the utility of the apparatus and methodology by evaluating wheat residue samples which were variably processed during harvest.

2. Materials and Methods

2.1. Apparatus Development

Three performance requirements were established. First, the apparatus should separate small grain residue into at least four size fractions. Second, the apparatus must be able to process a 3 to 4 kg sample in less than 10 min using a continuous rather than batch process. Third, the apparatus needed to process particles exceeding 100 mm in length without disrupting effective separation by plugging screens or impeding flow.

One approach considered but not pursued was a batch separator similar to the forage particle separator described in ASABE Standard S424.1 [15]. This approach was rejected because a batch process limits sample size and also leads to over-screening of the high aspect ratio particles that are common in small grain residue. Over-screening is the phenomenon where long, slender particles reside long enough to align with the screen openings and slip through longitudinally even when the length of the particle is much greater than the size of the screen opening [25].

Compared to physical screeners, image analysis (IA) can provide much greater information concerning the physical size of particles, including information in three dimensions [20,21,26]. However, arrangement of the particles with respect to one another is a vital aspect for success with this method. A singulated arrangement of particles where particles do not overlap or touch one another is typically required for an accurate analysis [20,21,26]. Therefore, IA processing was rejected because the need to hand separate particles to prevent particle overlap required too much time to meet the second performance criteria. Additionally, because small grain residue is a mix of very fine particles and long straw, some screening would still be required to separate these two disparate size fractions before imaging.

The separation approach pursued was based on a gyratory screener using a cascade of screens that were oscillated to produce rotary motion at the inlet and linear motion at the outlet. Gyratory screeners are characterized as a continuous separation process in which particles oversized for a given screen exit quickly, reducing chances of over-screening. These screeners have a relatively long stroke that help spread material across the full width of the screens and stratifies the bed of material, so that the finer particles will work their way down to the screen surface [25]. The screens on gyratory screeners are typically configured at a slight angle below the horizontal to allow gravity to propel material towards the outlet [25].

The initial screen stack consisted of three screens of varying opening size and screening area which produced four fractions. The initial opening sizes of these screens was determined based on the lengths of residue desired in each fraction, initial testing, and concepts discussed in the literature. Finner et al. [27] and Gale and O'Dogherty [28] discussed the concept of separating materials by screening in which a particle would fall through an opening with a diameter that was twice the particles length. However, Yang [21] showed that the measured mean length of slender grass particles were approximately five times the calculated geometric mean diameter of the screen openings as determined using screener described in ASABE Standard S424.1 [15]. Initial testing with a Rotex model 12 continuous gyratory screener (Rotex Global, Cincinnati, OH, USA) suggested that screens might pass wheat residue particles which were six to eight times the opening diameters. Considering these concepts, opening diameters of 12.7 and 6.4 mm were chosen for the top and middle screens, respectively, to achieve cutoff lengths of approximately 100 mm and 50 mm. The diameter of the bottom screen openings was 4.5 mm.

After preliminary tests it was evident that these initial screen openings produced shorter cutoff lengths than were intended, and both bottom fractions contained considerable amounts of fine material. As a result, new screens with round holes of 19.0, 12.7, and 7.9 mm diameters were used for the top, middle, and bottom screens, respectively (Table 1, Figures 1 and 2). Initial testing had also shown that long, tangled, bent, or otherwise irregularly shaped pieces of residue often lodged in the screens and decreased screening efficiency, so it was desired to first remove this material by pre-screening. A 325 mm long pre-screening section was added which consisted of thirteen 8 mm round bars spaced 38 mm on-center and aligned parallel to the longitudinal axis of the screener. A majority of the sample would fall through this parallel bar grate to the screens below while long, tangled particles exited via a separate outlet to create a pre-screened fraction. The apparatus had adjustments for stroke length, oscillation frequency and decline angle. Preliminary tests were used to determine the appropriate values for these variables [29]. In the final configuration, the screen stack was declined from inlet to outlet at a slope of 7 degrees and was driven at a frequency of 300 rpm (5 Hz) through a stroke length of 50 mm.

Table 1. Properties of screens used in the final configuration of the gyratory screener.

Screen	Screen Length [b]	Hole Diameter	Hole Location		Screen Thickness	Total Screen Area	Screen Open Area
Position [a]	(mm)	f [c] (mm)	X [c] (mm)	Y [c] (mm)	(mm)	(m^2)	(%)
C	1000	19.0	44	25	5.0	0.55	51
D	990	12.7	30	17	2.7	0.54	48
E	810	7.9	16	9	1.9	0.45	63

[a] See Figure 1. [b] All screens were 550 mm wide. [c] See Figure 2.

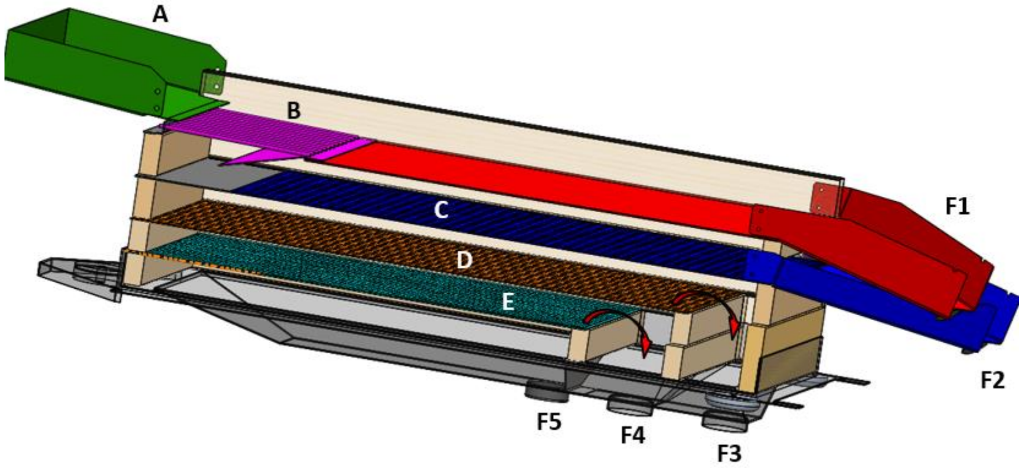

Figure 1. Schematic of gyratory screener showing (A) input pan; (B) pre-screening section; (C) top, (D) middle, and (E) bottom screens. Material passing through pre-screener was fed onto the top screen. Material passing over pre-screener was fraction 1 (F1); material passing over the top, middle or bottom screens were fractions F2, F3 and F4, respectively; and material passing through the bottom screen was fraction F5.

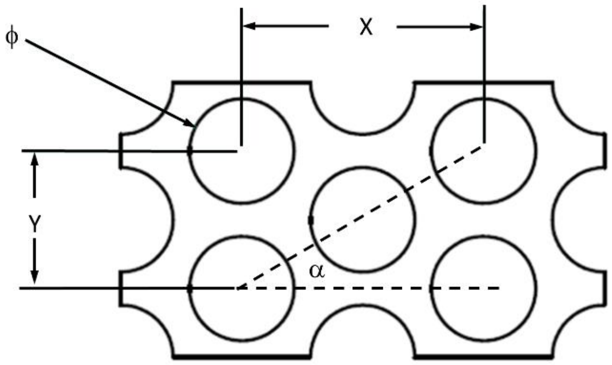

Figure 2. Pertinent screen dimensions and geometry for top, middle and bottom screens (see Table 1). The angle α was 30 degrees for all screens.

To process a sample, it was hand fed into the input pan (A, Figure 1) where the rotary motion spread the material across the pre-screening section (B, Figure 1). Long, tangled material which passed over this section exited via the pre-screened fraction outlet (F1, Figure 1). Material that fell through the pre-screener landed on an unperforated surface so that it would lay flat before moving to the first (top) screen surface (C, Figure 1). Material that fell through either the top or middle screens would land on the screen below it. Material that passed over any of these three screens was collected in separate fractions. In this manner, five fractions were created: pre-screened (F1), material that passed over any of the three screens (F2–F4), and material that passed through the lower screen (F5). The apparatus was powered by an electric motor and its overall approximate dimensions were 1.7 m H × 0.9 m W × 2.5 m L (Figure 3). Because of the substantial weight subjected to the oscillating motion, the apparatus had to be secured to the ground.

Figure 3. The gyratory screener with the fraction collection containers.

2.2. Experiments Conducted

Two experiments were conducted on wheat harvested at the University of Wisconsin Arlington Agricultural Research Station using a John Deere (Moline, IL, USA) model 9860 STS combine. The crop residue was processed to varying extents by adjusting the residue chopper speed and residue chopper stationary knife engagement (Figure 4 and Table 2). Experiment 1 was a full factorial with two chopper speeds x two knife positions. Experiment 2 investigated three treatments: (1) no residue processing; (2) 0 mm knife engagement and 1600 rpm chopper speed; and (3) 90 mm knife engagement and 2500 rpm chopper speed. In Experiment 2, the first treatment was created by raising the residue chopper out of the path of material that exited the combine harvester. No other changes to the combine harvesters' configuration were made once an experiment began. The header height was set at approximately 10 cm so that most of the plant was harvested and the crop height prior to harvest was approximately 80 and 90 cm tall in Experiments 1 and 2, respectively.

The residue chopper rotor was 1310 mm wide with 30 pairs of knives distributed on four rows. The rotor knives dragged material past 35 stationary knives with a spacing of 37 mm. Stationary knife position was quantified by the radial distance the knives extended into the residue chopper housing (Figure 4).

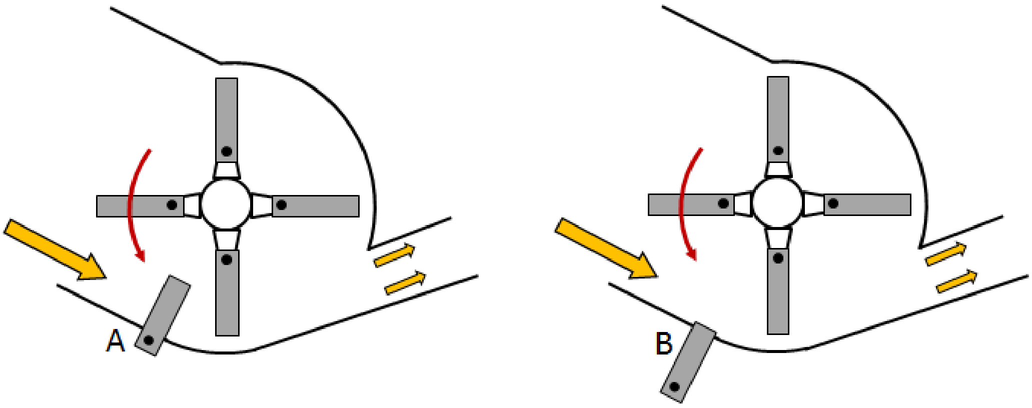

Figure 4. Schematic of combine harvester residue chopper showing stationary knife in full 90 mm radial engagement (**A**) and 0 mm engagement (**B**) positions.

Table 2. Combine harvester experimental conditions for material collected for separation with developed screener.

Experiment Number	Stationary Knife Engagement [a] (mm)	Residue Chopper Speed (rpm)	Ground Speed ($km \times h^{-1}$)	Replicate Samples per Experimental Condition	Moisture Content (% w.b.)	
					Grain	Residue
1 [b]	0.90	1600, 2500	3.2	9	15	29
2 [c]	0.90	1600, 2500	3.2	3	14	24

[a] Radial distance knives extended into the residue chopper housing. [b] Full factorial: two engagements × two speeds. [c] Three treatments: no residue processing; 0 mm knife engagement and 1600 rpm chopper speed; and 90 mm knife engagement and 2500 rpm chopper speed.

ASABE Standard S343.4 [30] categorizes small grain residue (also called material-other-than-grain, i.e., MOG) as two materials. Straw is defined as MOG discharged from the exit of the separator and chaff is defined as material discharged from the top sieve of the cleaning system. Wheat straw is considered to consist mainly of stems while wheat chaff is considered to consist of hulls, leaves, awns, and weed seeds [31]. However, research has shown that chaff not only consists of these materials but may also have broken straw and long stems [31]. The combine harvester used in this research deposited MOG from both the threshing/separation rotor and the top sieve into the residue chopper, so separation could not be conducted on the straw and chaff streams independently.

Complete crop residue samples were collected after exiting the machine but before that material contacted the ground. In both Experiments, 1.0 × 2.0 m screens were placed on the ground as the combine passed such that material was collected on the screens before it landed on the ground (Figure 5). The residue spreading/distribution system was disabled so the residue was placed in a narrow windrow approximately 2 m wide. In both Experiments, typical sample mass was approximately 3 to 4 kg (wet basis). It was observed that straw and chaff had different moistures with the latter drier than the former. Therefore, all samples were oven dried before screening because subsequent evaluations were based on the mass collected from each fraction. Samples were placed in burlap bags, oven dried for 72 h at 50 °C, and then allowed to equilibrate prior to separation. Separate sub-samples of both grain and residue were collected at the time of harvest and moisture content was determined in accordance with ASABE Standards S352.2 and S358.3 [32,33].

Figure 5. Sample collection where screens were placed on the ground as the combine passed so residue was collected before it landed on the ground.

Following drying of the residue samples, the screening apparatus was used to separate the samples into length-based fractions. With the machine running, the entirety of each sample was gradually fed as evenly as possible onto the input pan and allowed to flow through the machine. Time to screen a typical 3 to 4 kg sample was approximately 1 min. Each of the five fractions was then weighed to the nearest 0.2 g on a 6000 g scale and the mass was recorded. Time to process a typical sample, including screening, weighing, and recording data, was 2 to 3 min.

To characterize particle length in each of the five fractions F1–F5 in Experiment 1, 30 random particles from each fraction were hand-measured to the nearest millimeter. This was done for all 36 replicate samples for fractions F1 and F2 and from eight random replicate samples for fractions F3, F4 and F5. Each of the four treatments was represented twice in these eight samples. Hand measurements were made from every sample in fractions F1 and F2 because the range of particle lengths in these fractions was greater than particles in fractions F3, F4 and F5. Additionally, fractions F1 and F2 had not passed through any screens, so hand measurements of some particles were required to characterize the length of these particles. This is similar to the procedure required of material on the top screen of the ASABE Standard S424.1 forage particle screener [15].

Measuring particles as described above required several thousand hand-measurements for the 36 replicates samples collected. The standard deviation of the hand-measured particles in each fraction was used to calculate the minimum number of measurements required to achieve a confidence interval of ±10% of the average particle length determined from the hand-measured particles (Equation (1)). Based on results from Experiment 1, 12 random particles were hand measured in Experiment 2 for each fraction F1 through F4 and replicate sample (i.e., 48 hand measurements per replicate sample; 432 total hand measurements required).

$$N_t = ((Z \cdot SD)/CI)^2 \tag{1}$$

where:

Z—critical value for the confidence interval (1.624 for 90% confidence level).

SD—standard deviation of the hand-measured particles in each individual fraction.

CI—confidence interval of ±10% of the average particle length per fraction.

N_t—number of hand-measured particles required.

In ASABE Standard S424.1 [15], the mean length of finely chopped forage particles on an individual screen is defined by Equation (2). Based on the screen sizes and Equation (2), the L_{ave} for fractions F2 through F5 were 27, 16, 10 and 4 mm, respectively. These values could have been used to calculate the sample geometric mean length (*GML*) of the aggregate sample (Equation (3)). However, using Equation (2) to define particle length of small grain residue was not considered appropriate because long slender particles are often many times longer than the mean length determined using the screen hole diameters [21]. Therefore, the average length of the hand-measured particles for each fraction was used as $\overline{x_i}$ in Equation (3).

$$L_{ave_i} = \sqrt{D_i \cdot D_{i-1}} \tag{2}$$

$$GML = log^{-1}\left[\frac{\sum(M_i \cdot log\ \overline{x}_i)}{\sum M_i}\right] \tag{3}$$

where:

L_{avei}—average particle length of the ith screen based on screen hole diameters.

D_i—diameter of screen opening of the ith screen.

M_i—percentage of total sample mass in the ith fraction.

$\overline{x}_i$—average hand-measured particle length of the ith fraction.

GML—geometric mean length

In this project, an important goal was to quantify residue processing level by separating small grain residue into three size categories of less than 50 mm, 50 to 125 mm, and greater than 125 mm. The portion of an individual sample in one of these three size categories was determined by multiplying the percentage of the total mass in each of the five fractions by the proportions of that fraction that were within these three size categories as quantified by the hand-measured particles and then summing this product over all five fractions (Equations (4)–(6)).

$$F_{lt} = \sum\left(M_i \cdot f_{i_{lt}}\right) \tag{4}$$

$$F_b = \sum\left(M_i \cdot f_{i_b}\right) \tag{5}$$

$$F_{gt} = \sum\left(M_i \cdot f_{i_{gt}}\right) \tag{6}$$

where:

f_{ilt}—proportion of the hand-measured particles in the ith fraction less than 50 mm.

f_{ib}—proportion of the hand-measured particles in the ith fraction between 50 to 125 mm.

f_{igt}—proportion of the hand-measured particles in the ith fraction greater than 125 mm.

F_{lt}—fraction of total sample mass less than 50 mm.

F_b—fraction of total sample mass between 50 and 125 mm.

F_{gt}—fraction of total sample mass greater than 125 mm.

The experimental data for both Experiments was statistically analyzed using the Fit Model platform in JMP Pro version 13.5 (SAS Institute Inc., Cary, NC, USA). Differences among means were tested using the Tukey's HSD test or Students t-test with significance declared at $p < 0.05$.

3. Results

Material collected in the top four fractions were mainly stem particles (Figure 6) while material in fraction F5 was mainly fine chaff consisting of hulls, awns and finely shredded leaves and stems.

The average hand-measured particle length of each fraction was between four and five times the expected particle length based on Equation (2) (Figure 7). This "over screening ratio" illustrates the need to hand measure some particles to characterize the material length from each fraction. In all comparisons, the measured particle length of each of the top four fractions was statistically different between different experimental conditions

(Figure 8). This result suggests that hand measuring some particles from each of the top four fractions for each experimental treatment is required to appropriately estimate overall particle length using Equation (3). Particle length of the material in fraction F5 was consistent across all treatments and both Experiments and can reasonably be assumed to be 15 mm (Figure 8).

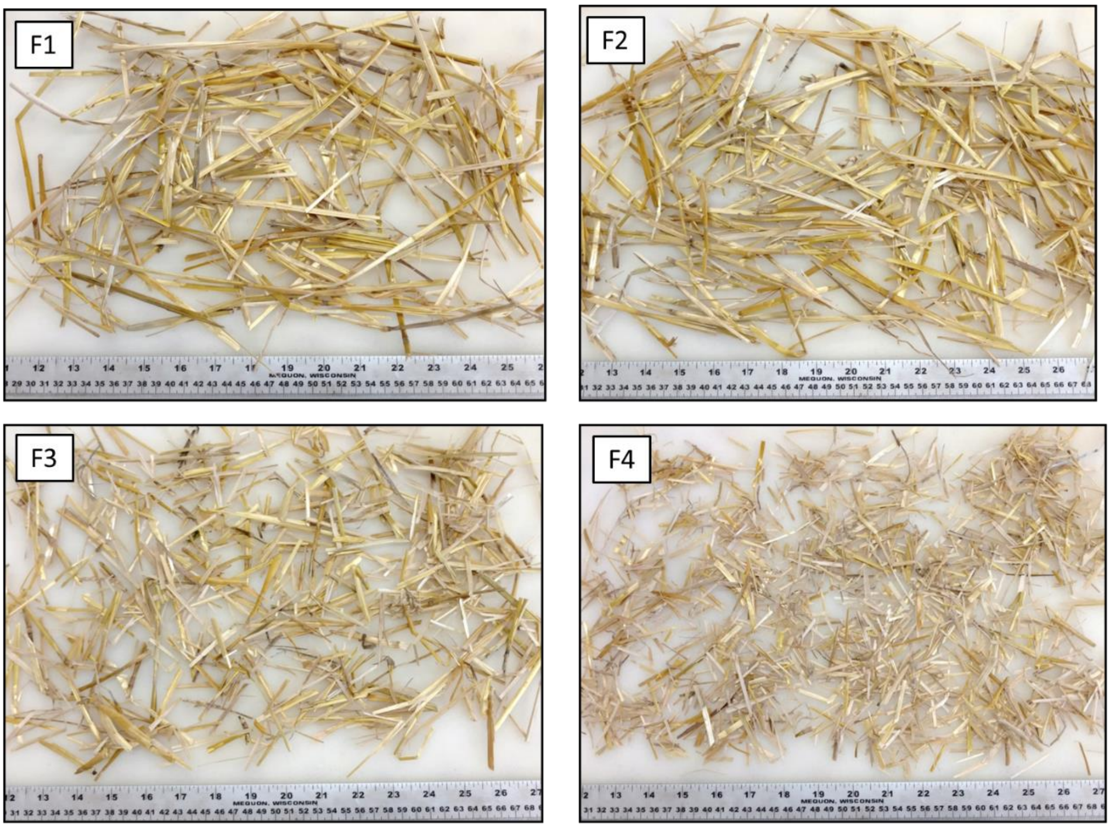

Figure 6. Wheat residue collected in fractions F1 through F4 (see Figure 1).

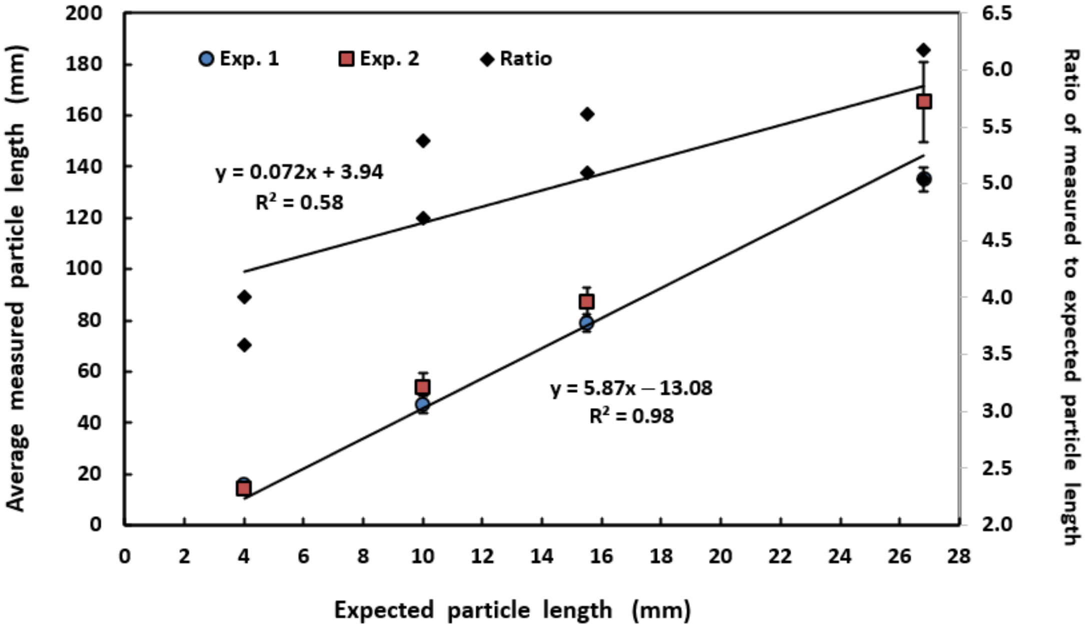

Figure 7. Particle length of hand measured particles and over-screening ratio versus expected particle length (based on Equation (2)) for Experiments 1 and 2. Error bars represent standard error of the mean.

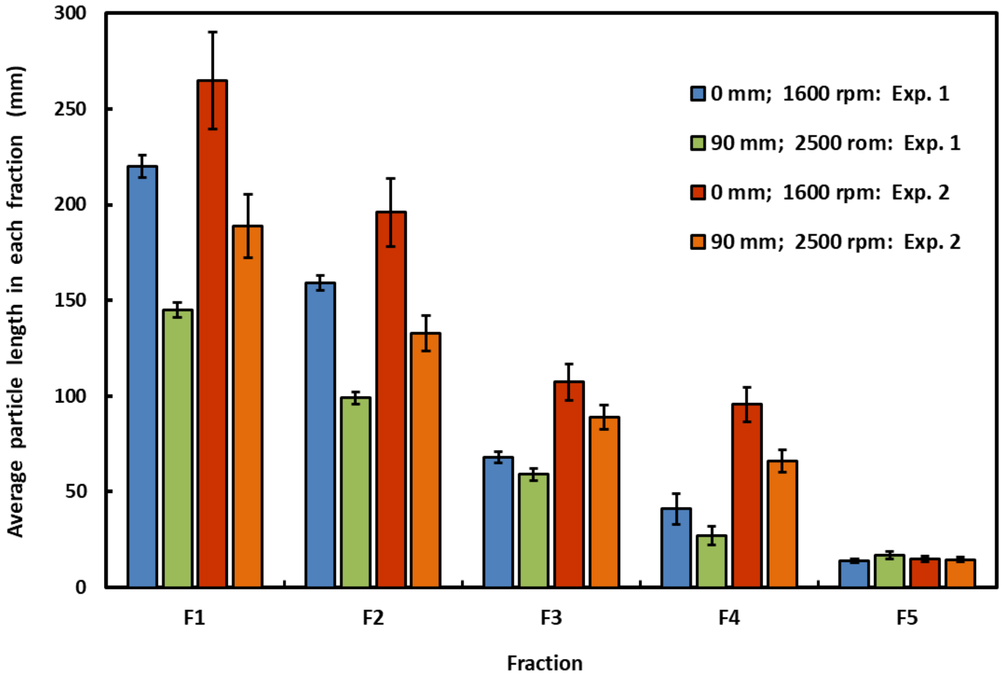

Figure 8. Average hand-measured particles from fractions F1 through F5 for Experiments 1 and 2 for two stationary knife engagements (0 or 90 mm) and two residue chopper speeds (1600 or 2500 rpm). Error bars represent standard error of the mean.

Using Equation (1), it was determined using Experiment 1 data that a total of 43, 44, 41, and 61 particles should be hand measured to characterize particle length in fractions F1 through F4, respectively. Greater number of measurements were needed for fraction F4 because the standard deviations were closer to the average particle length. No hand measurements would be needed for fraction F5 because it was mainly fine chaff with an average particle size that can reasonably be assumed to be 15 mm. As the number of replicate samples increases, the number of measurements required per replicate sample would decrease. For instance, if the number of replicate samples was four, then approximately 12 to 15 particles from each replicate sample should be measured for each of fractions F1 through F4. Measuring and recording the length of this number of particles increased the time to process a sample by approximately 3 min, so the total time to process one sample was approximately 6 min.

In Experiment 1, between 35% and 44% of the sample mass was within the desired size range of 50 to 125 mm (Table 3). As the residue chopper was configured to perform more aggressive size-reduction, the fraction of material in the desired size range increased and the fraction greater than 125 mm declined. However, the fraction of material less than 50 mm increased. To create a significant difference in the length of the straw (i.e., fractions F1–F4) required the most aggressive residue chopper configuration (i.e., fastest chopper speed and maximum knife engagement). Individually increasing either the chopper speed without changing knife engagement or the knife engagement without changing the chopper speed had approximately the same impact on the particle length distribution.

In Experiment 2, only 9% to 28% of the processed residue was within the desired size range of 50 to 125 mm (Table 4). Compared to no processing, processing with the least aggressive chopper settings increased the mass of small particles but produced no statistical difference in the particle length of the straw (i.e., fractions F1–F4). Processing residue with the most aggressive chopper configuration resulted in a statistically smaller fraction longer than 125 mm, reduced the length of the straw fraction, and increased the fraction in the desirable size range. However, the fraction less than 50 mm also increased.

Table 3. Summary of particle-size distribution and length from Experiment 1 using various combine residue chopper configurations.

Residue Chopper Speed (rpm)	Stationary Knife Engagement [a] (mm)	Average Particle Length [b] (mm)		Proportion of Total Sample Mass [d] (%)		
		Straw & Chaff [c]	Straw [c]	<50 mm	50–125 mm	>125 mm
1600	0	84a	96ab	23c	35c	42a
1600	90	69b	87ab	26bc	40b	34b
2500	0	72b	101a	27b	39b	34b
2500	90	55c	80b	32a	44a	24c
SEM [e]		1.5	4.0	0.7	1.0	0.6
p-value		0.525	0.007	0.235	0.390	0.707
Averaged by knife engagement						
	0	77a	98a	24b	38b	38a
	90	64b	84b	29a	42a	29b
SEM [e]		1.04	2.9	0.5	0.7	0.4
p-value		<0.001	0.001	<0.001	<0.001	<0.001
Averaged by chopper speed						
1600		78a	92a	25b	37b	38a
2500		62b	91a	29a	42a	29b
SEM [e]		1.04	2.9	0.5	0.7	0.4
p-value		<0.001	0.801	<0.001	<0.001	<0.001

[a] Stationary knife engagement, see Figure 4. [b] Average particle length calculated from Equation (3). [c] Calculated using material from fractions F1–F5 (straw and chaff), or only fractions F1–F4 (straw). [d] Proportion of total (F1–F5) sample mass that was within each size category (Equations (4)–(6)). [e] Standard error of the mean. Means within a column with different markers (a–c) differ using Tukey's HSD test or Student *t*-test at $p < 0.05$.

Table 4. Summary of particle-size distribution and length from Experiment 2 using various combine residue chopper configurations.

Residue Chopper Speed (rpm)	Stationary Knife Engagement [a] (mm)	Average Particle Length [b] (mm)		Proportion of Total Sample Mass [d] (%)		
		Straw & Chaff [c]	Straw [c]	<50 mm	50–125 mm	>125 mm
[e]	[e]	133a	249a	34b	7b	59a
1600	0	77b	233a	40b	9b	52a
2500	90	42c	110b	54a	28a	18b
SEM [f]		5.7	6.6	1.2	2.2	2.9
p-value		0.003	0.001	0.003	0.012	0.004

[a] Stationary knife engagement, see Figure 4. [b] Average particle length calculated from Equation (3). [c] Calculated using material from fractions F1–F5 (straw and chaff), or only fraction F1–F4 (straw). [d] Proportion of total (F1–F5) sample mass that was within each size category (Equations (4)–(6)). [e] Residue was not processed by the residue chopper. [f] Standard error of the mean. Means within a column with different markers (a–c) differ using Tukey's HSD test at $p < 0.05$.

4. Discussion

The developed separator and procedures facilitated separation of wheat residue into fractions that quantified statistically significant ($p < 0.05$) differences between residue that was processed variably by the combine harvester's residue chopper. These results were consistent across both experiments (Tables 3 and 4). Statistically significant ($p < 0.05$) differences in the three residue size categories were determined for changes to either the chopper speed or the stationary knife engagement. Increasing the rotational speed of the residue chopper likely decreased the particle-size due to greater cutting frequency and greater impact energy from the rotating knives. Increasing the extent of knife engagement with the material also decreased the particle-size, likely because a greater fraction of the residue would interact with the stationary knives.

Miu [19] noted the first requirement of a combine harvester residue management system is to produce consistent and uniform chop length. The results presented here show that goal remains to be achieved. In one published study, approximately 56%, 43% and 1% of wheat residue was within the size categories suggested here (i.e., <50 mm, 50 to 125 mm and >125 mm) [18]. Lundin [34] harvested wheat and barley over nine trials and reported that approximately 65%, 25%, and 10% were within these categories. El-Hanfy [35] reported that average rice straw particle size varied between 42 and 72 mm with smaller average length as chopping rotor speed increased. The fraction of particles greater than 60 mm increased from 30% to 83% as chopper speed decreased.

We chose a continuous, rather than batch, screener to reduce the issue of over- screening. However, the data presented in Figures 7 and 8 clearly show that over-screening occurred. This is why some hand measurement of particle length is required to accurately characterize the material length in each fraction. Over-screening ratios of 2.6 to 11.5 were reported with greater ratios as screen size decreased, however the screening method was not described [18]. Our results report smaller over-screening ratios with a much narrower range (Figure 7) and the ratio decreased with screen size.

The treatment in Experiment 2 that was not processed by the residue chopper showed that more than one-third of the residue mass that exited the threshing and separation systems was less than 50 mm (Table 4) even before processing in the residue chopper. This is consistent with results from Stubbe [36] who reported that most of the MOG that passed through the threshing concave and separation grate was less than 50 mm and consisted of hulls, leaves, and awns. In all cases, processing with the residue chopper reduced the fraction longer than 125 mm, increased the fraction within the desirable range of 50 to 125 mm, but also increased the mass fraction less than 50 mm. Alternative residue management systems that size reduce long straw without creating more fine particles should be investigated.

These experiments were conducted to determine if the developed apparatus and methodology could determine statistical differences in the residue particle-size distribution as impacted by residue chopper settings. This was the case in both Experiments. There could be residue chopper design alternatives or configurations that were not investigated here that might more effectively reduce particle length and provide a more uniform particle-size distribution. Published research results concerning small grain residue size have reported average particle size and size distribution [18,34,35,37]. However, we found no published data that used statistical analysis to determine if significant differences existed between combine harvester residue chopper configurations. This research provides is a new approach that can provide future researchers a methodology to statistically differentiate residue chopper performance in terms of residue size distribution.

To make meaningful representation of particle size distribution through histograms or cumulative plots, for instance as described in ISO 9276-1 [38], requires separating material into many more fractions than the five fractions used here. These graphical representations of finely ground material particle distribution typically use the screen opening when plotting the fraction undersized. This approach would not be appropriate for small grain residue because as Figures 7 and 8 show, particles that pass through the screens used here are many times the screen opening, and that the over screening ratio was different for different treatments. This is the rationale why some hand measurements to adequately describe size distribution are required. We chose to classify small grain residue into three size categories (<50 mm, 50–125 mm, >125 mm) but the developed apparatus and methodology could be used to categorize residue into segments with different limits (see Equations (4)–(6)) or even into a different number of segments.

Based on the results and our observations, the procedure for quantifying small grain residue should include: (a) collecting a 3 to 4 kg sample that includes all the chaff and straw as it exits the combine; (b) collecting material before it lands on the ground; (c) collection of baseline samples that have not been processed by the residue chopper; (d) drying samples in low temperature forced air dryer prior to separation so that variable sample moisture does not impact the mass fractions; and (e) for each treatment, hand-measuring approximately 40 to 60 particles for each of the fractions F1–F4.

Material was hand fed into the device. We found that this allowed some hand separation of tangled material which improved material flow. A conveyor could be used to feed the device in a more controlled manner, but untangling material prior to processing would still be advised. Changes that could be considered to improve material flow through the screener would include a longer pre-screener section and increasing the width of the screens from the current 55 cm to accommodate larger samples.

5. Conclusions

The objectives of this research were met in that a gyratory screening apparatus was developed and successfully employed to partition small grain residue into five size fractions. The process was continuous, so a 3 to 4 kg sample could be processed, hand-measurements of particle-length made, and data recorded in less than stated goal of 10 min per sample. Hand-measurement of approximately 40 to 60 particles per fraction (F1–F4) was needed for each treatment considered. Using the developed system and procedures, statistically significant ($p < 0.05$) differences were identified for variably processed wheat residue. In all cases, more intensive processing with the residue chopper reduced the mass fraction longer than 125 mm, increased the fraction within the range of 50 to 125 mm, but also increased the fraction less than 50 mm. The designation of the portion of residue that is within these defined size categories can provide a useful means of comparing and summarizing the extent of residue processing by the combine harvester.

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