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Article

Ash Content and Calorific Energy of Corn Stover Components in Eastern Canada

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Abstract: Corn stover is an abundant agricultural residue that could be used on the farm for heating and crop drying. Ash content and calorific energy of corn grain and six stover components were measured from standing plants during the grain maturing period, between mid-September and mid-November. Ash of stover in standing corn averaged 4.8% in a cool crop heat unit zone (2300–2500 crop heat units (CHU)) and 7.3% in a warmer zone (2900–3100 CHU). The corn cob had the lowest ash content (average of 2.2%) while leaves had the highest content (from 7.7% to 12.6%). In the fall, ash content of mowed and raked stover varied between 5.5% and 11.7%. In the following spring, ash content of stover mowed, raked and baled in May averaged 3.6%. The cob and stalk located below the first ear contained the highest calorific energy with 17.72 MJ·kg^{-1}. Leaves and grain had the lowest energy with an average of 16.99 MJ·kg^{-1}. The stover heat of combustion was estimated at 17.47 MJ·kg^{-1} in the cool zone and 17.26 MJ·kg^{-1} in the warm zone. Based on presented results, a partial "cob and husk" harvest system would collect less energy per unit area than total stover harvest (44 *vs*. 156 GJ·ha^{-1}) and less biomass (2.51 *vs*. 9.13 t·dry matter (DM)·ha^{-1}) but the fuel quality would be considerably higher with a low ash-to-energy ratio (1.45 *vs*. 4.27 g·MJ^{-1}).

Keywords: corn stover; ash; calorific energy; corn components; cob; harvest

1. Introduction

In Eastern Canada, considerable energy is required on farms from October to April because of the prevailing cold weather. Heating is needed for several agricultural activities, notably greenhouses, various livestock buildings, grain drying and feed pelleting. At the present time, fossil fuels remain the most important source of energy on Canadian farms. Because crop residues are abundant and conveniently located in rural areas, they could become a sustainable source of thermal energy for agriculture. Such biomasses could reduce dependence to fossil fuels and reduce the global carbon footprint. For example in Québec, corn stover left in the field after grain harvest represents an estimated yield of 8.6 $t \cdot ha^{-1}$ and is available from an average area of 380,000 ha of grain-corn cultivated each year [1].

From data collected in the United States, corn stover could profitably be used as an energy source to dry corn grain on the farm [2]. This study used a calorific value of 16.5 $MJ \cdot kg^{-1}$ for corn stover but other researchers found higher energy content. Helsel and Wedin [3] recorded calorific values for corn stover between 16.4 and 17.4 $MJ \cdot kg^{-1}$. They found that corn cob had the highest energy content among 12 different types of biomass. They also observed that calorific energy of corn varied on a yearly basis. Pordesimo *et al.* [4] also observed energy content ranging between 16.7 and 20.9 $MJ \cdot kg^{-1}$ during the grain harvest period. In Eastern Canada, small corn stover bales with an average of 18.57 $MJ \cdot kg^{-1}$ energy and 5.88% ash were used in a small furnace but resulted in incomplete combustion because of the high ash content [5].

The combustion of high ash biomass generally leads to solid agglomerates, greater emission of fumes, and accelerated metal wastage due to gas-side corrosion [6,7]. Handling large quantities of ash may also be cumbersome and costly. Ash is generally affected by hybrid variety, soil type, fertilization practices, and maturity [8]. Demirbas [9] reported that corn stover had a high natural ash content (5.1%) compared to wood (0.5% to 1.7%). However, most harvested biomasses have a higher ash level than their natural content due to soil contamination [10]. Ash content of corn stover in round bales was measured as high as 23.0% [11]. A low ash-to-energy ratio is therefore desirable and may be improved by appropriate handling of biomass in the field.

In Eastern Canada, field dry down of corn stover is considerably limited during the fall because of the prevailing cold and wet climate. Field conditions soon after grain harvest are generally inadequate for harvesting dry stover (<15% moisture content (MC)). However, leaving corn stover on the ground throughout the winter and harvesting it in the spring offer the possibility of collecting a very dry stover (<10% MC) [12,13]. Moreover, spring harvest provides extended soil protection against erosion by leaving a crop residue cover from November to April. However, less stover yield is available in spring compared to the previous fall because of natural degradation (average 21% less yield according to [13]). For combustion purposes, the winterization of corn stover may be beneficial by reducing the concentration of some minerals through leaching [14]. Reduction in minerals by delayed harvest was also reported for other energy crops such as miscanthus and switchgrass [15,16]. Nevertheless, there are very few studies on the effects of delayed harvest on fuel quality of corn stover. Therefore, the objectives of this study were (1) to measure ash content and calorific energy of corn stover during an extended period in the fall; (2) to evaluate the ash content of stover baled in the spring; and (3) to simulate various biomass harvest scenarios for combustion.

2. Materials and Methods

2.1. Harvest Sites and Sample Preparation

Corn stover was obtained from two sources: (1) standing crop prior to grain harvest; (2) field stover chopped after grain harvest and collected from windrows or from bales. Standing corn plants were sampled weekly in experimental plots during the grain maturing period in two climatic zones from early September to mid-November 2008. Hybrids Elite 46T07 and Elite 30A27 were grown in Saint-Augustin-de-Desmaures, QC, Canada (46.732° N, 71.517° W) in a relatively cool zone of 2300 to 2500 crop heat units (CHU). Hybrids Elite 46T07 and Elite 25T19 were grown in Saint-Rosalie, QC, Canada; (45.606° N, 72.914° W) in a warmer zone of 2900 to 3100 CHU. Each week, five corn plants from each hybrid and site were partitioned into grain and six stover components (cob, husk, upper leaves, lower leaves, upper stalk, lower stalk). Total biomass and moisture content have been reported in [1]. The line of separation of lower leaves and upper leaves was the first ear, as well as for lower and upper stalks. Each corn component was ground with a laboratory mill (model ED-5, Thomas Scientific, Swedesboro, NJ, USA) using a 1-mm screen.

In large commercial corn fields (average 2-ha plots), stover was mechanically handled after grain harvest at two sites (Table 1). Site 1 was located in La Présentation, QC, Canada (45.615° N, 73.070° W) in a 2900–3100 CHU zone where grain was harvested on 1 November 2008. Site 2 was located 44 km South-West from the first site in Saint-Philippe-de-Laprairie, QC, Canada (45.318° N, 73.451° W, 2900–3100 CHU zone) where grain was harvested on 12 November 2008. Besides two plots windrowed in fall 2008, three other plots, one at site 1 and two at site 2, were mowed and raked in spring 2009. All five plots were baled in spring 2009 at dates and with equipment indicated in Table 1. Ten samples were taken from large square bales and ten other samples from large round bales, while 20 samples were taken from small square bales for calorific value and ash content measurements per plot. Immediately after baling, stover samples were taken off the bale surface rather than by coring because of the difficulty of tube sampling through the very dry and brittle biomass.

Windrows were also sampled weekly in the fall until the first snowfall and once in the spring before baling. At site 1, windrows were actually sampled from 5 November to 3 December (five weekly samples) and on 30 April. At site 2, windrows were sampled from 19 November to 3 December (three weekly samples) and on 24 May. Grab samples were taken at 51 mm from the top and at 51 mm from the bottom of the windrow to avoid soil contamination.

Table 1. Sequence of operations for each plot, dates and equipment to collect stover after grain harvest in fall 2008. Stover windrows were baled in spring 2009 [12].

Date of operation	Site 1		Site 2		
	Fall Plot	**Spring Plot**	**Fall Plot**	**Spring Plot**	**Spring Plot**
	(1.83 ha)	(3.08 ha)	(2.16 ha)	(2.68 ha)	(1.68 ha)
5 Nov. 2008	Mowing [1]	-	-	-	-
	Raking [2]	-	-	-	-
19 Nov. 2008	-	-	Mowing [3]	-	-
	-	-	Raking [2]	-	-
26 Apr. 2009	Raking [2]	Mowing [1]	-	-	-
	-	Raking [2]	-	-	-
29 Apr. 2009	Raking[2]	Raking [2]	-	-	-
30 Apr. 2009	Large rect. baling [5]	Large rect. baling [5]	-	-	-
24 May 2009	-	-	Raking [2]	-	-
25 May 2009	-		Round baling [6]	Shred-windrow [4]	Shred-windrow [4]
	-	-	-	Round baling [6]	Small rect. baling [7]

Notes: Equipment used: [1] Disc mower, New Idea model 5208, 2.4 m wide (Duluth, GA, USA); [2] Parallel bar rake, New Holland model 5208, four windrow wide or 9.8 m (Burr Ridge, IL, USA); [3] Disc mower, Taarup model 2424, 2.4 m wide (Kvernaland, Norway); [4] Flail shredder-windrower, Hiniker model 5610, 4.5 m wide (Mankato, MN, USA); [5] Large rectangular baler, Case IH model LBX332, typical bale size 1.83 m × 0.90 m × 0.81 m (Burr Ridge, IL, USA); [6] Large round baler, John Deere model 458, typical bale size 1.22 m diameter × 1.22 m width (Moline, IL, USA); [7] Small rectangular baler, New Holland model 315, typical bale size 0.35 m × 0.45 m × 0.81 m (New Holland, PA, USA).

2.2. Combustion Tests

The calorific energy of the seven components of standing crops was measured for samples taken during week 3 (17 September 2008), week 6, week 9, and week 12 (19 November 2008) using an 1108P bomb inserted in a 6100 calorimeter (Parr Instrument Co., Moline, IL, USA) calibrated for uniform measurements. Three replicates were made from about 1 g of kernel and cob, and 0.7 g of husk, leaf and stalk material, transformed into pellets and weighed with a precision scale of 0.0001 g. Pellets were inserted into a bomb pressurized to 3.1 MPa with 99.5% oxygen purity. Calibration tests were conducted after every 40 runs using benzoic acid capsules of 26.4 $MJ \cdot kg^{-1}$ (6 318.4 $cal \cdot g^{-1}$); the average deviation was 0.29 $MJ \cdot kg^{-1}$.

2.3. Ash Measurements

Ash content of stover components of standing crops was measured with a TGA701 Leco thermogravimetric analyzer (St. Joseph, MI, USA). Ash was expressed as the mass percent of residue remaining after 3 h of dry oxidation at 525 °C based on ASTM E1755-01 Standard [17]. Because of limited instrument availability, only 54 samples were evaluated for ash. Samples were selected among four weeks (3, 6, 9, and 12), two hybrids, two sites and six components to allow one-factor analyses of ash content. Ash content was also measured for raked and baled corn stover representing a composite mix of components. Samples were taken from windrows or bales as described in the previous section. Samples were analyzed by the same procedure as for standing crops [17].

For both calorific and ash data, a repeated analysis of variance (ANOVA) was performed to measure the effect of time. A paired Student's *t*-test was used to conduct simple comparison while Tukey's Honestly Significant Difference (HSD) test was used for multiple pairwise comparisons. A significance level (α) of 0.05 was used and the R software was chosen for statistical computations [18].

2.4. Simulation of Stover Harvest

A simulation was done to estimate potential stover harvest and its quality in terms of ash content and calorific energy, especially in the context of on-farm use for animal bedding and small-scale heating which appear to be the main potential applications in Eastern Canada [5,13]. Four scenarios were considered. The first scenario assumes that only cobs are harvested behind a combine (e.g., H165 Cob harvester; Redekop, Saskatoon, SK, Canada). The second scenario collects cob and husk with a cob harvester and stover processor (e.g., Cob Collection Attachment; Hillco Technologies, Nezperce, ID, USA). The third scenario collects all stover components above the ear; this can be achieved by using a combine equipped with a forage harvester header and a stover processor [19]. The fourth scenario uses equipment similar to the third scenario; the whole stover is harvested by lowering the forage header closer to the ground. Simulation results compare total biomass, ash and energy for the four scenarios.

3. Results and Discussion

3.1. Ash Content of Standing Corn Plants

Ash content of standing corn stover was compared among hybrids, sites and components at four dates between September and November, just before grain harvest. The effect of time on stover ash content revealed a non-significant effect at a *p*-value of 0.503 (54 data points). According to a paired Student's *t*-test analysis, differences in ash between hybrids grown at a same site were non-significant at a probability of 0.108 (16 data points collected at the 2900–3100 CHU site). Values were therefore averaged over time and hybrids (Table 2). Corn grown in the high CHU zone had a significantly ($p < 0.01$; 26 data points) higher ash content (average 7.3%) than corn grown in the lower CHU zone (average 4.8%). However, statistical results did not show a significant difference ($p > 0.05$; 10 data points) between ash content of the 46T07 hybrid (a 2300 CHU hybrid) sampled in either the low CHU zone or the high CHU zone. The significant difference in ash content between the two CHU zones may be explained by a combination of factors such as microclimate, morphological differences between hybrids, soil type, and fertilization practices within each site.

For both CHU zones, the husk and cob fractions had the lowest ash content with average values ranging between 2.07% and 3.20% (Table 2). Leaves were the stover component with the highest ash content from 7.69% to 12.59%; there was no significant difference between upper and lower leaves. The ash content difference was also non-significant between lower and upper stalk fractions. Xiong *et al.* [20] reported corn stalks and leaves containing ash concentrations of 4.31% and 8.37%, respectively for hybrids grown in China. Those values are close to ash levels recorded at the 2300–2500 CHU site.

Table 2. Average ash content of corn stover components from standing crops sampled in two crop heat unit (CHU) zones during grain maturing period (from 17 September to 19 November 2008).

Corn Stover Components	2300–2500 CHU		2900–3100 CHU	
	Mass Ratio (%)	Ash Content (%) [a]	Mass Ratio (%)	Ash Content (%)
Cob	21.8	2.07 [a]	18.6	2.26 [a]
Husk	8.4	2.53 [a]	8.9	3.20 [a]
Lower leaves	12.8	7.69 [b,c]	15.0	12.59 [c]
Upper leaves	13.8	8.13 [c]	17.2	12.44 [c]
Lower stalk	32.8	4.62 [b]	28.8	6.59 [b]
Upper stalk	10.5	4.92 [b,c]	11.4	5.86 [b]
Tukey's HSD	-	2.68	-	1.92
Total weighted stover	100.0	4.80	100.0	7.31

Notes: Different letter superscripts (a, b, c) in the same column denote significant differences among stover components according to the Tukey's HSD test (α = 0.05).

3.2. Ash Content of Windrowed and Baled Corn Stover

Ash content of raked corn stover at site 1 (La Présentation, QC, Canada) varied between 9.42% and 11.69% from 5 November (day of raking) to 3 December 2008 (Figure 1). There appears to be some initial soil contamination once the stover is on the ground. An important rainfall (30.4 mm) occurred on 15 November which could explain an ash content reduction due to leaching at site 1 (9.42% ash recorded on 19 November). However, wind or splashing due to light rain could have re-contaminated the windrows in subsequent weeks. At site 1, the effect of time was non-significant on ash content (*p*-value of 0.612). However, a significant time effect (*p*-value < 0.001) on ash content was observed at site 2 (Saint-Philippe-de-Laprairie). Indeed, ash increased from 5.49% on 19 November to 10.46% on 3 December, where wind and light rain could have caused soil contamination over time.

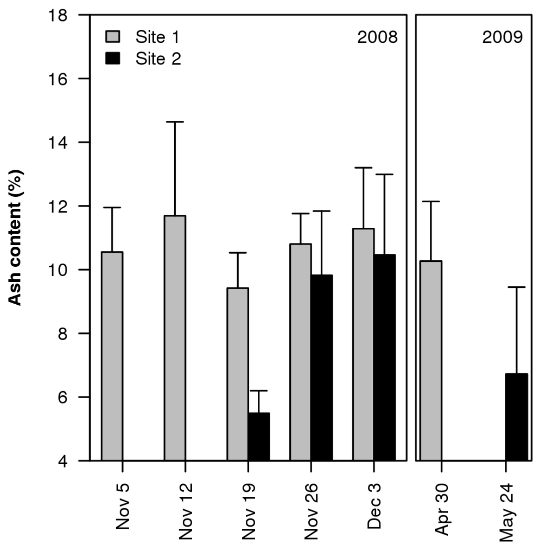

Figure 1. Ash content of windrowed corn stover left on the ground at two sites of similar climate (2900–3100 CHU) sampled in fall 2008 and in spring 2009. Error bars denote the standard deviation.

In spring 2009, average ash of windrowed stover was 10.27% and 6.73% at sites 1 and 2, respectively. For site 1, ash content of windrows sampled in the spring was not significantly different (p-value = 0.399) to the measurements made on 3 December 2008 (11.29%). At site 2, ash was significantly lower (p-value < 0.001) in the spring than on 3 December 2008 (10.46%). The high standard deviations of ash in windrowed stover (1.82%) reflect heterogeneity due to soil contamination and variability in sampling.

Table 3 shows ash of bales from two sites, mowed and raked either in fall or spring, with all bales harvested in spring. On site 1 (La Présentation), bale ash of spring-mowed stover was 5.21% and significantly lower (p-value = 0.022) than bale ash of fall-mowed stover (7.03%). On site 2 (Saint-Philippe-de-Laprairie), bale ash was also lower in the spring-mowed stover (3.59%) but not significantly different (p-value = 0.085) from fall-mowed stover (4.33%). For three plots out of four, the standard deviation of bale ash was lower than the average value of 1.82% for weekly sampled windrows (Figure 1).

Table 3. Ash content of corn stover bales at two sites for two mowing-raking periods (fall or spring). All windrows were baled in spring.

Site	Mowing and Raking Period	Bale Ash (%)	
		Average *	**Std Deviation**
Site 1 (La Présentation)	Fall 2008	7.03 ^{b}	1.83
	Spring 2009	5.21 ^{a}	1.48
Site 2 (Saint-Philippe de Laprairie)	Fall 2008	4.33 ^{a}	1.18
	Spring 2009	3.59 ^{a}	0.52

Note: * Different letter superscripts (a, b) denote significant differences according to Student's t-test ($\alpha = 0.05$).

Bales mowed and raked in the spring had a lower ash content than bales mowed and raked in the previous fall. In China, stover ash of standing corn declined from 15% in late August to 6.4% in mid-March [21]. Baled stover with the lowest ash values (Site 2, Spring 2009) was actually handled with a single pass shredder-windrower while other fields were handled in two separate operations of mowing and raking. The combination of spring harvest and simultaneous mowing-conditioning appears to reduce ash content by winter leaching and minimal soil contamination until baling. The very low ash content (3.6%) of spring harvested stover with simultaneous shredding-windrowing also compares favorably to a single-pass grain and stover fall harvest system in Wisconsin where stover ash averaged 4.9% [22]. These latter researchers also tested multi-pass harvest of stover in the fall with flail-shredding, raking, and chopping. Stover ash collected with the multi-pass scenario averaged 9.8%.

3.3. Calorific Energy of Corn Components

Calorific energy was measured from standing corn plants sampled from 17 September to 19 November 2008, every three weeks. The cob fractions had the highest calorific energy with values ranging from 17.70 to 18.34 $MJ \cdot kg^{-1}$ (Figure 2). Meanwhile, leaves (averaged for lower and upper fractions) had the lowest energy from 16.60 to 17.04 $MJ\ kg^{-1}$. Cob results were similar to the 17.10 to 18.16 $MJ \cdot kg^{-1}$ range reported by [3]. For all corn components, the time effect was statistically non-significant although the probability level for cob was close to α with 0.068. In fact, cob energy increased by 4% from 29 October to 19 November but data were limited at the last date because only one site (2900–3100 CHU) was sampled on 19 November.

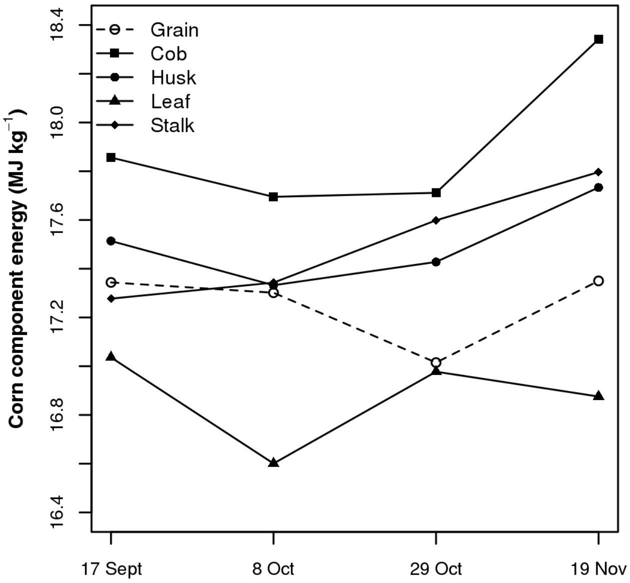

Figure 2. Corn component energy of standing crop as a function of sampling date, averaged for hybrids and sites.

Table 4 shows calorific values of corn stover components at two sites on a specific date (29 October). Over the two sites, the cob and upper-stalk had significantly higher calorific energies than the other corn components with values close to 17.70 MJ·kg^{-1}. For the 2300–2500 CHU zone, the component with the lowest energy was the grain with 16.98 MJ·kg^{-1}. The leaves located below the first ear had the lowest energy (16.98 MJ·kg^{-1}) for the 2900–3100 CHU zone. According to work by [20], corn stalk (18.92 MJ·kg^{-1}) had a greater energy than leaves (17.99 MJ·kg^{-1}). They reported energy values as high as 19.35 MJ·kg^{-1} for stalk sampled in China. On 29 October, the weighted average of stover gross energy was generally higher (17.47 MJ·kg^{-1}) for hybrids grown in the 2300–2500 CHU zone.

Table 4. Calorific energy of corn plant components sampled from the standing crop on 29 October 2008.

Corn Component	Calorific Energy (MJ·kg^{-1}) [a]		
	2300–2500 CHU	2900–3100 CHU	Overall
Grain	16.98 [a]	17.12 [b,c]	17.01 [a]
Cob	17.62 [b]	17.80 [c]	17.71 [b]
Husk	17.49 [a,b]	17.36 [c]	17.43 [a,b]
Lower-leaves	17.38 [ab]	16.18 [a]	16.92 [a]
Upper-leaves	17.57 [b]	16.35 [a,b]	17.04 [a]
Lower-stalk	17.50 [ab]	17.37 [c]	17.46 [a,b]
Upper-stalk	17.87 [b]	17.56 [c]	17.74 [b]
Tukey's HSD ($\alpha = 0.05$)	0.54	0.83	0.56
Stover	17.47	17.26	17.41

Notes: Different letter superscripts (a, b, c) in same column denote significant differences among stover components according to the Tukey's HSD test ($\alpha = 0.05$).

During the overall sampling period, the calorific energy of corn stover was significantly higher (*p*-value of 0.0011) for the 2300–2500 CHU zone with values ranging from 17.27 to 17.64 MJ·kg^{-1} (Figure 3). Those results corroborate with the low ash content of corn stover measured for the 2300–2500 CHU hybrids (Table 2). For the 2900–3100 CHU zone, stover energy was low in mid-September with values around 17.00 MJ·kg^{-1} and increased to 17.50 MJ·kg^{-1} toward the end of the sampling period. Energy of stover at the 2900–3100 CHU site ranged from 16.86 to 17.45 MJ·kg^{-1}. Those results were very close to the 16.42 to 17.41 MJ·kg^{-1} measured by [3] for corn stover sampled in 1974 and 1975. However, values reported by [4] for corn plants sampled from 9 August to 26 November 2001 in Tennessee were in the lower end of the 16.7 to 20.9 MJ·kg^{-1} range. The calorific energy of the 46T07 hybrid grown in the 2300–2500 CHU zone was higher than the same hybrid sampled in the 2900–3100 CHU zone. However this difference was not statistically significant with a resulting paired Student's *t*-test of 0.082.

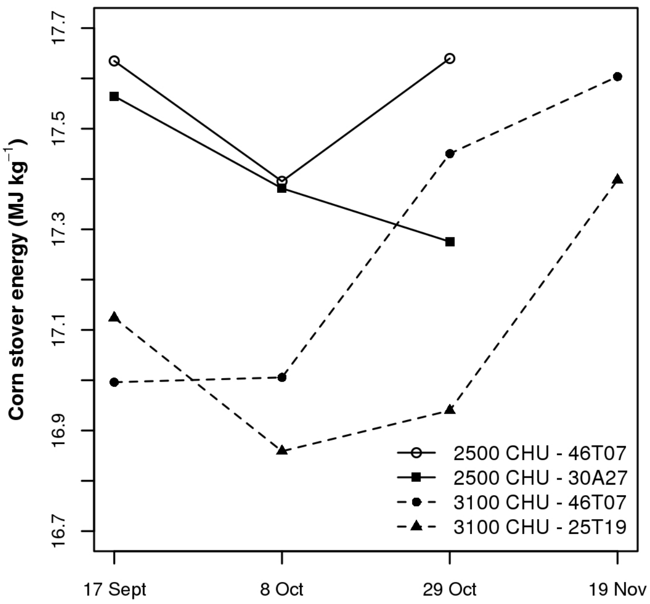

Figure 3. Calorific energy of corn stover from various standing hybrids in two crop heat unit (CHU) zones.

3.4. Harvesting Corn Stover for Combustion

Few studies have highlighted the possibility to enhance biomass quality by harvesting only specific corn stover components [19,23]. The simulation results in Table 5 are based on standing crop stover quality observed in two climatic zones described in the materials and methods section.

Corn cob was the stover component with the lowest ash content and the highest calorific energy. So all harvest scenarios collecting other components than cob had a greater ash content and a lower unit energy value. Cob harvest yielded 25 and 30 GJ·ha^{-1} in the 2300–2500 and 2900–3100 CHU zones, respectively. For this first scenario, a higher energy yield was calculated for the 2900–3100 CHU zone since the calorific energy and the cob biomass yield were greater than for the 2300–2500 CHU zone. The unit calorific energy of whole stover harvest was the lowest for both zones but the total energy yield was the highest with 116 and 156 GJ·ha^{-1} for the low and high CHU zones, respectively. Whole stover harvest also resulted in the highest ash yields considering ratios of ash-to-energy of 2.73 and 4.27 g·MJ^{-1} for low and high CHU zones. For all scenarios of the 2300–2500 CHU zone, ash-to-energy ratios were lower than those calculated for the 2900–3100 CHU zone. The largest increases of ash-to-energy ratio were observed when more fractions than cob and husk were harvested.

Table 5. Biomass, ash, and energy yield of corn stover for four harvest scenarios.

Harvest Scenario	Ash Content (%)	Calorific Energy (MJ·kg^{-1})	Ash to Energy Ratio (g·MJ^{-1})	Yield	
				Biomass (t·DM·ha^{-1})	Energy (GJ·ha^{-1})
2300 to 2500 Crop Heat Unit zone					
Cob	2.07	17.62	1.17	1.44	25
Cob + Husk	2.20	17.58	1.25	1.99	35
Stover above ear [a]	4.22	17.64	2.39	3.60	64
Whole stover	4.80	17.56	2.73	6.62	116
2900 to 3100 Crop Heat Unit zone					
Cob	2.26	17.80	1.27	1.70	30
Cob + Husk	2.56	17.66	1.45	2.51	44
Stover above ear [a]	6.26	17.24	3.63	5.13	88
Whole stover	7.31	17.12	4.27	9.13	156

Notes: [a] Stover above the ear includes cob, husk, upper-leaves and upper-stalk.

4. Conclusions

Ash content and calorific energy of corn stover were measured on standing corn plants sampled in the fall. Additional ash measurements were taken on corn stover from windrows left in the field up to six months after grain harvest and from bales harvested in the spring. Average value of ash in standing stover was 4.8% in a cool 2300–2500 crop heat unit (CHU) zone and 7.3% in a warmer 2900–3100 CHU zone. Ash content in standing plants did not change significantly between September and November. Higher ash levels were found in windrowed stover, in the range of 5.5% to 11.7% in November and December after grain harvest. Corn stover bales harvested in the following spring contained ash levels between 3.6% and 7.0%. The lowest stover ash content was observed in plots that were mowed and raked simultaneously in the spring, and then baled soon after. Leaving the standing corn stover throughout the winter was beneficial for mineral leaching and ash reduction.

The calorific energy of standing corn stover varied between 16.86 and 17.64 MJ·kg^{-1}. The effect of time between September and November was non-significant. However, stover energy was statistically higher for hybrids grown in the cooler, 2300–2500 CHU zone. The cob fraction had the highest calorific energy among corn components with values around 17.71 MJ·kg^{-1}. Four harvest scenarios were analyzed. The whole stover scenario resulted in the highest total energy yield of 116 and 156 GJ·ha^{-1} for the 2300–2500 and the 2900–3100 CHU zones, respectively. This scenario also yielded the highest ash-to-energy ratios (2.73 and 4.27 g of ash·MJ^{-1}, in the two zones respectively). The selective harvest of only cob as a solid fuel resulted in lower ash to energy ratios (1.17 and 1.27 g·MJ^{-1}). Partial harvest may be considered if a reduction of the ash-to-energy ratio is an important factor.

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Author Contributions

Pierre-Luc Lizotte and Philippe Savoie designed the experiments. Pierre-Luc Lizotte performed the experiments, analyzed the data and drafted the paper under supervision of Philippe Savoie and Alain De Champlain. Pierre-Luc Lizotte, Philippe Savoie and Alain De Champlain discussed results, reviewed and finalized the paper.

Conflicts of Interest

The authors declare no conflict of interest.

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