Title: Assessment of corn silage kernel processing score via digital image processing techniques.

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Abstract:
In 2013 6.3 million acres were dedicated to growing corn silage in the United States. These acres yielded approximately 118 million tons of silage used for animal feeding operations. Silage choppers are equipped with kernel processing rollers that crack the corn kernels, making them more easily digested by livestock. Currently, assessment of the corn kernel particle size distribution, or kernel processing score (KPS), is done by sending a sample to a laboratory. This method provides an accurate representation of KPS, but only after the corn silage has been harvested. Development of a method to characterize KPS during harvest would allow producers and custom harvesters to adjust their silage choppers for the crop being harvested, accounting for variations. These adjustments would provide consistent KPS results and allow for the production of high quality corn silage. Image processing have been identified as a viable tool for characterizing particle size distribution. Mobile electronic devices equipped with cameras (i.e. smart-phones) provide a unique opportunity to implement image processing methods outside of a laboratory setting. The goal of this study is to assess image processing techniques as a means of determining particle size distribution in corn silage. Histogram plots showing the particle size distribution, the percentage of particles smaller than 4.75 mm, and geometric mean particle size were generated from images of 10 g sub-samples. The percentage of particles smaller than 4.75 mm determined by image processing was linearly related to the percentage of particles smaller than 4.75 mm determined by sieving methods with a coefficient of determination of 55%. Comparison of geometric mean particle size across varying camera resolutions showed that the smart phone and the DSLR camera were not statistically different at a 95% confidence level.

Introduction:

In 2013 6.3 million acres were dedicated to growing corn silage in the United States (USDA, 2014). These acres yielded approximately 118 million tons of silage used for animal feeding operations (USDA, 2014). Silage choppers are equipped with kernel processing rollers that reduce the particle size of the whole kernels making them more easily digestible for livestock. The current method for assessing corn kernel particle size distribution is a sieving process carried out in a laboratory. Samples, post-harvest, are sent to the laboratory and results are returned post analysis. A 600 ml sample of whole plant corn silage is placed in a Ro-Tap machine with varying sieves and is shaken for 10 minutes. The percentage of the sample that is smaller than 4.75 mm is the Kernel Processing Score (KPS). This method provides sufficient information about the quality of the forage, but does not provide this information when it is most relevant, i.e. while the crop is being harvested. Adjustments made to forage choppers during harvest can affect the quality of the harvested corn silage, and providing producers and custom harvesters a tool to assess the performance of the machine would allow for adjustments to be made. These adjustments made during harvest will lead to a consistently high quality corn silage being produced.

Kernel processing improves starch digestibility of corn silage by breaking the corn kernel into smaller pieces. Weiss and Wyatt (2000) found that kernel processing increased the total digestible nutrients of conventional corn silage by 5.3%. Even at greater theoretical lengths of cut where available energy within the silage is reduced, milk yield can be maintained or increased with aggressive kernel processing (Cooke and Bernard, 2005). Adequate kernel processing is crucial for maintaining corn silage quality.

Typically, the weather window for ideal corn silage harvest and processing is small. Custom harvesters and dairy farmers lack the time to send samples of either processed corn silage to a lab for quality assessment and KPS. Shinners and Holmes (2013) outlined a method for separation of the processed kernels from plant material to better assess KPS during harvest. Removing the plant material allows operators to observe the corn kernels directly and visually assess whether the kernel processing is adequate. This method provides a check for producers and custom harvesters but is a subjective assessment of KPS. The development of a method to more objectively assess KPS in near real time would allow producers to maintain a more uniform and high quality product.

Image analysis has been utilized in several fields for particle size analysis. Shahin et al. (2004) utilized image analysis to assess seed size distribution of green peas, yellow peas, soybeans, and chickpeas. Results showed that seed size measurements could be obtained from an image and resulting size distributions agreed with results from sieving analysis. Igathinathane et al. (2009) utilized a flatbed scanner to determine particle size from digital images of eight different types of food grains. Results showed that particle size determination was 96.6% accurate when compared to measurement with digital calipers. Igathinathane et al. (2008) outlined a method for characterizing particle size and shape of food grains and biomass particles using image analysis. An image analysis plugin was developed for image processing software that produced particle size measurements within 1.3% of the actual particle size. Savoie et al. (2013) performed particle size analysis on chopped forage utilizing image analysis to determine particle length, width, and thickness. Traditional sieving was shown to underestimate the true particle length by 31% compared to image based particle size analysis. Savoie et al. (2014) utilized image analysis to assess length and shape of woody biomass particles compared to sieving. Results showed that sieving underestimated the particle size due to long narrow pieces falling through the sieves. Audy et al. (2014) quantified the size and shape of forage particles using image analysis and the multi-scale bending energy method. Results showed that image analysis procedures coupled with the multi-scale bending energy method could very accurately characterize the shape and cumulative mass of the particles compared to sieving methods.

The prevalence of smart-phones equipped with cameras within our society makes image analysis a good fit for determining the KPS of corn silage during harvest. Development of image analysis methods for determining KPS and translating those methods into a user friendly smart-phone application would allow producers and custom harvesters to characterize KPS during harvest. The availability of this information would allow producers and custom harvesters to make adjustments to their machines in order to produce the highest quality corn silage possible.

The objective of this research was to develop a computer based program to determine KPS, or more specifically, particle size distribution of corn silage samples using image analysis.

Materials and Methods:

Initial Software Development:

Three existing processed corn kernel samples, housed in the Biological Systems Engineering Department (BSE) at the University of Wisconsin – Madison, were used to construct the initial particle size analysis program. These samples were collected prior to be ensiled and were processed at 2, 3, and 5 mm processor roll gaps. The age of the samples was unknown.

Sub-samples were collected and individual corn kernel particles were spread on a black counter surface (fig. 1). The samples were spread in a square shape (31 x 31 cm) with care being taken that no individual particles were contacting one another, so that the image produced would be a best case scenario for identifying individual particles and accurately determining their size. In order to determine the size of each particle within the image an object of known size was included. For this research a United States Penny was placed in the image, which provided a known diameter of 19.05 mm. The diameter of the penny was determined using digital calipers.

Figure 1. Original image format for image based particle size distribution analysis. Layout dimensions of approximately 31 x 31 cm and a United States Penny located in the lower left corner for scaling purposes.

Particle size distribution was determined via a script written in MATLAB (2014b, The Mathworks, Inc., Natick, Mass.) and utilized some built-in functions of the image processing toolbox. Specific steps for processing an image to determine particle size distribution are listed below:

1. Set threshold: removes any small artifacts within the image that are not processed kernels.
2. Read image
3. Convert image to gray scale
4. Convert image to black and white
5. Fill any interior gaps within the particles
6. Remove the unused border from the image
7. Extract data using REGIONPROPS
8. Superimpose numbers on each particle
9. Convert measurements from pixels to cm
10. Sort the final data
11. Generate histogram
12. Calculate geometric mean particle size (GMPS)
13. Calculate percentage of sample smaller than 4.75 mm

<u>Software Refinement:</u>

In order to assess the image analysis software's ability to determine particle size distribution a collaboration agreement was set up with Dr. Randy Shaver's lab. A survey had been conducted on kernel processing of producers within Wisconsin, Illinois, and Minnesota and a total of 38 samples were shared for image analysis. These samples were taken from the feed bunker and had been ensiled. The plant material had been separated so that only small plant particles and corn kernels remained and the samples had also been dried.

For image analysis, three 10 g sub-samples were collected from the larger sample provided by the survey. Each sub-sample was spread evenly on a matte black surface and the penny was placed on the surface as well. Images were collected with three different cameras for each 10 g sub-sample. The images were collected with a smart phone at 8 Megapixel resolution, a Nikon S6100 point-and-shoot camera at 16 Megapixel resolution, and a Nikon DSLR 7100 camera at 24.1 Megapixel resolution. Each image collected was analyzed with the developed MATLAB software. The percentage of particles smaller than 4.75 mm was calculated as well as geometric mean particle size (GMPS).

Statistical Analysis:

Differences in camera resolutions were analyzed by ANOVA using PROC MIXED in SAS (v9.3, SAS Institute, Cary, N.C.). Means were separated using Fisher's LSD (Saxton, 1998) at a confidence interval of 95% ($\alpha = 0.05$).

Results and Discussion:

An image analysis script was successfully developed to determine particle size distribution for processed corn kernels. Figures 2 – 7 show the original image, processed image, and resulting histograms for one 10 g sub-sample at the three differing camera resolutions. This process was repeated for three times for each sample collected from the survey.

Figure 2. Original image of sample 100 taken with the smart phone (8 Megapixel resolution) (left). Black and white processed image of sample 100 taken with the smart phone (right).

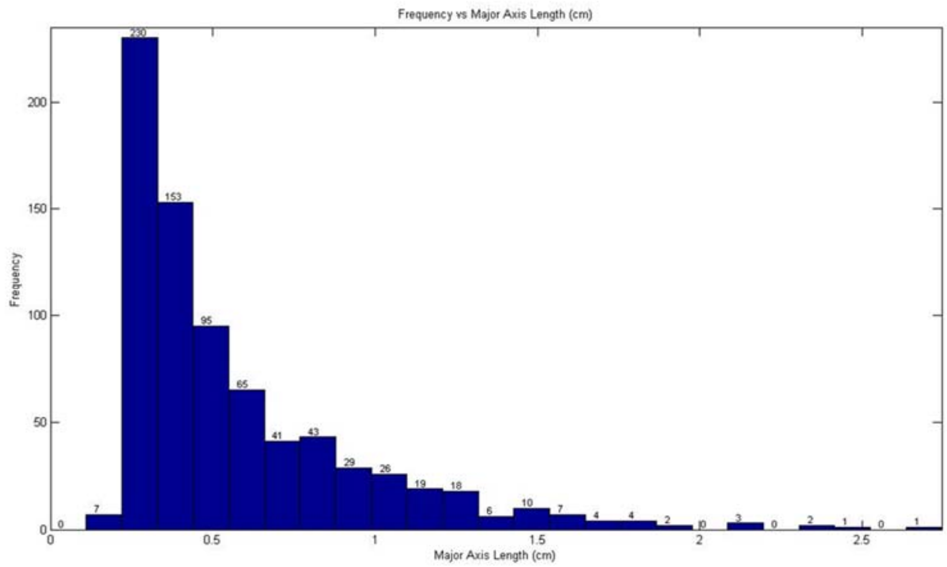

Figure 3. Histogram results from sample 100 taken with the smart phone (8 Megapixel resolution).

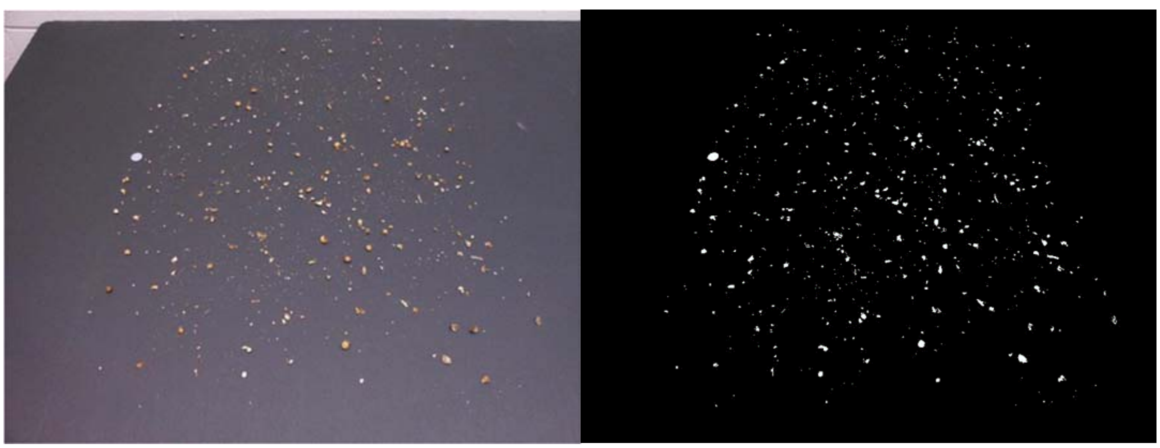

Figure 4. Original image of sample 100 taken with the Nikon S6100 (16 Megapixel resolution) (left). Black and white processed image of sample 100 taken with the Nikon S6100 (right).

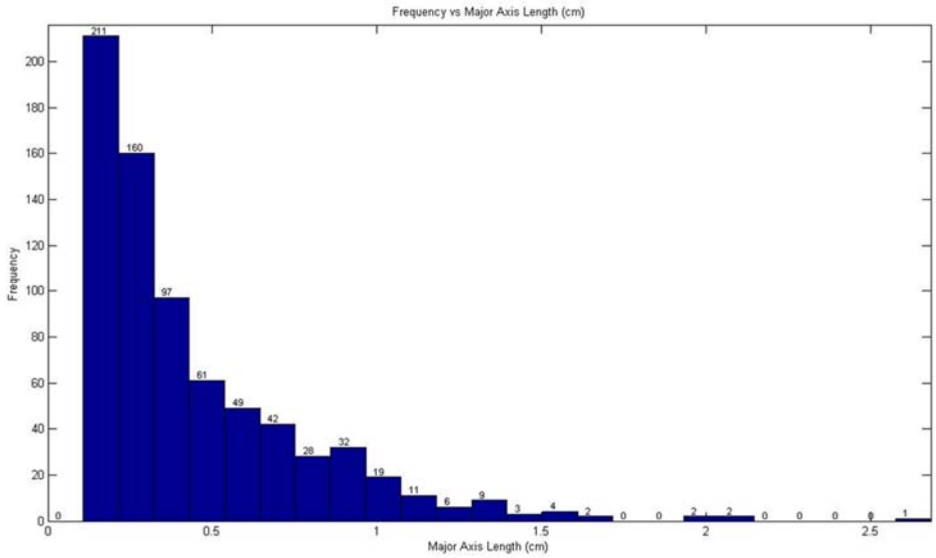

Figure 5. Histogram results from sample 100 taken with the Nikon S6100 (16 Megapixel resolution).

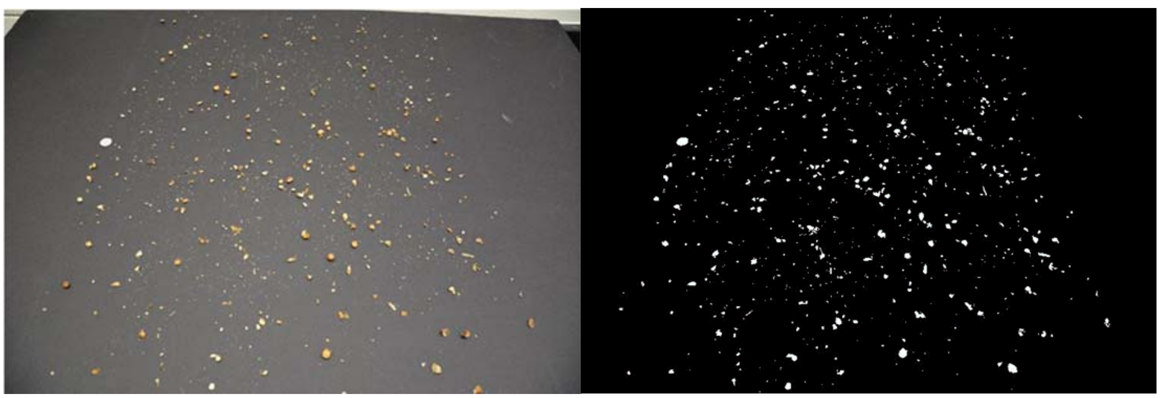

Figure 6. Original image of sample 100 taken with the Nikon DSLR (24.1 Megapixel resolution) (left). Black and white processed image of sample 100 taken with the Nikon DSLR (right).

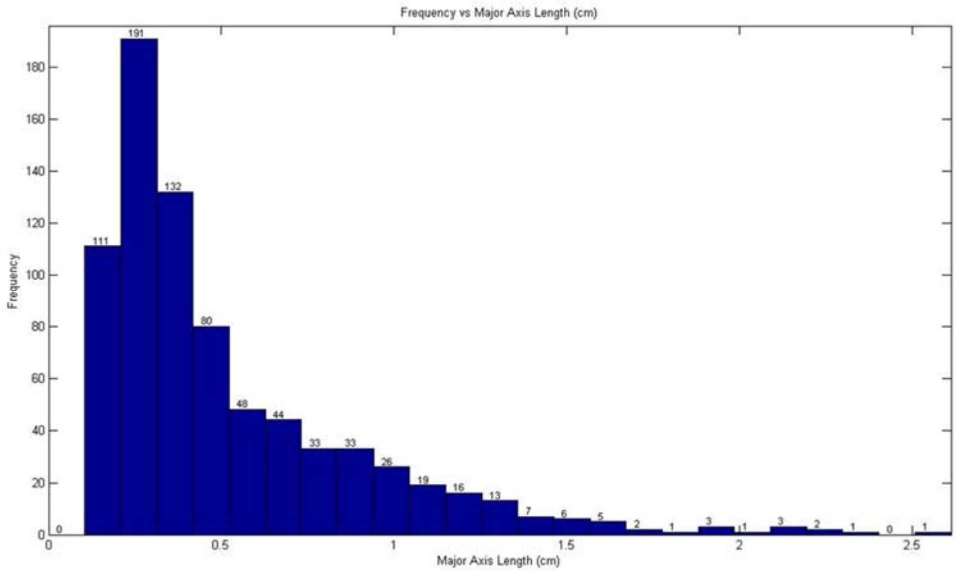

Figure 7. Histogram results from sample 100 taken with the Nikon DSLR (24.1 Megapixel resolution).

It is obvious in viewing Figures 3, 5, and 7 that a slightly different particle size distribution resulted from each camera even though the subject of the image was the same. This can be attributed to the determination of the minimum particle size allowable within the image, i.e. the initial threshold to remove artifacts. The threshold was set using the image from the smart phone to remove objects that should not be counted and then adjusted at higher resolutions to maintain a uniform particle count within the image. The particle count could not always be set to exactly equal with the current implementation of the code, thus distributions varied slightly. Also, bin sizes for the histograms were set to be a constant 25 bins with centers being determined by the largest particle within the image. Further refinement of the particle size distribution script would allow for a threshold algorithm that would maintain equal number of particles between images and relate the bin size directly to that of the Ro-Tap sieves used in KPS determination.

Initial comparison of corn silage processing score (CSPS), performed by Dr. Shaver's lab, to the percentage of the sample smaller than 4.75 mm determined via image analysis showed that the two methods were not well correlated. Results from linear regression showed a coefficient of determination (R^2) value of 0.07 which indicated that 93% of the variability within the data was not accounted for by the linear model. Upon further investigation, there is a difference between CSPS and the percentage of particles smaller than a certain sieve size, in this case a number 4. Figure 8 shows the regression results of the percentage of the sample smaller than 4.75 mm as determined by image analysis vs. Ro-Tap sieving methods. The coefficient of determination, in this case, is 0.55 indicating that 55% of the variability in the data was accounted for by the linear model. While this is not a stunning result, it is more promising than the earlier comparison to the CSPS. A contributor to this variability is that only three sub-samples are being analyzed from each 600 ml survey sample. Determination of the number of sub-samples required to characterize an entire sample would most likely improve this correlation.

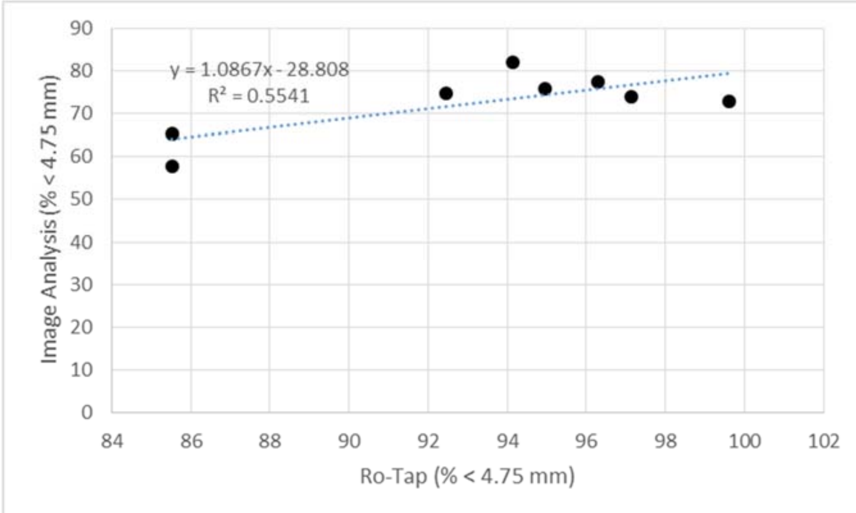

Figure 8. Linear regression results comparing the percent of the sample smaller than 4.75 mm determined via image analysis and traditional Ro-Tap methods.

Table 1 shows the results of the differing camera resolutions on geometric mean particle size determination. The smart phone and DSLR camera were not found to be statistically different, while the S6100 was statistically different from the smart phone and the DSLR camera. It was noted that the Nikon S6100 was not functioning properly and it was difficult to acquire a picture suitable for processing. With this being an issue with data collection the Nikon S6100 will be excluded from future testing. These results do show, however, that the smart phone camera measured geometric mean particle size equally as well as the more expensive DSLR camera. This indicates that a smart phone application for corn silage particle size distribution determination is possible.

Table 1: Camera resolution comparison results.

Camera Type	**Estimated Geometric Mean Particle Size (cm)**	**Standard Error (cm)**	**Letter Grouping**
Smart Phone (8 MPix)	0.378	0.0196	A
DSLR (24.1 MPix)	0.363	0.0196	A
Nikon S6100 (16 MPix)	0.303	0.0196	B

Note: All letter groupings found were significant at confidence level of 95% (P-value < 0.05).

Conclusions:

Results from this study show that image analysis is a viable method for determining particle size distribution of processed corn kernels in corn silage samples. Histogram plots showing the particle size distribution, the percentage of particles smaller than 4.75 mm, and geometric mean particle size were determined from images of 10 g sub-samples. The percentage of particles smaller than 4.75 mm determined by image processing was linearly related to the percentage of particles smaller than 4.75 mm determined by sieving methods with a coefficient of determination of 55%. Comparison of geometric mean particle size across varying camera resolutions showed that the smart phone and the DSLR camera were not statistically different at a 95% confidence level. This result indicates a smart phone application for particle size distribution determination is possible.

Future Work:

This work has the potential to provide producers and custom operators with a more accurate method for checking the kernel processor roller settings during harvest, which will maintain or improve corn silage quality. Several refinements should occur before this is possible:

- Determination of the number of sub-samples required to fully characterize the particle size distribution in a 600 ml sample of whole plant corn silage.
- Refinement of the thresholding process of the image analysis for more consistent distribution results between camera resolutions.
- Analysis of more samples in conjunction with KPS analysis to determine the percentage of particles smaller than 4.75 mm that correlates to an adequate processing level.
- Assessment of wet corn silage samples, simulating analysis in-field at the time of harvest and calibration to adequate processing cut-off levels.
- Conversion of final MATLAB code to a smart phone application for public distribution.

Acknowledgements:

Funding for this study was provided by the Midwest Forage Research Program of the Midwest Forage Association.

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Keywords:

Corn Silage, Kernel Processing Score, Image Analysis, Particle Size Distribution