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SUMMARY

In this paper, we describe ongoing efforts to solve challenges to using straw for bioenergy and bioproducts. Among these, silica in straw forms a low-melting eutectic with potassium, causing slag deposits, and chlorides cause corrosion beneath the deposits. Straw consists principally of stems, leaves, sheaths, nodes, awns, and chaff. Leaves and sheaths are higher in silica, while chaff, leaves and nodes are the primary source of fines. Our approach to reducing silica is to selectively harvest the straw stems using an in-field physical separation, leaving the remaining components in the field to build soil organic matter and contribute soil nutrients.

KEYWORDS: Wheat straw, silica, selective harvest, bioenergy, combustion, whole crop utilization

INTRODUCTION

On August 12, 1999, President Clinton issued an Executive Order to stimulate the creation and early adoption of technologies needed to make biobased products and bioenergy cost-competitive in large national and international markets. The Order recognized that these technologies can not only create new markets for farm and forest waste products, but also have the potential to reduce our Nation's dependence on foreign oil and improve air and water quality.

Agricultural crop residues are a valuable renewable resource from which to produce biobased products. In 1999, American farmers harvested 53,909,000 acres of wheat *(1)*. The straw from this acreage of wheat represents over 100 million tons annually. Currently, some of the straw is harvested (baled) for use as livestock bedding or low-grade animal feed. However, these low-grade uses provide only a minimal return. Nationally only about 3.2% of the economic return on wheat is from straw *(1)*. Producers, including the National Association of Wheat Growers and the Idaho Wheat Commission, have long recognized the potential economic and environmental benefits in producing bioenergy and bioproducts from excess wheat straw residue.

In the recent National Research Council Report *(2)* on research priorities for biobased industrial products, development of "equipment and methods to harvest, store, and fractionate biomass for subsequent conversion processes" is listed as a key research priority. Another prominent theme of the report is development of technologies for the effective and economic utilization of lignocellulosic biomass, particularly waste sources such as crop residues.

To completely utilize all biomass, it must be recognized that not all parts of the crop residue are equally valuable. Just as a flourmill only wants the grain delivered, biofuels and chemical processors only want the high yielding cellulose and hemicellulose biomass components delivered. The cellulose rich vascular tissues of crop stems contain the greatest amount of sugars for digestion and conversion to biofuels and chemicals (Figure 1). The formerly physiologically active tissues of leaves, sheaths and awns are heavily impregnated with process fouling minerals, and these tissues also contain higher amounts of other organic components (i.e., protein, lipids, pigments, pectin, organic acids) than the stems. The more complex molecular components of these non-stem tissues are more valuable if directed to other applications (i.e., cattle feed, left in the field as a soil amendment, direct extraction of specifically engineered and/or naturally occurring chemicals). Thus, for cost-efficient utilization of straw and other crop residues, the undesirable components must be removed.

However, the current paradigm for straw utilization includes the necessity to transport all the components of the straw to the point of utilization; there is no cost-efficient way to remove the undesirable components before transporting it. This is expensive not only because of the low bulk density of straw, but also because it brings the less valuable components to the manufacturer's gate and creates economic and environmental liabilities. We describe a strategy for reducing the amount of undesirable residue components shipped to centralized biorefineries. This strategy varies somewhat depending on the end use, but generally consists of an in-field physical fractionation that reduces silica content. Additional distributed processing steps such as limited fungal degradation of the straw in windrows to improve its digestibility are also described.

MATERIALS AND METHODS

Wheat straw. Four varieties of wheat straw were selected for use in this study. The varieties selected and sources included: (1) Stephens – soft white winter, produced in Rupert, ID; (2) Boundary – hard red winter, produced in Monteview, ID; (3) Whitebird – soft white spring, produced in Idaho Falls, ID; and (4) Westbred 936 – hard red spring, produced in Rupert, ID. These varieties were selected from an Idaho Wheat Commission list of the most popular existing and new wheat varieties developed for the intermountain and Pacific Northwest wheat growing regions. The varieties produced by and available from collaborating growers determined the four varieties that were finally selected for this work. Grant 4-D Farms produced and baled large quantities of Westbred 936; this variety was used for all the large-scale separation and bioprocessing studies.

All straw utilized in the studies was produced during the year 2000 cropping season. Twenty large bales of Westbred 936 (1.2 m × 2.4 m bales (4 ft × 8 ft)) were produced and stored in a stack at the side of the field at Grant 4-D Farms, and only the protected center bales were used for the studies. Six 0.61 m × 1.2 m (2 ft × 4 ft) straw bales of Stephens, Boundary, and Whitebird straw were also collected. Additional Boundary straw was collected in 1.2 m × 2.4 m (4 ft × 8 ft) bales. To better handle the straw for the laboratory studies, these large bales were rebaled into smaller 0.61 m × 1.2 m (2 ft × 4 ft) bales containing about 22.7 kg (50 lb) each. The small bales of all varieties were stored in covered storage.

Analytical methods. Wheat straw compositions were measured by acid hydrolysis using the Quantitative Saccharification Technique *(3)*. Carbohydrate concentrations in hydrolysates were measured by high performance liquid chromatography (HPLC) using a BioRad HPX-87P column with distilled water as eluent, as previously described *(4)*. Ash compositions were determined by ashing the straw samples to constant weight at 650 °C for 18-24 hours in a muffle furnace. Silicon, potassium and chlorine content of the ashed samples were determined by Energy Dispersive Spectrometry (EDS) *(5)*, at 10-20 KeV using a Phillips XL30ESEM. In the method, the ashed straw was placed in a thin film on double-sided tape onto a carbon-coated aluminum disk. The disk is carbon-coated to prevent charging. For each measurement, a region of the surface was scanned for 5-10 minutes. Two regions of the disk were scanned to verify homogeneity of the sample. Standards were prepared by weighing, grinding, mixing and ashing reagent grade silicates, oxides and chlorides. These were mounted on the double-sided tape and mounted on the disks, and counted under the same conditions as the straw ash. Calibration curves were prepared and used to adjust the values from the internal quantitative program on the EDS system for matrix effects. Wet methods and Wavelength Dispersive Spectrometry were used to verify the results.

Partitioning of wheat straw biomass using plot harvesting equipment. The first phase of the research on the mechanical separation was conducted to determine whether the higher value wheat straw components (the stems) could be mechanically separated from the rest of the material using preexisting plot harvesting equipment. Several small bales of wheat straw were threshed and separated at the University of Idaho experiment station in Aberdeen, ID, using their small plot harvesting equipment. The equipment used for the tests is shown in Figure 2, and included a stationary tined-cylinder thresher (on the left in the foreground) and a small plot combine harvester (on the right in the back). Each machine was initially tested separately, while adjusting airflow and cylinder speeds to separate the straw stems from the remaining fractions. Neither machine alone adequately separated the stems from the other material.

Using this equipment, the most effective separation method for separation of the bulk of the stem fraction from the nodes (without optimization for stem yield) was to first pass the straw through the tined-cylinder thresher. The aggressive threshing action of the tines (see Figure 3) broke the stems near the nodes, and the more dense nodes exited through the airflow separation and out the grain discharge. Separated nodes are shown in Figure 4. Each fragment in Figure 4 also contains a residual stem segment on either side as a result of the stem breaking at a small distance from the node. Although this reduces stem yield, the purpose of these tests was to test in-field methods for separating the stems. In the eventual system chosen, the separation will be optimized for maximum yield of stem recovery.

The remaining straw fractions were discharged from the rear of the tined-cylinder thresher onto the ground, after internal airflow separation. This pile, comprised primarily of stems and chaff, was collected and fed into the plot combine harvester. The plot combine harvester further separated the stems from the chaff, and the material that exited off the straw walkers was primarily the desired straw stems. Nearly all of the remaining straw material was discharged from the sieves just below the straw walkers. As discussed earlier, in order to be economically feasible, this separation must be done on a single pass across the field through the crop being harvested.

RESULTS AND DISCUSSION

Straw and ash compositions. The compositions of three of the wheat variety straws utilized were measured by the Quantitative Saccharification method and are shown in Table 1. These compositions are typical for wheat straw, although the Westbred 936 variety had a higher ash content due to a significantly higher potassium concentration than the other two varieties. Estimated compositions of the plant polymer and ash fractions are shown in Table 2. The ash content was estimated using the Energy Dispersive Spectrometry capabilities on a Scanning Electron Microscope.

Field-scale partitioning of wheat straw biomass. Samples of Westbred 936 wheat straw were perfectly separated by hand to provide a "best separation" target, and also by machine using the plot-harvesting equipment. All fractions were then analyzed for ash content, shown in Figure 5. The elemental composition of each ash sample, including silicon (Si), potassium (K) and chlorine (Cl) contents, was then estimated using Scanning Electron Microscope with Electron Dispersive Spectrometry SEM-EDS. The silica contents of the perfectly separated fractions are shown in Figure 6. The ash content of the whole straw used in the perfect hand separations was 9.0 wt%, of which 24% was silica, giving 2.2% silica in the whole straw. The ash content of the perfectly separated stems was 6.1 wt%, of which 20% was silica, and thus the silica content of the perfectly separated stems was 1.2 wt%. Therefore perfect separation reduced ash content by 32% and silica content by 45%. This is the benchmark to which the mechanical separation was compared.

The mechanical separation was performed on straw from a different field / bale, resulting in slightly different ash and silica contents in the whole straw. The ash content of the whole straw used in the mechanical separations was 11.2 wt%, of which 12% was silica, giving 1.3% silica in the whole straw. The ash content of the mechanically separated stems was 8.8 wt%, of which 8.3% was silica, and thus the silica content of the mechanically separated stems was 0.73 wt%. Thus, the mechanical separation reduced ash content by 23% and silica content by 44%. In the mechanical separation, the straw is separated into two fractions, which we classify as "stem" and "chaff" (Figure 7). The results of these tests are very positive and show that our mechanical separation process is capable of reducing the silica content of the straw by selectively harvesting predominantly straw stems.

CONCLUSIONS

Mechanical separations of wheat straw stems using plot harvesting equipment were as good as perfect fractionation of stems by hand. These results indicate that existing harvesting equipment can be modified to do this fractionation if proper adjustments are made to the equipment settings. Mechanical separation of the stems reduced the ash content of the harvested fraction by 20% and the silica content by 44%.

ACKNOWLEDGEMENTS

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TABLES

Table 1: Compositions of straw stems of several wheat varieties utilized in this study.

	Wt% of Component for various varieties		
Component	Westbred 936	Boundary	Stephens
<u>Carbohydrates</u>			
Glucan	40.6	40.4	39.3
Xylan	25.2	25.8	25.1
Galactan	0.4	0.4	0.4
Mannan	2.5	3.2	2.7
Arabinan	nd[a]	nd[a]	nd[a]
Lignin[b]	14.5	18.1	17.8
Ash	9.0	4.1	5.4
% Recovery[d]	92.2	92.0	90.7

a nd = None detected

b Lignin with extractives

c Difference from 100% due to unknown uronic acid content and to recovery errors in the procedure.

Table 2: Compositions of straw stem ash from the several wheat varieties utilized in this study.

	Wt% of Component for various varieties		
Component	Westbred 936	Boundary	Stephens
Cellulose[a]	40.6	40.4	39.3
Hemicellulose[b]	28.1	29.4	28.2
Lignin[c]	14.5	18.1	17.8
Ash	9.0	4.1	5.4
SiO_2	2.3	2.8	3.2
K	3.5	0.3	0.2
Cl	2.3	0.020	< 0.020
Other	0.9	1.0	2.0
% Recovery[d]	92.2	92.0	90.7

a Cellulose estimated as total glucan

b Hemicellulose estimated as sum of xylan, galactan, mannan, and arabinan

b Lignin with extractives

d Difference from 100% due to unknown uronic acid content and to recovery errors in the procedure.

FIGURE LEGENDS

Figure 1: Simplified anatomical structure of a wheat plant ready for harvest, which needs to be fractionated into the grain (food), stem (bioenergy) and remaining residue (returned to field).

Figure 2. University of Idaho plot harvesting machinery used for the mechanical separation.

Figure 3. The cylinder and concave tines of the tined-cylinder thresher, visible through the open cover.

Figure 4. Nodes separated from the stems using the tined-cylinder thresher.

Figure 5. Distribution of ash in hand-separated straw fractions of Westbred 936. Each bar represents wt% ash for each respective fraction.

Figure 6. Distribution of silica in hand-separated straw fractions of Westbred 936. Each bar represents wt% silica for each respective fraction.

Figure 7. Silica reduction achieved for Westbred 936 using the plot-harvesting equipment.

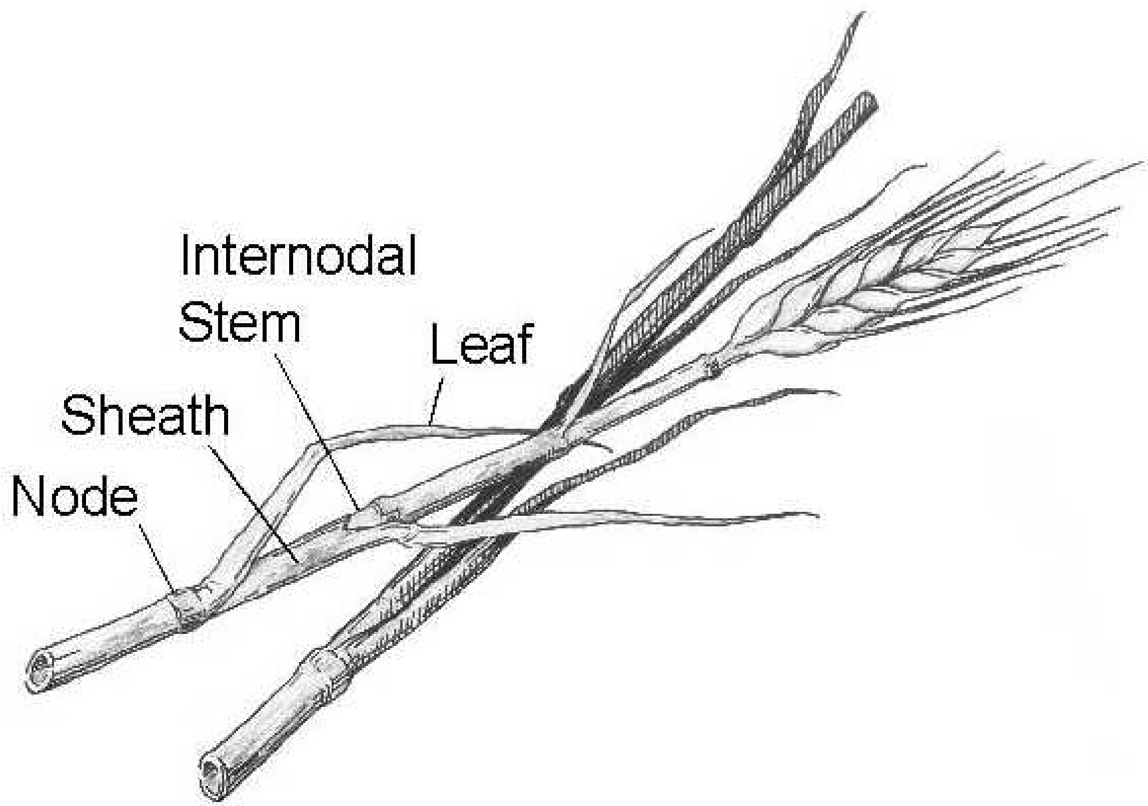

FIGURE 1 – Hess, Thompson, Hoskinson, Shaw, and Grant

FIGURE 2 – Hess, Thompson, Hoskinson, Shaw, and Grant

FIGURE 3 – Hess, Thompson, Hoskinson, Shaw, and Grant

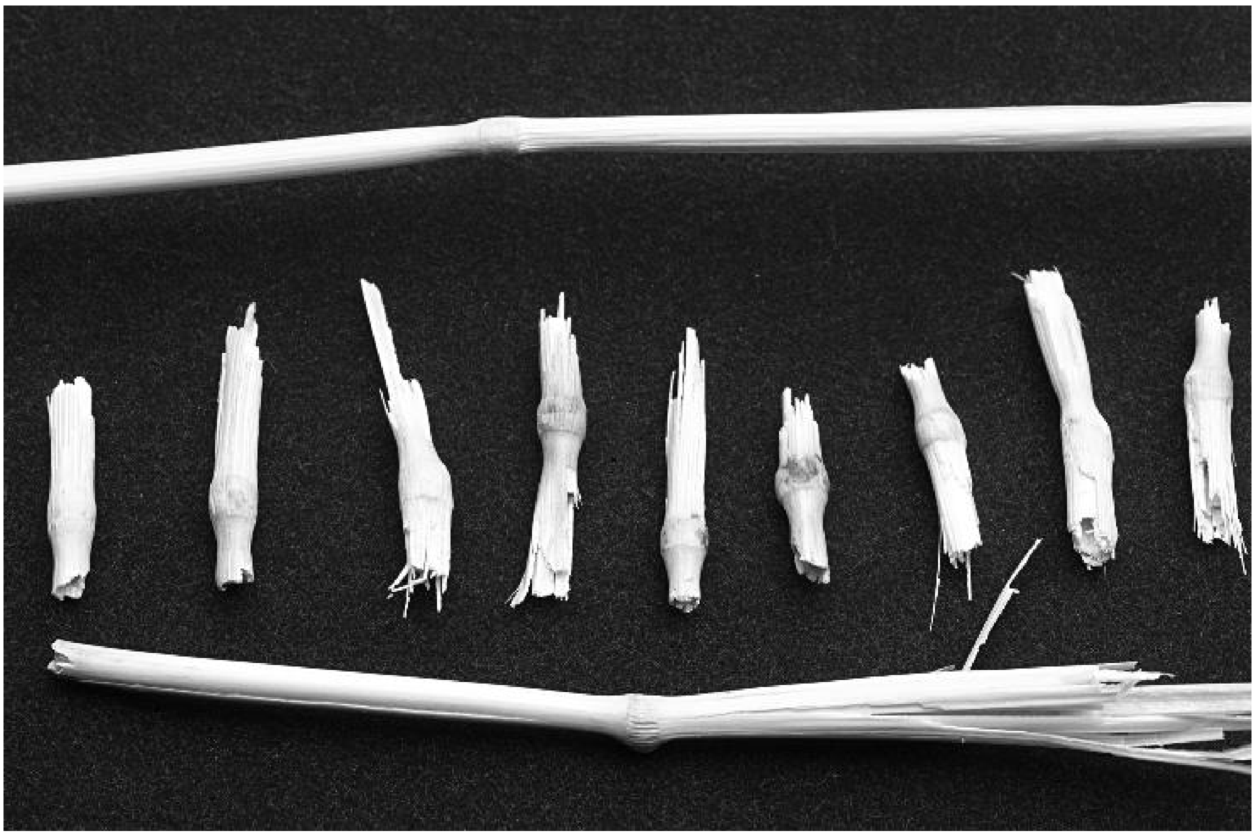

FIGURE 4 – Hess, Thompson, Hoskinson, Shaw, and Grant

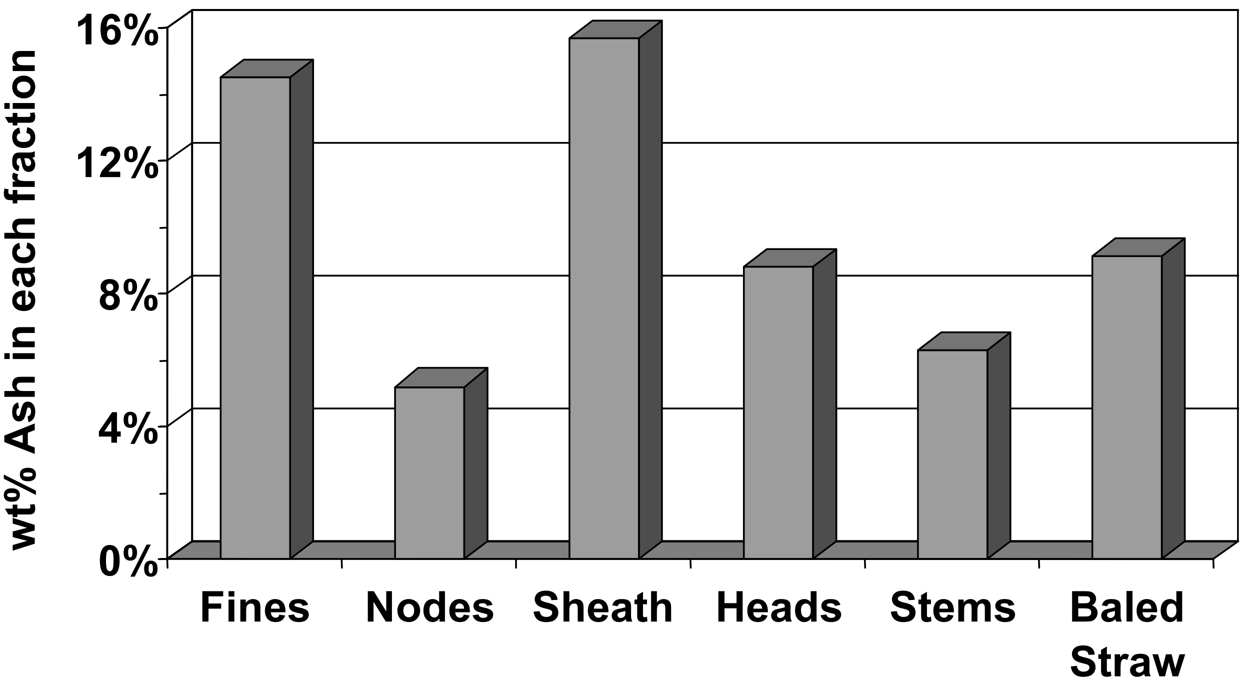

FIGURE 5 – Hess, Thompson, Hoskinson, Shaw, and Grant

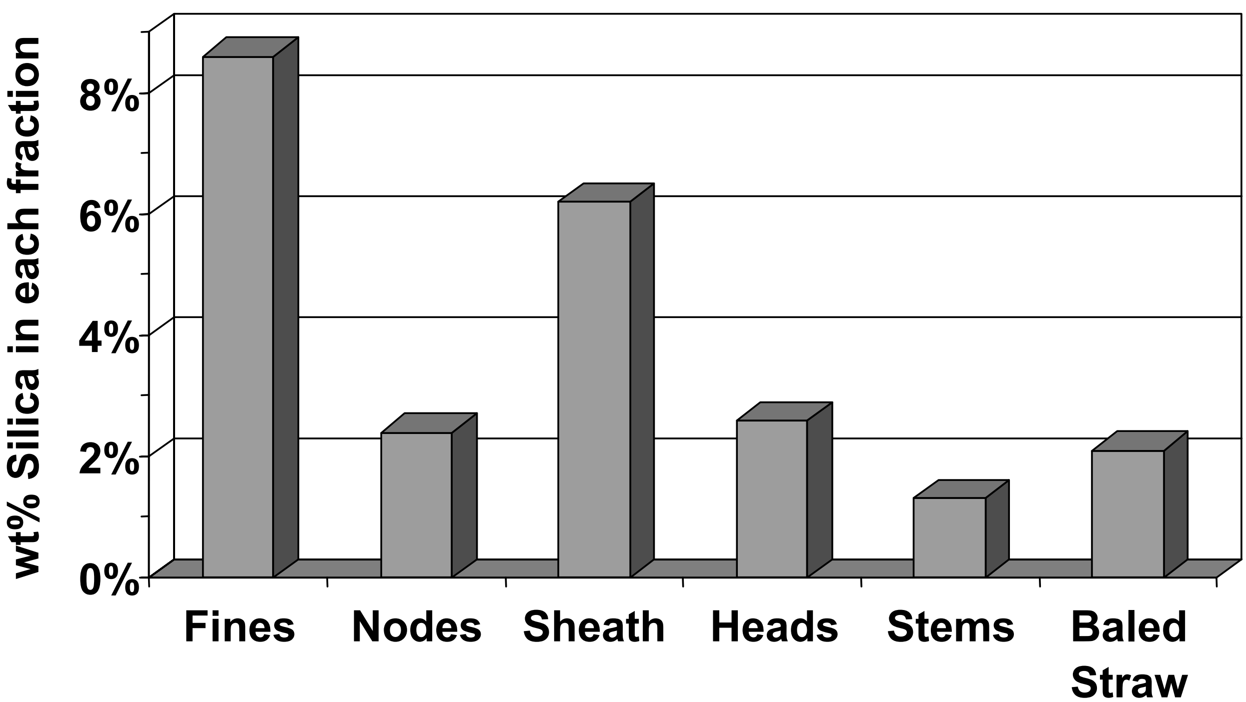

FIGURE 6 – Hess, Thompson, Hoskinson, Shaw, and Grant

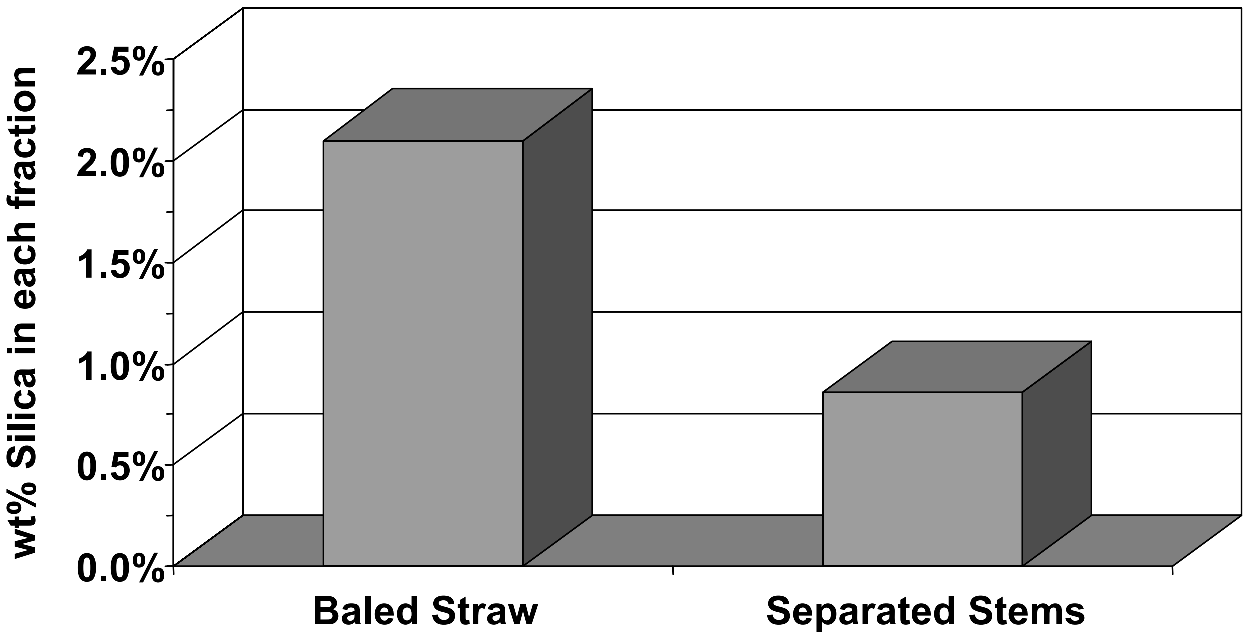

FIGURE 7 – Hess, Thompson, Hoskinson, Shaw, and Grant