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An ASABE Meeting Presentation

Paper Number: 084085

LOOSE-FILLED AND TAPPED DENSITIES OF CHOPPED SWITCHGRASS, CORN STOVER AND WHEAT STRAW

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Written for presentation at the
2008 ASABE Annual International Meeting
Sponsored by ASABE
Rhode Island Convention Center
Providence, Rhode Island
June 29 – July 2, 2008

Abstract. *Bulk density is one of the important engineering property of biomass having significant impact on the supply logistics and processing in ethanol production facilities using lignocellulosic materials. Bulk density of most of the comminuted biomass significantly increased by tapping. Switchgrass, wheat straw and corn stover were chopped in a knife mill at different operating conditions including four different screens having 50, 25, 19, 12 mm diameter. Mean loose-filled bulk densities were 67.5 ± 18.4 kg/m^3 for switchgrass, 36.1 ± 8.6 kg/m^3 for wheat straw, and 52.1± 10.8 kg/m^3 for corn stover. Mean tapped bulk densities were 81.8 ± 26.2 kg/m^3 for switchgrass, 42.8 ± 11.7 kg/m^3 for wheat straw, and 58.9 ± 13.4 kg/m^3 for corn stover. The maximum volume reduction ratio observed for switchgrass, wheat straw and corn stover was 0.159, 0.165, and 0.154, respectively for fine-chopped samples and 0.107, 0.117, and 0.098, respectively for coarse-chopped samples. By tapping, the infinite compressibility was highest for chopped switchgrass followed by chopped wheat straw and corn stover as indicated by the 'a' values in Sone's model. Degree of difficulty in packing was minimum for chopped wheat straw followed by chopped switchgrass and corn stover. This indicated that the chopped wheat straw particle compacts very rapidly by tapping compared to chopped switchgrass and corn stover. Hausner ratio, a measure of internal friction, determined after 50 taps ranged from 1.114 to 1.321 for chopped switchgrass, 1.105 to 1.309 for chopped wheat straw and 1.060 to 1.239 for chopped corn stover.*

Keywords. *Switchgrass, wheat straw, corn stover, bulk density, tapped bulk density.*

Introduction

In the present world economy, much importance is placed on the production of energy from biomass. Energy production from biomass has increased sustainability and environmental benefits (Knauf and Moniruzzaman, 2004; Sokhansanj et al. 2006). Biomass sources include forestry residues, purpose grown agricultural crops, organic, agricultural, agro-industrial and domestic wastes (Demirdbas, 2001). Among the agricultural sources, switchgrass, corn stover, and wheat straw have potential to be used as raw material for biorefineries.

Raw material supply logistic problems for biorefineries include material handling, size reduction, drying, and storage systems (Wright et al. 2006). Biomass size reduction is an important unit operation in which biomass with varying physical characteristics are comminutioned to a product with reduced particle size for thermochemical or biochemical methods. A knife mill is traditionally used for chopping forages and agricultural crop residues. Biomass with long, rigid stems such as corn stover, as well as thin, flexible stems like switchgrass and wheat straw can be chopped in a knife mill. Subsequent size reduction operations in a hammer mill and/or disc mill can further reduce particles as well as powders.

Some of the important characteristics of biomass that have significance in relation to efficient handling operations in a biorefinery are variability in physical and chemical characteristics, and spoilage due to moisture content (Sokhansanj et al. 2003). Bulk density is a physical characteristic that depends on particle size distribution, moisture content, and product processing history (Barletta et al. 1993). Bulk density affects functional properties such as compressibility and flowability.

Bulk density of comminuted biomass was less than 300 kg/m^3 (Lam et al. 2007). Low density combined with high compressibility of the biomass led to poor flowability (Fasina, 2006). Hence the compaction behavior of biomass is very important for flowability and transport related issues. The compaction behavior of non-food powders under compression and vibratory conditions were studied using various models (Kawakita and Ludde, 1971; Tabil and Sokhansanj, 1997; Adapa et al., 2005). Mani et al. (2004a) studied the compaction behavior of biomass under compression using the models developed by Cooper and Eaton (1962) and Kawakita and Ludde (1971). Even though the compaction behavior under vibration and tapping of metallic and pharmaceutical powders were studied using various models, the model developed by Sone (1969) performed well for biomaterials (Peleg and Bagley, 1983). Sone's model was tested in biomaterials for understanding the behavior for proper filling of containers for packaging purposes (Kaletunc and Breslauer, 2003). However, in biorefineries, large quantities of biomass may need to be processed in different process lines subjected to vibrations and various flow conditions (Fayed and Otten, 1984).

The objectives of this study were: 1. To determine the effect of particle size on the densities of biomass chopped in a knife mill, and 2. To evaluate the compaction behavior of chopped biomass subjected to tapping.

Methods and Materials

Raw material

Switchgrass, wheat straw and corn stover were chopped in a knife mill at different rotational speed, feed rate, and screen sizes. Screen opening diameters of 50, 25, 19 and 12 mm were used. The chopped biomass had varying particle size and distribution and were used as raw material for experiments.

Particle size

Particle size was classified using ASAE S424.1-specified screens (ASAE, 2004). The mass fractions retained on the screens having diagonal opening dimensions of 1.65 mm, 5.61 mm, 8.98 mm, 18.0 mm, 26.9 mm, and pan were used to determine the geometric mean length (X_{gm}) and standard deviation (S_{gm}).

Loose-filled bulk density

The loose filled bulk density was measured using a cylindrical aluminum container with 149 mm diameter and 143 mm height. Biomass was filled in layers with approximately 1 cm thickness, and care was taken to avoid any unfilled spaces due to entangling of biomass particles. The mass of biomass in the container was determined using an electronic balance (± 0.01 g). The loose filled bulk density in kg/m^3 was determined as:

$$Loose\ filled\ bulk\ density\ (\rho_L) = \frac{Mass\ of\ the\ biomass}{Volume\ of\ the\ biomass} \tag{1}$$

All the loose filled bulk density measurements were made in triplicate.

Tapped bulk density

The container with biomass was tapped on a wooden platform 50 times with an approximate amplitude of 20 mm. The reduction in height of the top biomass surface was measured using a vernier caliper (± 0.01 mm). The settled distance was measured at a total of nine locations. Four locations were near the inside wall of container. Another four were at 50% of radius. One measure was taken at the center of the container. The reduction in volume of biomass was calculated as an imaginary cylindrical volume having diameter of the container and height of average settled distance. The tapped bulk density was calculated as

$$Tapped\ bulk\ density\ (\rho_T) = \frac{Mass\ of\ the\ biomass}{Cylinder\ volume - settled\ volume\ reduction} \tag{2}$$

All the tapped bulk density measurements were made in triplicate.

Compaction behavior

The compaction behavior of switchgrass, wheat straw and corn stover under tapping was studied using the model developed by Sone (1972) for biomaterials. Two samples of chopped switchgrass having X_{gm} of 3.30 mm and 14.06 mm, two samples of chopped wheat straw having X_{gm} of 3.69 and 10.68 mm and two samples of chopped corn stover having X_{gm} of 3.22 and 12.79 mm were selected as contrasting values for modeling. For comparison purpose, similar particle size distributions in switchgrass, wheat straw and corn stover were deliberately selected. The three coarse samples were chopped using similar operating conditions with 50 mm classifying screen in the knife mill whereas the three finer samples were chopped using 12 mm classifying screen in the knife mill with similar operating conditions. The chopped biomass samples were filled in to the aluminum cylinder used for the determination of the density. Reduction in volume was recorded for every 5 taps. Measurements were made in triplicate for all the samples. Volume reduction ratio (γ_n) and number of tapping (n) data were used for modeling. The relationship between the volume reduction ratio and the number of tappings is given by

$$\gamma_n = \frac{(V_0 - V_n)}{V_0} = \frac{abn}{1+bn} \quad (3)$$

Where ‘V_0’ is the initial volume, ‘V_n’ is the volume after n taps, and ‘a’ and ‘b’ are constants. The value of constants ‘a’ and ‘b’ were determined as explained by Peleg and Bagley (1983). The equation can be rewritten in the linear form

$$\frac{n}{\gamma_n} = \frac{1}{ab} + \frac{n}{a} \quad (4)$$

The slope and intercept values of the linear relationship between ‘(n/γ_n)’ Vs ‘n’ values were used to determine the values of ‘a’ and ‘b’.

Hausner ratio

During modeling studies, no reduction was observed in volume after 50 taps for all three chopped biomass materials studied in our experiments. Hausner ratio (Grey and Beddow, 1969; Kaletunc and Breslauer, 2003) was determined as:

$$Hausner\ ratio = \frac{Tapped\ bulk\ density\,(\rho_L)}{Loose\ filled\ bulk\ density\,(\rho_T)} \quad (5)$$

Results and Discussion

Compaction characteristics

The relationship between the volume reduction ratio and the number of taps is given in Figure 1. All three biomass materials had reached the maximum volume reduction ratio by 50 taps. Highest volume reduction ratio was observed for chopped wheat straw followed by chopped switchgrass and chopped corn stover. The maximum volume reduction ratios observed for finely chopped switchgrass, wheat straw and corn stover were 0.159, 0.165, and 0.154, respectively. The maximum volume reduction ratios observed for coarsely chopped switchgrass, wheat straw and corn stover were 0.107, 0.117, and 0.098, respectively. The difference in volume reduction ratio between three chopped biomass particles may be due to difference in shape, strength, particle density and surface roughness properties. The ground corn stover contained lot of fiber-like particles (from rind) in addition to other irregular shaped particles (from pith) and affected the compaction characteristics.

The linear relationship between ‘n’ and ‘n/γ_n’ for chopped switchgrass, wheat straw and corn stover is shown in Figure 2. In the Sone’s model, ‘a’ value represents infinite compressibility by tapping, and ‘b’ value represents the degree of difficulty of tapping (Sone, 1969). In our experiments, we observed, ‘a’ values of the fine chopped particles was significantly higher than the coarse chopped biomass particles, indicating that the infinite compressibility was higher for fine chopped biomass particles. Infinite compressibility was highest for chopped switchgrass indicated by the ‘a’ values followed by wheat straw and corn stover (Table 1). We observed that ‘b’ values of all the fine chopped biomass were less than the coarse chopped biomass (Table 1). This indicated that as the particle size decreased, the samples compacted easily leading to rapid increase in bulk density by tapping. In the same way, the difficulty in packing/compacting by tapping of corn stover was highest followed by switchgrass and wheat straw indicated by the ‘b’ values (Table 1).

Loose filled bulk density

Loose filled bulk density of chopped switchgrass was found to be highest followed by chopped corn stover and wheat straw in a knife mill. Loose filled bulk density of chopped switchgrass ranged from 41.49 to 105.18 kg/m^3 for samples having X_{gm} of 12.12 to 2.65 mm (Table 2). Loose filled bulk density of chopped wheat straw ranged from 22.67 to 52.21 kg/m^3 for samples having X_{gm} of 12.27 to 3.19 mm (Table 3). Loose filled bulk density of chopped corn stover ranged from 33.23 to 69.05 kg/m^3 for samples having X_{gm} of 14.89 mm to 3.22 mm (Table 4). Loose filled bulk density of chopped switchgrass and chopped corn stover having X_{gm} of 3.2 ± 0.2 mm was 108.0 % and 38.6 % higher than chopped wheat straw. In the same way loose filled bulk density of chopped wheat straw and chopped corn stover having X_{gm} of 12.3 ± 0.5 mm was 80.6 % and 35.1 % higher than loose filled bulk density of chopped wheat straw. As the particle size increased, loose filled bulk density of the biomass decreased. Mani et al. (2004c) also observed the same trend during grinding studies on wheat straw, switchgrass and barley straw in a hammer mill. This was expected because, as the particle sizes increased, pore spaces formed between the irregularly arranged particles increased. The loose-filled bulk densities (kg/m^3) of the chopped switchgrass (BD_{SG}), corn stover (BD_{CS}), wheat straw (BD_{WS}) as a function of the geometric mean length (X_{gm}, mm) were as follows:

$$BD_{SG} = 103.37 - 4.670 * X_{gm} \qquad (R^2=0.80) \qquad (6)$$

$$BD_{WS} = 55.244 - 2.79 * X_{gm} \qquad (R^2=0.87) \qquad (7)$$

$$BD_{CS} = 74.305 - 2.643 * X_{gm} \qquad (R^2=0.74) \qquad (8)$$

R^2 values indicated that the loose-filled bulk density measurement is a very good indicator of particle size and vice versa. Both intercept and slope values were found to be maximum for switchgrass. Increased slope value for switchgrass indicated that loose-filled bulk density decreased as the particle size increased, to a greater degree than other tested biomass.

Tapped bulk density

Tapped bulk density was highest for chopped switchgrass followed by chopped corn stover and wheat straw. Tapped bulk density of the chopped switchgrass ranged from 47.10 to 136.86 kg/m^3 for samples having X_{gm} of 14.06 to 2.65 mm (Table 2). Tapped bulk density of chopped wheat straw ranged from 25.01 to 65.49 kg/m^3 for samples having X_{gm} of 12.27 to 3.19 mm (Table 3). Tapped bulk density of chopped corn stover ranged from 37.17 to 85.55 kg/m^3 for samples having 14.89 to 3.22 mm (Table 4). Tapped bulk density of chopped switchgrass and chopped corn stover having X_{gm} of 3.2 ± 0.2 mm was 120.6 % and 38.6 % higher than tapped bulk density of chopped wheat straw. In the same way the tapped bulk density of chopped switchgrass and chopped corn stover having X_{gm} of 12.3 ± 0.5 mm was 80.6 % and 28.6 % higher than chopped wheat straw having similar geometric mean particle length. The geometric mean length (X_{gm}, mm) predicted the tapped bulk density (kg/m^3) of the ground switchgrass (TBD_{SG}) with the following linear regression equation:

$$TBD_{SG} = 132.58 - 6.60 * X_{gm} \qquad (R^2=0.79) \qquad (9)$$

The linear regression models for the prediction of tapped bulk density of chopped switchgrass (TBD_{CS}) and tapped bulk density of chopped wheat straw (TBD_{WS}) using geometric mean length for corn stover and wheat straw were as follows:

$$TBD_{WS} = 69.100 - 3.81 * X_{gm} \qquad (R^2=0.87) \qquad (10)$$

$$TBD_{CS} = 86.364 - 3.27 * X_{gm} \qquad (R_2=0.74) \qquad (11)$$

The intercept and slope values of the regression models to predict the tapped bulk density using geometric mean length was always higher than the corresponding intercept and slope values of the regression models to predict the loose filled bulk density. The difference between the slope value of the regression models to predict the tapped bulk density and loose bulk density using geometric mean length was highest for chopped switchgrass (1.93). The difference was 1.031 for chopped wheat straw and 0.627 for chopped corn stover. Increased difference in slope value of the regression models for loose filled bulk density and tapped bulk density indicated that the increase in bulk density was higher when the X_{gm} was less and the increase in bulk density was less when the X_{gm} was more during tapping. These variations might be due to variation observed in the infinite compressibility achieved during tapping, variations in particle density and degree of compaction due to variation in size, shape and surface characteristics. The lowest difference was observed for corn stover and this indicated that the increase in density was low and fairly uniform for all the particle size distributions.

Hausner ratio

Hausner ratio of the three chopped biomass in a knife mill, using varying classifying screen sizes from 12.5 mm to 50 mm, ranged from 1.114 to 1.321 for switchgrass, 1.105 to 1.309 for wheat straw and 1.060 to 1.239 for corn stover. For food powders having fairly uniform size, shape and higher bulk density, Hausner ratio of 1.0 to 1.1 is considered to be free flowing, 1.1 to 1.25 is considered to be medium flowing, 1.25 to 1.4 is considered to be difficult flowing and over 1.4 is considered to be very difficult in flowing (Hayes, 1987). Thus, chopped biomass was considered to be not a free flowing material. In general as the particle size increased, the Hausner ratio decreased for all three chopped biomass particles tested in our experiments (Figure 3). The change in Hausner ratio with change in the particle size was maximum for switchgrass followed by wheat straw and corn stover. This indicated that there is greater possibility of affecting the flowability of chopped switchgrass by altering the particle size. Kostelnik and Beddow (1970) found that the Hausner ratio is extremely sensitive to particle shape. In our experiment, the least Hausner ratio with chopped corn stover might be due to particle shape of fibrous rind and non-fibrous pith. The minimum changes in the Hausner ratio as the particle size increase with corn stover indicated that corn stover had the minimum possibility of affecting the flowability by altering the operating conditions and resulting particle size during communition in a knife mill.

Conclusions

Experiments were conducted to determine the compaction characteristics by tapping affecting the density of biomass chopped in a knife mill. Chopped switchgrass had the highest loose filled bulk density and tapped bulk density followed by chopped corn stover and wheat straw. The results also indicated that the chopped switchgrass had the maximum infinite compressibility by tapping followed by wheat straw and corn stover. However, chopped wheat straw settled much rapidly during tapping compared to chopped switchgrass and corn stover. The Hausner ratio indicated that there is greater possibility of affecting the flowability of chopped switchgrass compared to chopped wheat straw and corn stover by altering the particle size in a knife mill. Chopped corn stover had the minimum infinite compressibility, Hausner ratio, and maximum difficulty in packing compared to other chopped switchgrass and wheat straw by varying the particle size in a knife mill.

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Table 1. Coefficients of Sone's model for switchgrass, wheat straw and corn stover*

Sample	a	B
Wheat straw (fine)	0.191[b]	0.090[f]
Wheat straw (Coarse)	0.121[e]	0.128[c]
Switchgrass (fine)	0.195[a]	0.097[e]
Switchgrass (Coarse)	0.140[d]	0.161[b]
Corn Stover (fine)	0.186[c]	0.100[d]
Corn Stover (Coarse)	0.108[f]	0.173[a]

*Values suffixed with different letters in a column were significantly different.

Table 2. Particle size and densities of ground switchgrass in a knife mill*

Treatment No.	X_{gm} (mm)	S_{gm} (mm)	Loose filled bulk density (Kg/m^3)	Tapped bulk density (Kg/m^3)	Hausner ratio
KMSG4	13.50	2.55	42.16^{zab}	47.12^{yz}	1.118
KMSG5	13.18	2.79	47.28^{xy}	53.09^{vw}	1.123
KMSG6	13.59	2.54	44.09^{za}	49.12^{xy}	1.114
KMSG7	12.79	2.55	43.67^{za}	48.93^{x-z}	1.121
KMSG8	12.38	2.50	41.49^{zab}	47.10^{yz}	1.135
KMSG9	14.06	2.64	43.97^{za}	49.30^{xy}	1.121
KMSG10	12.12	2.49	47.84^{x}	54.78^{uv}	1.145
KMSG12	12.32	2.54	45.26^{yz}	51.63^{wx}	1.141
KMSG13	2.65	2.51	105.03^{a}	136.56^{a}	1.300
KMSG14	2.99	2.47	104.60^{a}	136.86^{a}	1.308
KMSG15	3.49	2.69	104.18^{a}	134.10^{ab}	1.296
KMSG16	3.00	2.40	95.99^{d}	126.81^{d}	1.321
KMSG17	3.17	2.65	103.50^{ab}	132.07^{bc}	1.276
KMSG18	3.30	2.52	105.18^{a}	135.68^{a}	1.290
KMSG20	2.77	2.37	101.58^{bc}	131.29^{c}	1.292
KMSG21	7.55	2.80	66.11^{n}	77.25^{m}	1.168
KMSG23	9.35	2.58	59.84^{op}	71.79^{no}	1.200
KMSG24	9.43	2.64	58.10^{p-s}	67.95^{q}	1.169
KMSG25	7.63	2.68	55.79^{s-r}	69.10^{o-q}	1.239
KMSG26	8.50	2.92	61.36^{o}	74.30^{nm}	1.211
KMSG27	8.97	2.65	59.79^{op}	68.91^{o-q}	1.153
KMSG28	6.46	2.81	59.36^{op}	71.11^{op}	1.198
KMSG29	7.81	2.77	58.91^{pq}	69.01^{o-q}	1.171
KMSG30	9.20	2.65	53.49^{v}	62.44^{rs}	1.167
KMSG32	8.77	2.63	58.01^{p-t}	68.20^{pq}	1.176
KMSG33	9.83	2.78	60.04^{op}	71.72^{no}	1.195
KMSG34	8.32	2.52	55.70^{t-v}	64.33^{r}	1.155
KMSG35	11.40	2.91	56.56^{r-u}	64.92^{r}	1.148
KMSG36	9.43	2.71	51.12^{w}	58.08^{t}	1.136
KMSG37	8.39	2.84	50.33^{w}	56.84^{tu}	1.129
KMSG38	9.70	2.76	56.62^{r-u}	68.02^{q}	1.201
KMSG39	8.85	2.57	58.35^{p-r}	68.29^{pq}	1.170
KMSG40	14.69	2.62	55.36^{uv}	64.44^{r}	1.164
KMSG41	11.86	2.62	54.96^{uv}	61.21^{s}	1.114
KMSG42	5.77	2.65	76.41^{ij}	91.69^{g-i}	1.200
KMSG43	5.21	2.57	74.83^{jk}	88.05^{jk}	1.177
KMSG44	4.21	2.77	82.86^{e}	101.69^{e}	1.227
KMSG45	4.20	2.78	80.05^{fg}	98.25^{f}	1.227
KMSG46	5.55	2.66	76.72^{h-j}	94.59^{g}	1.233
KMSG47	5.33	2.69	70.69^{m}	85.51^{k}	1.210
KMSG48	6.29	2.78	68.12^{n}	81.06^{l}	1.910
KMSG49	4.70	2.45	$78.94g^{h}$	92.96^{gh}	1.178
KMSG50	5.34	2.63	74.77^{jk}	90.29^{h-j}	1.208
KMSG51	4.70	2.54	77.38^{hi}	94.47^{g}	1.221
KMSG52	4.45	2.58	74.87^{jk}	89.91^{ij}	1.201
KMSG53	4.45	2.50	81.26^{e-g}	101.78^{e}	1.253
KMSG54	5.04	2.70	73.26^{kl}	94.59^{g}	1.291
KMSG55	5.41	2.66	75.49^{i-k}	94.58^{g}	1.253
KMSG56	4.77	2.76	71.44^{lm}	90.86^{h-j}	1.272
KMSG57	6.24	2.72	72.20^{lm}	88.33^{jk}	1.223

*Mean values suffixed with different letters in a column were significantly different (LSD) at $P<0.05$.

X_{gm} – Geometric mean length. S_{gm} – Standard deviation

Table 3. Particle size and densities of ground wheat straw in a knife mill*

Treatment No.	X_{gm} (mm)	S_{gm} (mm)	Loose filled bulk density (Kg/m^3)	Tapped bulk density (Kg/m^3)	Hausner ratio
KMWS1	10.78	2.72	27.59^{o}	31.05^{q}	1.126
KMWS2	9.25	2.70	31.05^{h}	35.81^{p}	1.153
KMWS3	10.68	2.48	24.33^{p}	27.49^{r}	1.130
KMWS4	10.25	2.63	25.11^{p}	27.78^{r}	1.106
KMWS5	10.10	2.50	24.84^{p}	27.43^{r}	1.104
KMWS6	10.82	2.49	22.67^{q}	25.41^{st}	1.121
KMWS7	11.57	2.42	22.31^{q}	25.01^{r}	1.121
KMWS8	10.65	2.57	25.26^{p}	28.02^{t}	1.109
KMWS9	12.27	2.52	25.06^{p}	27.68^{r}	1.105
KMWS10	11.82	2.55	24.23^{p}	26.90^{rs}	1.110
KMWS11	10.39	2.38	24.57^{p}	26.96^{rs}	1.097
KMWS12	3.38	2.07	48.22^{c}	61.51^{bc}	1.276
KMWS13	3.67	2.18	50.79^{ab}	60.09^{bcd}	1.203
KMWS14	3.17	2.06	52.21^{a}	65.49^{a}	1.254
KMWS15	3.69	2.05	46.57^{d}	60.94^{cd}	1.309
KMWS16	3.35	2.12	50.46^{b}	62.75^{b}	1.244
KMWS17	3.50	2.08	48.12^{c}	59.70^{d}	1.241
KMWS18	5.42	2.27	32.96^{lm}	38.95^{o}	1.182
KMWS19	6.30	2.41	36.17^{ij}	41.58^{lm}	1.150
KMWS20	7.09	2.30	37.53^{hi}	44.91^{ij}	1.197
KMWS21	6.86	2.40	35.50^{jk}	42.18^{klm}	1.188
KMWS22	6.53	2.29	34.95^{kl}	41.56^{lm}	1.206
KMWS23	7.91	2.39	37.41^{hi}	42.88^{kl}	1.146
KMWS24	6.67	2.44	34.28^{kl}	39.67^{no}	1.157
KMWS25	7.77	2.50	37.72^{jk}	42.86^{nm}	1.177
KMWS26	7.06	2.15	38.49^{h}	44.74^{ij}	1.162
KMWS27	7.09	2.37	38.21^{h}	45.44^{i}	1.189
KMWS28	7.48	2.49	33.97^{klm}	39.05^{o}	1.149
KMWS29	6.76	2.25	32.62^{m}	39.94^{p}	1.132
KMWS30	4.61	2.19	44.41^{e}	51.89^{e}	1.168
KMWS31	4.33	2.16	41.30^{gf}	48.35^{h}	1.171
KMWS32	4.21	2.15	43.91^{e}	50.67^{efg}	1.154
KMWS33	5.33	2.23	37.23^{ih}	45.17^{ij}	1.212
KMWS34	4.40	2.09	42.33^{f}	50.04^{fgh}	1.182
KMWS35	4.52	2.11	40.77^{g}	49.63^{fgh}	1.217
KMWS36	4.37	2.13	38.55^{h}	49.22^{gh}	1.277
KMWS37	4.47	2.18	40.46^{g}	49.87^{fgh}	1.233
KMWS38	4.36	2.19	36.23^{ij}	43.54^{jk}	1.202
KMWS39	5.19	2.23	41.80^{gj}	51.67^{efg}	1.226

*Mean values suffixed with different letters in a column were significantly different (LSD) at $P<0.05$.

X_{gm} – Geometric mean length. S_{gm} – Standard deviation

Table 4. Particle size and densities of ground corn stover in a knife mill*

Treatment No.	X_{gm} (mm)	Sgm (mm)	Loose filled bulk density (Kg/m^3)	Tapped bulk density (Kg/m^3)	Hausner ratio
KMCS3	14.89	2.22	33.23^{r}	37.17^{w}	1.119
KMCS4	13.86	2.27	39.16^{op}	44.66^{u}	1.141
KMCS5	14.03	2.28	42.39^{n}	49.45^{t}	1.167
KMCS6	14.48	2.18	36.78^{pq}	41.73^{v}	1.135
KMCS7	12.79	2.09	34.44^{qr}	38.35^{w}	1.114
KMCS9	3.56	2.27	69.05^{a}	85.55^{a}	1.239
KMCS10	3.26	2.37	66.56^{b}	80.24^{b}	1.205
KMCS11	3.22	2.42	65.16^{bc}	79.12^{bc}	1.214
KMCS12	8.56	2.41	50.60^{k-m}	57.17^{pq}	1.165
KMCS13	7.80	2.33	40.95^{no}	45.13^{u}	1.102
KMCS14	7.73	2.22	50.80^{kl}	56.90^{pq}	1.120
KMCS15	6.85	2.50	50.10^{lm}	56.30^{qr}	1.124
KMCS17	7.80	2.27	53.79^{ij}	62.49^{mn}	1.162
KMCS19	6.42	2.59	56.22^{hi}	60.43^{no}	1.075
KMCS20	7.40	2.46	51.35^{kl}	54.41^{rs}	1.060
KMCS21	7.52	2.31	59.07^{e-g}	63.33^{lm}	1.072
KMCS22	8.02	2.10	65.88^{b}	70.59^{gh}	1.071
KMCS23	7.65	2.31	54.38^{ij}	58.34^{o-q}	1.073
KMCS24	8.55	2.20	61.89^{d}	67.61^{ij}	1.092
KMCS25	8.62	2.39	48.21^{m}	51.98^{s}	1.078
KMCS26	6.40	2.49	54.83^{ij}	62.91^{lm}	1.147
KMCS27	5.49	2.50	62.18^{d}	72.06^{fg}	1.159

*Mean values suffixed with different letters in a column were significantly different (LSD) at $P<0.05$.

X_{gm} – Geometric mean length. S_{gm} – Standard deviation

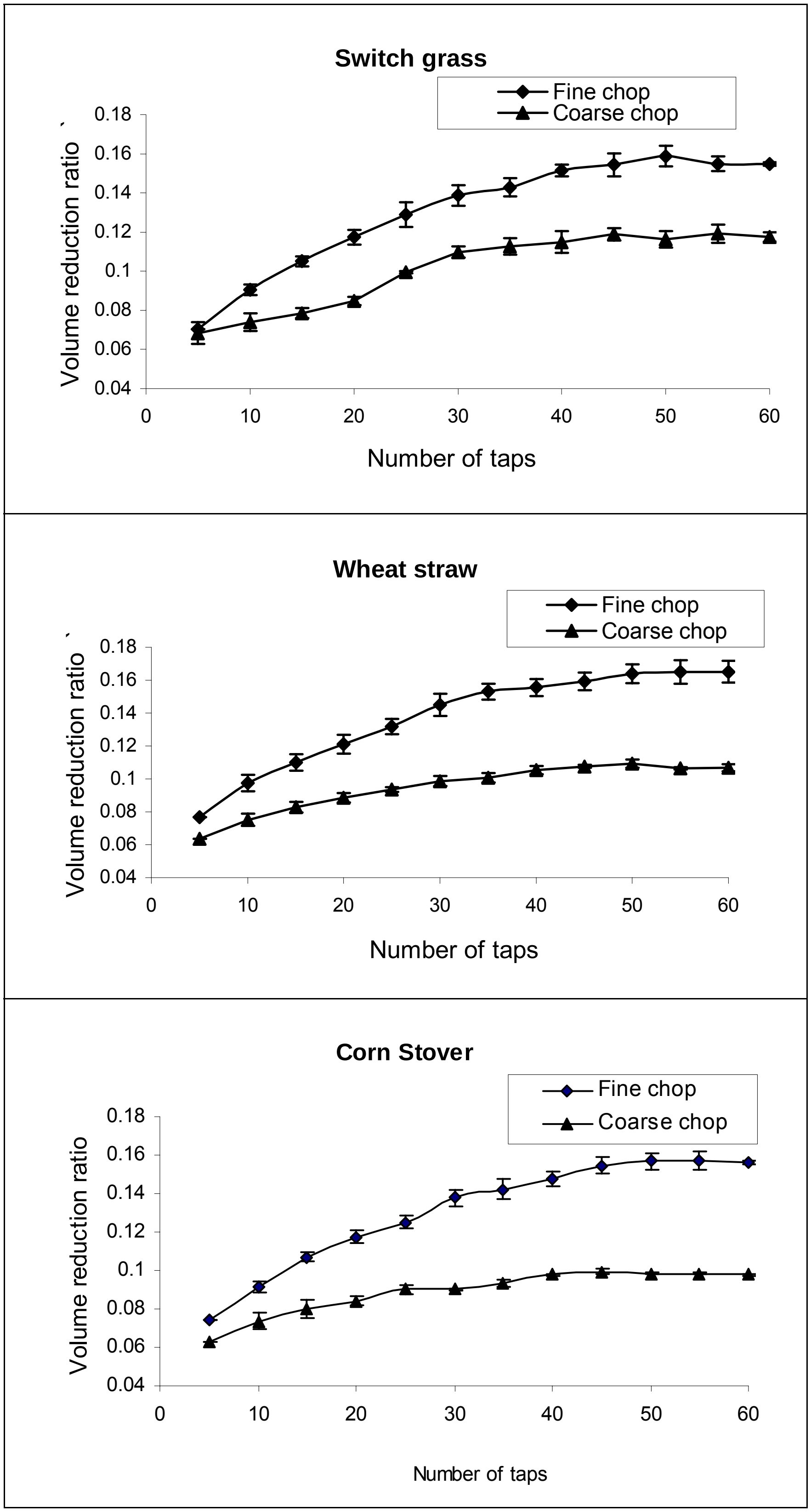

Figure 1. Effect of number of taps on volume reduction ratio of biomass.

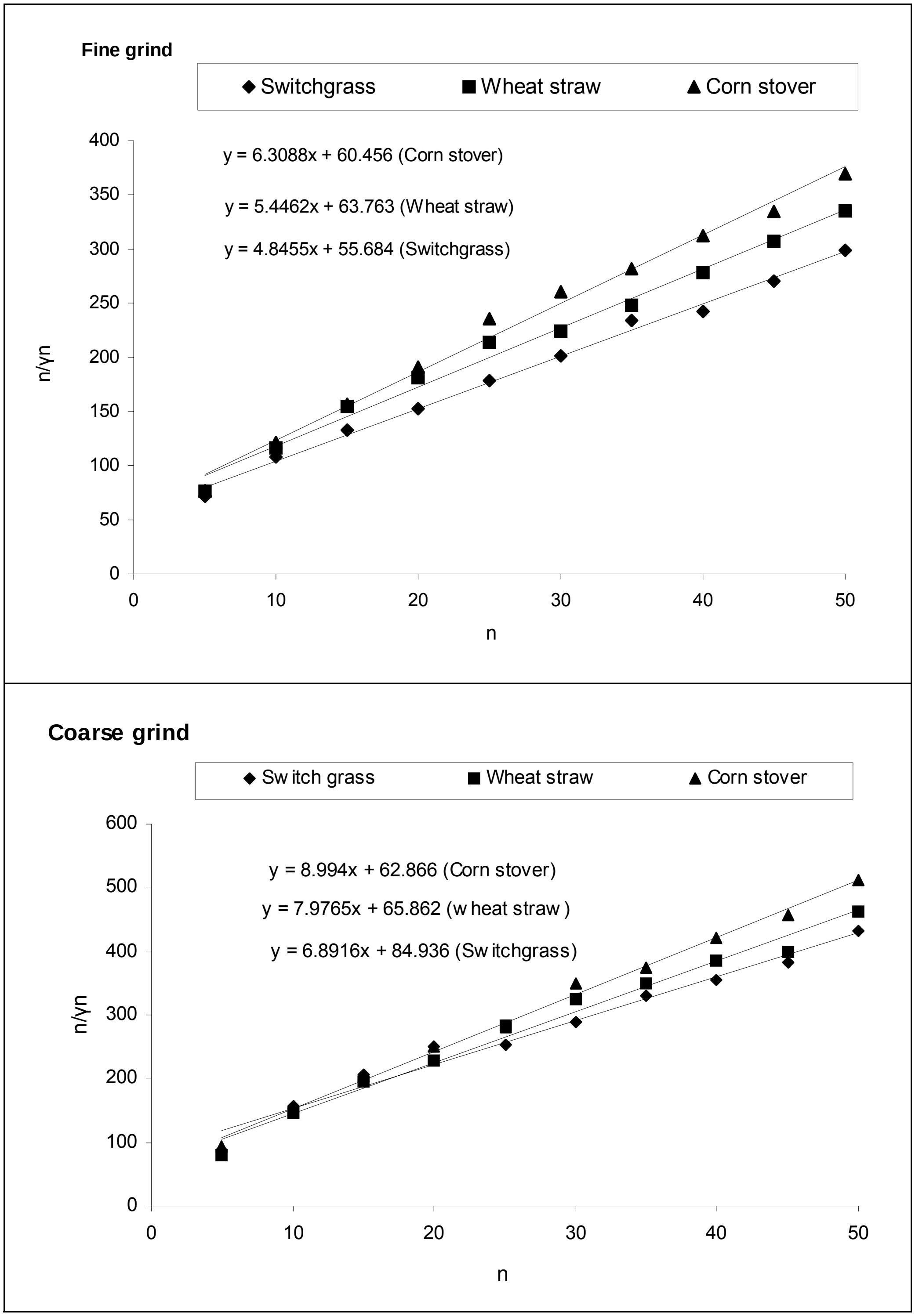

Figure 2. Linear relationship between number of taps (n) and ratio of n/volume ratio (n/γ_n).

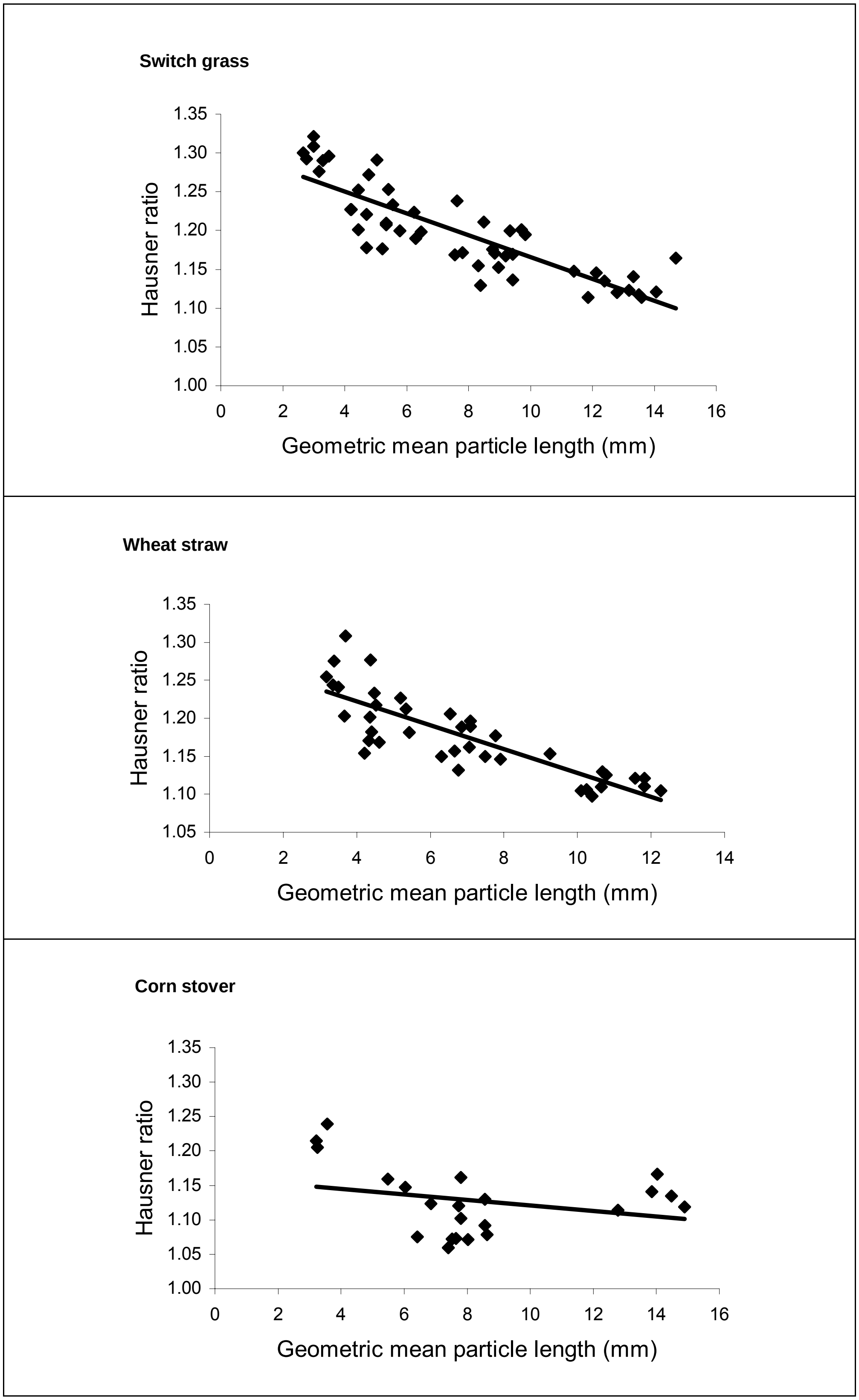

Figure 3. Effect of particle size on Hausner ratio of ground biomass.