Artificial drying of corn stover in mid-size bales

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Savoie, P. and Descôteaux, S. 2004. **Artificial drying of corn stover in mid-size bales**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **46**: 2.25-2.34. A pilot-scale bi-directional batch dryer was used to dry either nine corn stover bales (0.89 m high by a horizontal section of 0.81 m by 1.52 m per bale) on one layer or 18 bales on two layers. Corn stover bales had an average initial moisture content of 56% (range of 49 to 66%) and an average dry matter (DM) density of 117 kg/m³ (range of 87 to 144 kg DM/m³). One layer of corn stover bales dried during 40 h with air at 40˚C, without recirculation, followed by 12 h with air at 67˚C, with 89% recirculation of exhaust air. Airflow direction was alternated every 8 h up to 40 h. The final average moisture content was 19%, with a range of 7 to 30%. Two layers of corn stover bales dried during 90 h with air at 61˚C (89% recirculation continuously). The final average moisture content was 18% (range of 8 to 38%). After a one-week period for transport, storage, and handling, six selected bales sampled at 75 locations indicated some re-hydration (4% units in the one-layer batch; 1% unit in the two-layer batch). Drying increased moisture content variation within bales (average SD of 13.2% after drying; 4.3% prior to drying). Estimated energy cost for drying from 55 to 12% moisture content ranged between $56 and $98/t DM depending on the type of dryer and the source of energy. Reducing the energy cost below $10/t DM would require field drying corn stover below 20% moisture prior to baling. Weather constraints and the cost of artificial drying are likely to limit the use of corn stover as a dry feedstock for future biomass applications in eastern Canada. **Keywords:** corn stover, biomass, drying, bale, storage, harvest.

Un séchoir pilote bidirectionnel a séché un lot de neuf balles (0,89 m de hauteur par une section horizontale de 0,81 m par 1,52 m par balle) de résidus de maïs sur une couche et un deuxième lot de 18 balles sur deux couches. Les résidus de maïs avaient une teneur en eau initiale moyenne de 56% (plage de 49 à 66%). La masse volumique moyenne sur une base sèche était de 117 kg/m³ (plage de 87 à 144 kg/m³). Une couche de balles a séché durant 40 h avec de l'air à 40˚C, sans recirculation, et durant 12 h additionnelles avec de l'air à 67˚C, avec recirculation de 89% de l'air de sortie. La direction de l'air était inversée à toutes les 8 h jusqu'à 40 h. La teneur en eau finale était de 19% en moyenne (plage de 7 à 30%). Deux couches de balles ont séché pendant 90 h avec de l'air à 61˚C (89% de recirculation d'air continue). La teneur en eau finale était de 18% en moyenne (plage de 8 à 38%). Après une période d'une semaine pour le transport, l'entreposage et la manutention, six balles sélectionnées dans les deux lots et découpées en 75 échantillons ont indiqué une légère réhydratation (4 unités de pourcentage dans le premier lot, une unité de pourcentage dans le deuxième lot). L'écart-type de la teneur en eau était plus grand après le séchage qu'avant (13,2% versus 4,3%). Le coût estimé de l'énergie pour sécher des balles de résidus de maïs de 55% à 12% de teneur en eau variait entre 56 et 98 $/t MS selon le type de séchoir. Il serait possible de réduire le coût d'énergie à moins de 10 $/t MS si le séchage au champ permettait de récolter les résidus de maïs à une teneur en eau inférieure à 20%. Les contraintes climatiques et le coût du séchage artificiel semblent limiter l'usage futur des résidus de maïs comme biomasse sèche pour l'est du Canada. **Mots-clés:** résidus de maïs, biomasse, séchage, balle, entreposage, récolte.

INTRODUCTION

Corn grain is an important field crop in Canada seeded on more than 1.2 million hectares yearly with a total production of 8.6 million tonnes and an average production of 6.9 t/ha (Statistics Canada 2004; Table 1). Corn production is mainly concentrated in Ontario (about 64% of Canadian production), Québec (33%) and Manitoba (3%) (Ontario Corn Grower Association 2004). After grain harvest, an abundant residue called stover is left on the ground. Corn stover is composed of stalks, cobs, husks, and leaves. The stover yield varies with geographic area, crop maturity, and crop variety. Edens et al. (2002) in Tennessee estimated that stover yield (11.7 t DM/ha) was practically the same as grain yield (11.6 t DM/ha) at physiological maturity (September 11) while Shinners et al. (2003) in Wisconsin observed a lower stover yield (10 t DM/ha) than grain yield (13 t DM/ha) at physiological maturity (between September 30 and October 14). The wetter and cooler climate of Wisconsin required later harvest and resulted in an average stover to total DM yield ratio of 43%. In Table 1, an average stover to total DM yield ratio of 45% is assumed. The average corn stover in Canada is estimated as 5.66 t DM/ha while the total amount is slightly greater than 7 million tonnes DM per year.

Table 1. Corn grain production in Canada and potential harvestable corn stover.

Year	Area (10^6 ha)	Production (10^6 t)	Grain yield (t/ha)	Estimated stover (t/ha)	Harvestable stover (t/ha)
1999	1.166	9.161	7.86	6.43	3.21
2000	1.206	6.954	5.77	4.72	2.36
2001	1.294	8.389	6.48	5.30	2.65
2002	1.299	8.999	6.93	5.67	2.83
2003	1.265	9.587	7.58	6.20	3.10
Average	1.246	8.618	6.92	5.66	2.83

The amount of stover that may be harvested sustainably depends on the soil's requirement for organic matter replenishment and protection against water or wind erosion. Nelson (2003) developed a model to predict how much crop residue could be removed after grain harvest while respecting tolerable soil loss limit mandated by the Natural Resources Conservation Service of USDA. Using NRCS's tolerable soil loss limit, Sheehan et al. (2002) estimated that, out of 40 Mt of corn residue produced in Iowa in 1998,

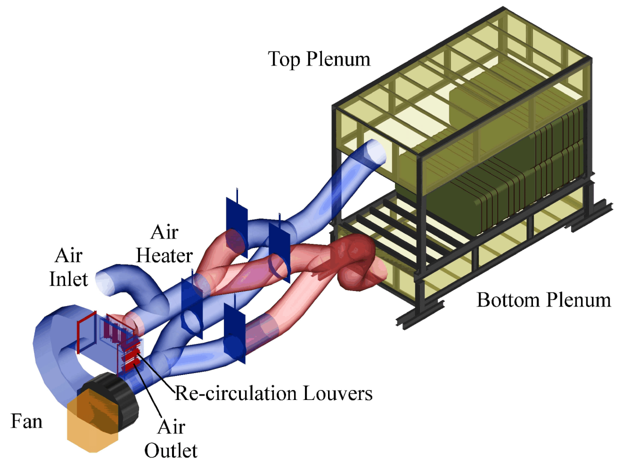

Fig. 1. Schematic view of the bale dryer with bi-directional airflow.

16 Mt or 40% could be removed under conventional tillage practices and 24 Mt or 60% under no-till practices. Current harvesting methods for corn stover offer the possibility of removing 50 to 60% of stover after grain combining. For example, Shinners et al (2003) baled between 4.3 and 5.4 t DM/ha of stover from fields averaging 8.6 t DM/ha of stover prior to baling. Considering that there is a mix of tillage systems and soil conditions, a 50% removal rate was assumed in Table 1. Therefore harvestable corn stover in Canada would average 2.83 t DM/ha or 3.5 Mt DM per year.

Some potential uses of corn stover include animal feed (usually after ammonia enrichment), energy by direct combustion, energy by hydrolysis and fermentation into ethanol, fibre for the pulp and paper industry, short fibre for the particle board industry, and long fibre for the oriented strand board (OSB) industry. Some applications such as combustion energy and OSB require a relatively dry product, usually of less than 12% moisture.

The moisture content of corn stover prior to grain harvest ranged from about 55% on September 1 to less than 15% on October 20 in Tennessee (Edens et al. 2002) while it ranged from 75% on September 1 to 55% on October 14 in Wisconsin (Shinners et al. 2003). Field drying of corn stover in Tennessee resulted in a linear moisture loss of 2% units/d on grass soil and 3% units/d on dry asphalt soil, making it relatively easy to reach a final moisture content below 15% for most of the stover. Field drying in Wisconsin was more difficult than in Tennessee because of the initially wetter stover at grain harvest and the frequent occurrence of rain in October and November. Shinners et al. (2003) concluded that wet harvest of corn stover was a better option than dry harvest under Wisconsin's climate.

Moisture and temperature conditions in Quebec and Ontario are more similar to Wisconsin than Tennessee. Dry conservation of corn stover in eastern Canada would therefore require some form of artificial drying. Artificial drying of large square bales has been developed for commercial hay (Descôteaux and Savoie 2003a, 2003b). The same type of drying could be applied to large or mid-size square bales of corn stover.

The objective of this work was to evaluate the artificial drying of corn stover harvested as mid-size rectangular bales. The experiment was carried out at a pilot scale dryer originally designed for commercial hay.

METHODS

Description of the pilot scale batch dryer

A pilot scale batch dryer for mid-size rectangular bales was built and installed at the Normandin Research Farm of Agriculture and Agri-Food Canada in May 2002. A short description of the dryer follows; a more detailed description can be found in Descôteaux and Savoie (2004). The dryer has a perforated floor area of 4.88 m by 2.44 m. This area was designed for batch drying of 6 mid-size square hay bales 0.81 m wide by 2.44 m long on one level (height of bales was 0.89 m) or 12 hay bales on two levels (height of 1.78 m). A centrifugal fan operated by an 11.2 kW electric motor was located at the end of the air duct, thereby creating a negative pressure (Fig. 1). A top plenum and a bottom plenum were connected to air ducts and control valves that allowed pulling air either downward or upward. This bi-directional airflow system was designed to change the direction of drying and reduce over-drying often associated with unidirectional airflow. The air was heated to about 60˚C with a 102 kW propane gas burner. A recirculation duct could return part of the exhaust air back into the dryer. The external bale surface between the two plenums was sealed with a plastic film that adhered very well to the crop because of suction.

Experiment #1: One-layer batch drying

Corn stover bales were harvested in the last week of October and the first week of November 2003 near Nicolet (Québec) after grain combining. The stover was left to dry in the field for periods varying between two and five days. Field drying was not monitored but the objective was to extend field drying as much as possible without rainfall. All bales were wrapped with plastic film to protect them from oxidation because of a required delay between harvest and artificial drying. The wrapped bales were transported to the batch experimental dryer in Normandin about 300 km north of Nicolet in November. In a commercial stover collection system, one would expect the dryer to be located in the corn growing area so there would be minimum delay between stover harvest and drying and no need for plastic wrapping. In this project, bales were dried on November 18-20 for experiment #1 and on November 21-24 for experiment #2, i.e. about three weeks after harvest.

Because the plastic wrapper had size handling limitations, corn stover bale length was set at 1.52 m rather than the typical 2.44 m for unwrapped hay bales. Nine stover bales could fit on one layer over the perforated floor of the batch dryer (Fig. 2). Bale numbers reflect the order of placement.

In experiment #1, a single layer of 9 bales was placed in the dryer. Bale height in the dryer was 0.89 m. Each bale was weighed initially on a flat scale (0-1000 kg, ± 0.5 kg) and core sampled with a cylindrical borer (38 mm diameter by 508 mm length) at two random locations for an estimation of initial moisture content by oven drying during 24 h at 103˚C according to ASAE (2002) Standard S358.2.

Ambient air which was relatively cool during the artificial drying period, between 0 and 8˚C, was heated by the propane gas burner to about 40˚C and pulled through the bales by the suction blower at an air velocity of about 0.20 m/s, i.e. an

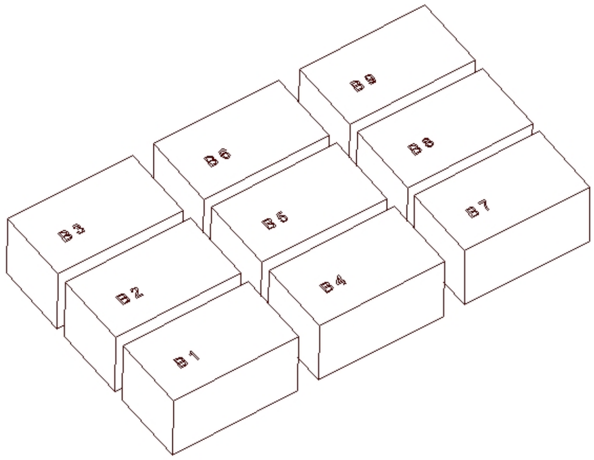

Fig. 2. Schematic view of placement of one layer of corn stover bales in dryer as in experiment #1.

airflow of 2.4 m³/s. Average pressure drop across the bales was 0.2 m of water (2 kPa). Drying was interrupted approximately every eight hours to weigh bales individually; exact drying time for each interval was recorded. Each interruption required about one hour to remove bales from the dryer, weigh them, and replace them in the same position back in the dryer. After each drying interruption, airflow direction was reversed, i.e. heated air entered alternately from the bottom plenum or the top plenum every 8-h period. During the first 40 h of drying, all exhaust air was released to the atmosphere and no exhaust air was recirculated. During the last drying interval which was prolonged to 12 h (period 40-52 h), a large proportion of exhaust air estimated at 89% was recirculated back to the burner and input air duct. This allowed to increase the input air temperature from 40˚C to over 60˚C with a similar propane heating power. After about 52 h of drying time (and about 57 h total time considering five interruptions for weighing), the nine bales were weighed and core sampled again at two positions for final moisture content. Bales were then stacked and stored in a cold barn.

Experiment #2: Two-layer batch drying

In experiment #2, two layers of nine bales were placed one over the other in the dryer. Bale numbers in Fig. 3 reflect the order in which bales were placed. Bale height in the dryer was 1.78 m. Each bale was weighed initially and core sampled at two random locations for an estimation of initial moisture content, as in experiment #1.

A large proportion of exhaust air estimated at 89% was recirculated back to the burner through the input air duct during the whole experiment which lasted 90 h. On average, 11% of ambient air was mixed with the recirculated air. The air mix was heated to an average air temperature above 60˚C throughout the experiment. Pressure drop across the bales was similar to pressure drop in experiment #1 (0.2 m water, i.e. 2 kPa) but air velocity was about 20% lower at 0.16 m/s, i.e. an airflow of 1.9 m³/s. Airflow direction was reversed once, after 16 h. Beside this one air inversion, drying was not interrupted during the 90-h period and bales were not removed from the dryer except at the end. After 90 h of drying time, the 18 bales were weighed and core sampled again at two positions for final moisture content.

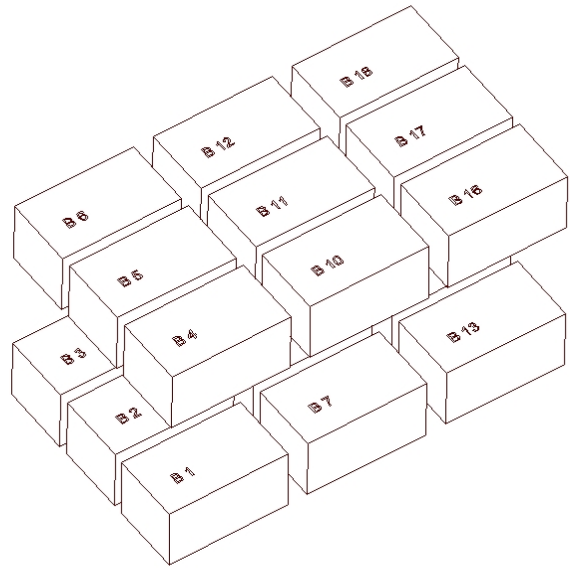

Fig 3. Schematic view of placement of two layers of corn stover bales in dryer as in experiment #2.

At the end of the second drying experiment on November 24, six dried bales were selected (three from experiment #1, three from experiment #2) along with one non-dried bale preserved with plastic wrap. These bales were transported to a cold storage shelter near the Laval University laboratory in Sainte-Foy (300 km south-east of Normandin). Over a period of one week (November 25 to December 2), the seven bales were sliced to take 75 samples for moisture content as shown in Fig. 4. Each bale was initially sliced vertically at about 115 mm from one side and again at 190 mm. This thin vertical slice (about 75 mm thickness) by the whole section (about 810 mm by 890 mm) was set on a horizontal table and sliced again in five strips. The five strips were sliced again to retain three samples per strip. Each sample was approximately a cube of 75 mm on the side. Four other vertical slices were taken every 305 mm from the first slice. The moisture content data were averaged on three horizontal planes of 25 samples each: an upper plane (140 mm from the top horizontal surface), a middle

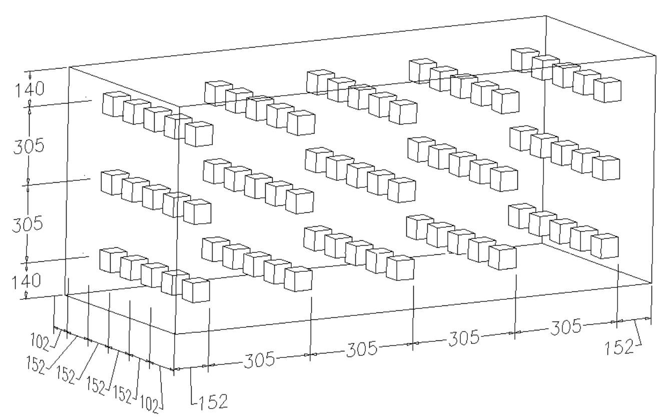

Fig. 4. Schematic view of 75 samples cut out from selected bales to estimate moisture content variation after drying and storage. Dimensions are in millimeters.

Table 2. Individual bale mass, measured moisture content (MC) on a wet basis, and estimated moisture content based on mass balance for drying experiment #1 (9-bale, one-layer, 52-h batch).

Bale number	Initial mass (kg)	Final mass (kg)	Measured initial MC (% w.b.)	Estimated final MC (% w.b.)	Measured final MC (% w.b.)	Estimated initial MC (% w.b.)
1	270	172	55.9	30.7	28.5	54.6
2	278	156	53.5	17.2	21.5	55.9
3	295	191	53.0	27.4	16.1	45.7
4	284	119	57.8	-0.9	19.3	66.2
5	291	144	38.5	-24.5	16.1	58.6
6	312	168	57.0	20.0	25.4	59.9
7	278	181	47.4	19.2	36.2	58.4
8	292	110	55.2	-19.2	7.2	65.1
9	233	129	52.6	14.4	9.5	49.9
Average	282	152	52.3	11.8	20.0	56.8

plane (445 mm from the top surface), and a lower plane (140 mm from the bottom). Grouping the moisture content data on horizontal planes was done to observe vertical differences since the drying airflow direction was perpendicular to the horizontal planes.

Instrumentation, control, and measurements during drying

The instrumentation and control system installed in the bi-directional dryer are described in detail in the paper by Descôteaux and Savoie (2004). The following measures were taken continuously and recorded every two minutes. Air temperature and relative humidity were measured at four points in the dryer: at the inlet just before entering the gas burner, at the top plenum, at the bottom plenum, and at the outlet just after the suction blower. Pressure drop across the bale stack was measured between the two plenums. Electrical current was measured at the blower. Thermistors could be placed at different positions to measure temperature in the bales, but this was not done in the current experiments, partly due to frequent handling of bales. On/off sensors recorded continuously whether the blower and the gas burner were activated or not. To meet safety requirements, the fan was always started two minutes before the gas burner to purge any residual gas prior to starting combustion.

A propane gas volume counter was manually read at every drying interval. Gas consumption was converted into energy (93,800 kJ/m³ of propane) and power by dividing by the time of the interval.

RESULTS and DISCUSSION

Experiment #1: One-layer batch drying

Table 2 shows the initial and final mass of individual corn stover bales during the total drying time of 52 h for the one-layer batch. The measured initial moisture content, based on two samples per bale, was 52.3%. When final moisture content was estimated from these measured initial moisture contents and a mass balance, three values were negative and erroneous. This is because two samples, each weighing less than 100 g, were not always representative of the average initial moisture content of the whole bale which weighed on average 282 kg. More samples would be necessary to obtain a more representative estimate of the initial moisture content. However, taking a large number of samples from each bale initially was not always feasible because of time constraints and the need to maintain bale integrity. Measured final moisture content, also taken from two small core samples at the end of drying, averaged 20.0%. From these measured final moisture contents and the mass balance, the average initial moisture content was estimated as 56.8%.

In principle, initial core moisture samples should be as representative of the entire bale as final core moisture samples because size and number of samples were the same. However, the very wet stalk appeared to be more resistant to shearing with the core sampler than the dry stalk. Some of the wet stalk may have been pushed sideways when coring for initial moisture. This phenomenon would lead to an underestimate of initial moisture content because the stalk is considerably wetter than other fractions , i.e. cob, husk, and leaf (Shinners et al. 2003). Larger core samples (diameter greater than 38 mm actually used) would likely improve the accuracy of initial moisture estimation.

Moisture content was less uniform at the end of drying (average standard deviation, SD, of 13.2%) than just before drying (SD of 4.3%) as discussed below in the section about moisture distribution within individual bales sampled at 75 points. Therefore average DM in each bale was estimated from the average DM based on measured initial and final moisture content samples, except for three cases (bales # 4, 5, and 8) where initial moisture content was clearly an underestimate (and DM an overestimate). In these three cases, only DM based on final measured moisture content was considered. On this basis, the average initial moisture content of the nine bales was estimated as 56.6% and the average final moisture content as 19.2%. Since the average bale volume was 1.10 m³, data in Table 2 allowed to estimate dry matter density of stover bales which ranged from 87 to 137 kg/m³, with an average and standard deviation of 110 and 14.7 kg/m³, respectively.

Figure 5 shows the average, minimum, and maximum moisture content of the nine corn stover bales during the one-layer batch drying experiment #1. Since bales were weighed every 8 h, intermediate moisture content values are relatively accurate based on mass balance. The initial moisture content ranged from 49 to 66% between bales. The difference in moisture content on a wet basis remained fairly constant (17% units) until 40 h. It widened to 23% units in the last 12 h of drying with final moisture content ranging from 7 to 30%.

Figure 6 shows the air temperature at four positions in the dryer as a function of time for the 9-bale batch. Heated air arrived in the hot plenum at 40˚C for the first five 8-h periods and was increased to an average of 67˚C in the sixth period because of air recirculation. Air coming out from the cooler plenum was at a average temperature between 16 and 27˚C for

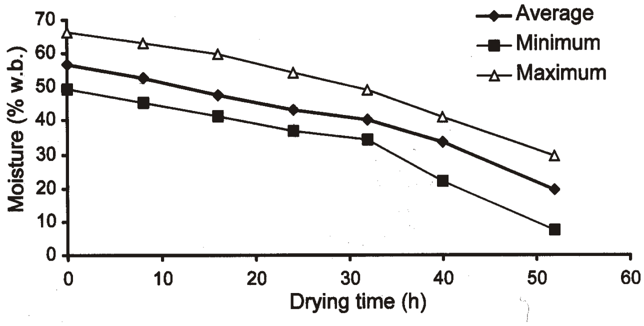

Fig. 5. Moisture content (wet basis) of corn stover bales during drying experiment #1 (9-bale batch on one layer 0.89 m high). Values are based on average DM from initial and final moisture content samples and mass balance for each bale.

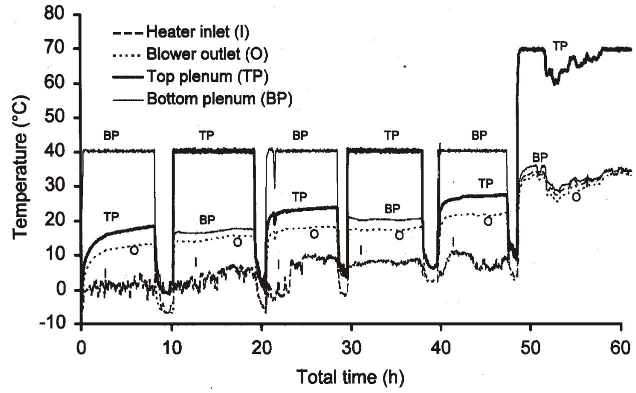

Fig. 6. Air temperature at four positions in the dryer as a function of total time for experiment #1 (9-bale batch). Airflow was interrupted and direction reversed five times after every 8-h period with about 1 h interruption for bale weighing. Inlet air was ambient except in the sixth drying period when about 89% exhaust (outlet) air was recirculated.

the first five periods, and averaged 33˚C in the sixth period. Inlet air was the ambient air for the first five periods; it gradually increased from an average of 1˚C during the first drying period to 8˚C during the fifth drying period. In the sixth drying period, inlet air was a mix of ambient air (about 11% at 8˚C) and recirculated outlet air (about 89% at 33˚C).

Experiment #2: Two-layer batch drying

Table 3 shows the initial and final mass of the 18 individual corn stover bales during the 90 h period of the two-layer batch drying. The measured initial moisture content, based on two samples per bale, was 55.4%. When the final moisture content was estimated from the measured initial moisture contents and a mass balance, one value was negative and erroneous while a few other values were probably too low (less than 5% estimated final moisture content in three other bales). However, the estimated final moisture content averaged over 18 bales was 16.1% and relatively close to the measured final moisture content averaged over 18 core samples which was 17.7%. As in the previous experiment, average DM was estimated for each bale on the basis of average of initial and final moisture content sampling except for four bales (# 2, 5, 10, and 11) where measured initial moisture contents were considered underestimates and only the final measured moisture content was used. The average initial moisture content was therefore estimated as 56.1% and the average final moisture content as 17.7%. In this second experiment, dry matter density of stover bales ranged from 94 to 144 kg/m³, with an average and standard deviation of 120 and 15.0 kg/m³, respectively. Over the two experiments (27 bales), DM density averaged 117 kg/m³, ranged from 87 to 144 kg/m³ and had a standard deviation of 15.3 kg/m³.

After averaging initial and final DM and correcting moisture contents in experiment #2 as explained above, the initial moisture content ranged from 49 to 62% between bales while the final moisture content ranged from 8 to 38%. The final moisture range was greater in the second experiment than in the first experiment (7 to 30%). Less uniform drying in the second experiment may be partly explained by the fact that there were two layers of bales rather

Table 3. Individual bale mass, measured moisture content (MC) on a wet basis, and estimated moisture content based on mass balance for drying experiment #2 (18-bale, two-layer, 90-h batch).

Bale number	Initial mass (kg)	Final mass (kg)	Measured initial MC (% w.b.)	Estimated final MC (% w.b.)	Measured final MC (% w.b.)	Estimated initial MC (% w.b.)
1	292	188	55.8	31.1	22.1	50.0
2	329	143	56.5	0.2	8.3	60.1
3	308	178	51.5	16.4	7.8	46.5
4	316	195	54.7	26.4	15.1	47.7
5	304	129	59.4	4.5	8.2	61.0
6	321	200	57.5	31.8	9.7	43.8
7	233	166	56.1	38.5	36.4	54.6
8	280	157	59.7	28.0	19.3	54.8
9	354	185	59.9	23.1	31.7	64.4
10	304	141	55.1	3.5	8.1	57.3
11	290	125	55.7	-2.8	9.8	61.1
12	317	173	53.6	15.0	24.9	59.0
13	316	178	58.0	25.2	18.5	54.3
14	333	154	56.9	7.1	11.2	58.8
15	224	139	43.8	9.7	42.8	64.4
16	295	140	56.4	7.8	7.4	56.2
17	279	132	56.7	8.4	11.2	58.1
18	299	178	50.4	16.6	25.5	55.6
Average	300	161	55.4	16.1	17.7	56.0

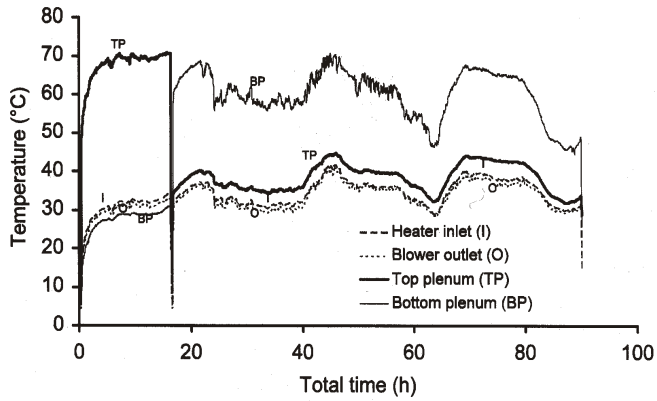

Fig 7. Air temperature at four positions in the dryer as a function of total time for experiment #2 (18-bale batch). Airflow was interrupted and direction reversed once after 16 h of drying. Inlet air was composed of about 89% recirculated outlet air and 11% ambient air.

than one (stacks 1.78 m high rather than 0.89 m) and by the fact that airflow direction was reversed only once after 16 h compared to five times in the first experiment.

Figure 7 shows the air temperature at four positions in the dryer for the 18-bale batch. Heated air arrived in the top plenum at an average of 68˚C for the initial 16-h period; it arrived in the bottom plenum at an average of 60˚C for the next 74 h. Heated air temperature averaged 61˚C over the entire 90 h. Air coming out from the cooler plenum was at an average temperature of 27˚C for the 0-16 h period, 38˚C for the 16-90 h period and averaged 36˚C over 90 h. Inlet air was composed of 89% recirculated air from the cooler plenum and 11% fresh ambient air. Inlet air temperature at the heater averaged 34˚C over the total drying time of 90 h.

Moisture distribution in individual bales

Three bales from each drying experiment were cut into 75 samples, as explained in the methodology, to estimate moisture distribution in individual bales. Table 4 presents moisture content of these six bales based on two core samples taken just after drying or on 75 sliced samples taken about one week after drying. The three bales from experiment #1 (bales 1, 3, and 7) had an average moisture content of 26.3% just after drying. The same three bales had an overall average moisture content of 30.5% one week after drying. This increased moisture content of about 4% units may have been caused by re-humidification during cold storage at about 0˚C either from the air, from snow which covered the ground during handling or from moisture migration between bales. Bales from both drying experiments were stacked together in the storage shelter. Since the final moisture content of bales ranged from 7 to 30% for drying experiment #1 and from 8 to 38% for drying experiment #2, some moisture could have migrated from wetter bales to drier bales.

Because bales were in a single layer and airflow direction was changed five times in drying experiment #1, one might have expected the middle horizontal plane of each bale to dry more slowly than the upper or lower planes that were first in contact with the heated air. In bales 3 and 7, the middle planes were indeed slightly wetter that the two other planes but this was not the case in bale 1. Bales dried in experiment #1 had a fairly uniform moisture content vertically. However, the overall standard deviation of individual moisture contents was relatively high (average 13.5%), indicating possibly more lateral than vertical variation in each bale.

The three bales from experiment #2 (bales 4, 8, and 16) had an average moisture content of 17.3% just after drying while their overall average moisture content was 18.5% one week after drying, i.e. about a 1% unit moisture increase. As was suggested for bales from experiment #1, bales from experiment #2 could also have re-humidified during cold storage. Trying to understand differences in moisture content between horizontal planes in experiment #2 is relatively complex because there were two layers of bales and a single airflow direction change after 16 h over the 90 h total drying time. Bales 4 and 16 were located on the upper layer (Fig. 3) which received the heated air during 16 h from the top plenum and the humidified and cooled air from the bottom plenum for 74 h (Fig. 7). The highest moisture plane, for both bales 4 and 16, was the lower plane

Table 4. Moisture content (% wet basis) in selected bales just after drying (2 samples per bale and mass balance) and after a one-week storage period (25 samples per horizontal plane). The three horizontal planes were located at 0.14 m from the top of bale, in centre (0.45 m from top), and at 0.14 m from bottom of bale.

Experiment number-bale number	Moisture content just after drying	Moisture content after drying and one-week storage					Probability of difference between planes
		Upper horizontal plane	Middle horizontal plane	Lower horizontal plane	Overall average	Overall S.D.	
E1-B1	29.6	28.1	29.1	31.5	29.6	10.6	0.469
E1-B3	21.7	27.5	36.9	33.3	32.6	17.9	0.007
E1-B7	27.7	29.7	30.8	27.4	29.3	12.1	0.530
E2-B4	20.7	27.5	27.2	30.1	28.3	17.3	0.664
E2-B8	23.7	20.7	20.9	16.0	19.2	11.6	0.027
E2-B16*	7.6	5.9	8.5	9.4	7.9	9.7	0.532
Not dried		64.3	61.3	63.1	62.9	4.3	0.015

*There were only 20 samples per horizontal plane for bale E2-B16.

Table 5. Moisture content (% wet basis) in selected bales just after drying and after a one-week storage period (15 samples per vertical plane). The five vertical planes were located at 0.15, 0.46, 0.76, 1.07, and 1.37 m from one end of a 1.52 m long bale along the axis of compression.

Experiment number-bale number	Moisture content after drying and one-week storage					Probability of difference between planes
	Vertical plane A	Vertical plane B	Vertical plane C	Vertical plane D	Vertical plane E	
E1-B1	24.4	27.0	32.2	33.9	30.5	0.077
E1-B3	47.0	44.8	41.4	15.8	13.8	<0.001
E1-B7	21.7	31.8	32.8	36.9	23.3	<0.001
E2-B4	38.4	33.2	38.4	26.6	4.6	<0.001
E2-B8	6.4	11.9	28.0	31.3	18.3	<0.001
E2-B16	11.8	NA*	12.5	3.4	3.9	0.023
Not dried	59.2	62.5	66.5	64.4	62.0	<0.001

*Samples of vertical plane B in bale E2-B16 were not available.

located near the centre of bales which were stacked over two layers. So bales tended to dry from the outer surface down to the centre when there was at least one airflow direction change. The other bale (8) was located on the bottom layer and it had its lowest moisture plane at the bottom, also nearest the plenum. The comparison of moisture content at three horizontal planes showed a significant difference in two bales out of six (Table 4). The comparison of moisture content at five vertical planes showed a significant difference in all six bales (Table 5). There appears to be more lateral than vertical variation in the moisture content within each bale after drying.

While bale 16 was the driest at 7.9% moisture, the bale located just under it, bale 13, had a final moisture content just after drying of 21.9% (based on two core samples and a mass balance, i.e. an average of measured moistures in Table 3). Information is not available to explain whether a higher airflow passed through bales 13 and 16 compared to other horizontal location on the surface of the whole drier. Bale 16 had a slightly lower dry matter density (118 kg/m³) than bale 13 (127 kg/m³) but their density was similar to the average (120 kg/m³). A number of other bales in experiment #2 had a considerably lower density. For example, bales 7 and 15 both had a DM density of about 95 kg/m³ which would normally offer less resistance to airflow and perhaps result in lower final moisture content, but this was not the case with final moisture contents of 37.5% and 26.2%, respectively.

A single wet corn stover bale, wrapped at harvest in October and cut up into 75 samples in December, indicated an average moisture content of 62.9% and a relatively low standard deviation of 4.3%. Artificial drying therefore increased the standard deviation of moisture content in bales (average 13.2% after drying).

A more accurate picture of moisture variation within each bale will require taking a large number of samples soon after drying to avoid confounding the possible effect of moisture migration during storage. Present results show that there might be more lateral than vertical variation in moisture, reflecting possible preferential airflows during drying. An increased number of bales, both before drying and just after drying, should be sampled to understand initial and final variation of moisture content laterally and vertically. In addition, the effect of storage on moisture migration within bales and between bales is an important management issue as it might affect the quality and mold content.

Energy requirements and comparison of the two drying experiments

Table 6 presents comparative results between both drying experiments, including air conditions and energy requirements. Air velocity averaged 0.21 m/s in the one-layer batch and 0.16 m/s in the two-layer batch. Pressure drop across the one-layer batch declined gradually from 211 to 191 mm water (2.07 to 1.87 kPa) over the six drying periods, i.e. as the moisture content in bales declined, so did pressure drop. The average pressure drop over the entire drying period was the same in both experiments (201 mm water). The hot plenum, cool plenum, and heater inlet temperatures were illustrated continuously in Figs. 6 and 7 for both experiments whereas average values per period are given in Table 6. Inlet air humidity indicates a higher absolute humidity in experiment #2 than in experiment #1 (0.0090 vs 0.0045 kg moisture/kg air, respectively) because of continuous air recirculation in experiment #2. The higher air recirculation in experiment #2 allowed maintaining a higher hot plenum temperature than in experiment #1 (61.4 vs 44.8˚C) with similar heating power (107.7 vs 98.3 kW) while providing a higher average evaporation rate (27.7 vs 21.6 kg/h). Air recirculation would appear to be favorable, but more experimentation and simulation are required to determine the optimal levels throughout the entire drying process. Exhaust air temperature indicates a temperature decline of about 3˚C between the cool plenum and the exhaust duct, 10 m further down. In experiment #1, the absolute humidity of exhaust air was higher than the absolute humidity of inlet air with a declining difference over time, corresponding to the declining evaporation rates observed generally as drying progressed. When air was recirculated at 89% (period 40-52 h in experiment #1 and throughout experiment #2), there was practically no difference in absolute air humidity between inlet and outlet air, within the instruments' precision (air relative humidity ±3%). The accuracy of current air property sensors needs to be improved to estimate moisture mass balance based on air as accurately as moisture mass balance based on bale weighing.

Ambient air temperature varied between 1 and 8˚C. The proportion of air recirculated was at the same level of 89% in

Table 6. Comparative drying and energy requirements for one-layer 9-bale (Experiment #1) and two-layer 18-bale (Experiment #2) batch drying of corn stover.

	Experiment #1 - Drying characteristics per period							Experiment #2
	0-8 h	8-16 h	16-24 h	24-32 h	32-40 h	40-52 h	0-52 h	0-90 h
Actual drying time (h)	8.05	9.03	7.93	8.35	7.73	12.74	53.83	90
Air velocity (m/s)	0.20	0.20	0.20	0.21	0.21	0.25	0.21	0.16
Pressure drop (mm H_2O)	211	208	203	201	194	191	201	201
Hot plenum temperature (˚C)	40.3	40.3	40.3	40.3	40.3	67.3	44.8	61.4
Cool plenum temperature (˚C)	15.9	17.0	23.0	20.4	26.7	33.0	22.7	36.4
Heater inlet temperature (˚C)	1.1	3.7	5.7	7.9	8.2	32.0	9.8	34.1
Heater inlet relative humidity (%)	82	66	61	61	68	24	60	27
Heater inlet absolute humidity (kg/kg)	0.0033	0.0033	0.0036	0.0040	0.0044	0.0072	0.0045	0.0090
Exhaust temperature (˚C)	11.4	14.8	17.6	17.5	21.5	30.8	19.8	33.1
Exhaust relative humidity (%)	69	45	38	40	36	26	40	29
Exhaust absolute humidity (kg/kg)	0.0057	0.0048	0.0048	0.0049	0.0058	0.0070	0.0056	0.0092
Ambient air temperature (˚C)	1.1	3.7	5.7	7.9	8.2	8.0	5.8	1.0
Recirculated air (%)	0	0	0	0	0	89	15	89
Evaporation (kg)	234	218	156	96	178	282	1165	2492
Evaporation rate (kg/h)	29.1	24.2	19.7	11.5	23.1	22.2	21.6	27.7
Unit evaporation (kg/h/bale)	3.25	3.03	2.17	1.33	2.48	2.61	2.40	1.54
Theoretical evaporative power (kW)	20.2	16.8	13.7	8.0	16.0	15.4	15.0	19.2
Actual heating (kW)	93.9	89.4	101.9	87.4	97.8	112.5	98.3	107.7
Actual blowing (kW)	12.7	12.7	12.7	12.9	12.8	13.5	12.9	13.4
Total power input (kW)	106.6	102.1	114.6	100.3	110.6	126.0	111.1	121.1
Energy efficiency (%)	19.0	16.4	11.9	7.9	14.5	12.2	13.5	15.9
Pipe heat loss PHL (kW)	32.4	29.9	31.1	26.9	30.4	50.6	33.6	57.5
Efficiency excl. PHL (%)	27.2	23.3	16.4	10.9	20.0	20.4	19.4	30.2

the last period of experiment #1 (40 to 52 h) and throughout the whole 90 h of experiment #2.

Water evaporation rate declined gradually in experiment #1 from period 0-8 h until period 24-32 h and then increased in period 32-40 h. There was no logical explanation except that airflow was reversed at the end of each 8-h period. Bale placement might have been tighter during the 32-40 h period compared to previous periods, thereby improving airflow through bales, reducing inter-bale airflow losses, and increasing evaporation from the bales. The relatively high evaporation rate during period 40-52 h was explained by the fact that air temperature was increased from 40˚C to 67˚C on account of air recirculation. In experiment #1 (9 bales), unit evaporation rate ranged from 1.33 to 3.25 kg/h per bale and total water evaporation rate ranged from 11.5 to 29.1 kg/h (average 21.6 kg/h). In experiment #2 (18 bales), no intermediate values were available but average evaporation rates were 1.54 kg/h per bale or 27.7 kg/h over the 90 h period. In the early periods of drying with two layers of bales (experiment #2), total evaporation likely peaked well above 30 kg/h since 29 kg/h was observed with a single layer of bales (experiment #1).

Theoretical evaporation power was estimated from the water evaporation rate, assuming a heat of vaporization of 2500 kJ/kg of water. This useful energy was divided by the total input energy from heating and ventilation (blowing) to estimate the energy efficiency which averaged 13.5% in experiment #1 and 15.9% in experiment #2. Air conduits were not insulated because the experimental dryer was originally intended to dry hay bales mainly in the summer. Drying corn stover bales in December occurred when ambient air was near 0˚C, about 20 to 25˚C lower than usual summer ambient air temperatures. Pipe heat loss was quite important for the corn stover bale drying experiments. By an approximate heat balance, the pipe heat loss was estimated as 0.6 kW per unit temperature difference (˚C) between the plenum temperature and the ambient temperature for both the hot plenum and the cool plenum. The pipe heat loss varied between 27 and 51 kW for experiment #1 and averaged 58 kW for experiment #2. Pipe heat loss was higher with air recirculation because of higher air temperatures in the plenums and higher loss to ambient air. With proper insulation, most of the pipe heat loss could be eliminated and thermal efficiency would have averaged 19% for experiment #1 and 30% for experiment #2.

Cost of artificial drying of corn stover bales

On the basis of the above experimental results, estimates were made on the cost of artificial drying of corn stover bales. Bales were assumed to have a dry matter density of 120 kg/m³. The desired final moisture content was 12%. The water evaporation rate was assumed to be 1.5 kg/h per bale and the energy efficiency 30%, similar to values obtained with a two-layer batch drying system. Calculations were made for initial moisture contents between 20 and 55% (Table 7). Two sources of heat energy were considered: combustion of natural gas and an electrical heat pump system with a coefficient of performance of 3 (units of heat per unit of electrical energy input). In the case of combustion, the heating energy requirement was therefore 8333 kJ/kg of water evaporated (2.31 kW h/kg). In the case of the heap pump, the energy requirement was 2777 kJ/kg of water evaporated (0.77 kW h/kg).

Table 7. Estimated time, energy, and variable cost for drying corn stover bales to 12% final moisture content with a gas burner or a heat pump.

Initial moisture content (% w.b.)	Drying time (h)	Heating energy (kW h/t DM)	Fan energy (kW h/t DM)	Energy cost with burner ($/t DM)	Energy cost with heat pump ($/t DM)
20	10.4	263	39	10.24	5.86
25	18.1	456	68	17.75	10.16
30	26.8	676	101	26.33	15.07
35	36.9	931	139	36.23	20.74
40	48.7	1228	183	47.79	27.36
45	62.6	1578	235	61.44	35.17
50	79.3	1999	297	77.82	44.55
55	99.6	2514	374	97.85	56.02

This latter value is equivalent to a specific moisture extraction rate (SMER) of 1.3 kg per kW h. Jon et al. (2000) reported SMER values of 2.2 to 3.2 for drying timber with a heat pump. However, Adapa et al (2002) estimated lower SMER values in the range of 0.5 to 1.1 kg per kW h with a heat pump used to dry alfalfa. The assumed SMER of 1.3 kg per kW h can probably be increased in the future with improved technology and optimized operating conditions. For both the combustion and heat pump systems, electricity was used to operate the fan. Unit energy costs were assumed to be $0.03 per kW h for natural gas ($8.33/GJ) and $0.06 per kW h for electricity.

In Table 7, the total energy cost for drying with a natural gas burner is seen to vary from $10 to $98/t of corn stover dry matter depending on the initial moisture content from 20% to 55%. If a heat pump system is used, the energy cost will range from $6 to $56/t DM. These costs do not include dryer fixed costs which could range between $10 and $20/t DM depending on the type of heat source (more expensive fixed costs with a heat pump system) and the annual use of the dryer. Total drying costs are therefore expected to be at minimum $20/t DM for relatively dry corn stover, harvested at 20% moisture and to climb to about $35/t DM at a moisture content of 30%. Artificial drying of corn stover wetter than 30% is likely to be too expensive for most potential uses as a feedstock.

Beyond the cost, there are several technical hurdles that need to be addressed before considering artificial drying of corn stover bales on a larger scale. One is the heterogeneity of moisture at harvest. The difference in moisture content between corn stover bales, i.e. the difference between maximum and minimum moisture, was initially in the order of 15 to 20% units. This difference was seen to continue or even increase during drying. An alternate approach to batch drying would be to dry separately each individual bale according to its initial moisture content by adjusting time, air temperature, and air velocity appropriately. Another approach is to consider wet storage rather than dry storage. Clarke (2001) reported wet storage costs for big bales between $4 and $15/DM t. Wet storage is definitely less expensive than dry storage with artificial drying. The choice of harvest and storage technologies for corn stover will have to take into account the end-application requirements in terms of moisture, particle length, tolerance of impurities such as mold, and the value that can be afforded for the feedstock.

CONCLUSIONS

1. The amount of corn stover left in the field after grain harvesting in eastern Canada is estimated at 7 Mt yearly. About one half of this biomass could be removed without negative impact to the soil and processed into bioenergy or bioproducts.
2. Because some potential uses require a dry feedstock, mid-size rectangular bales (0.81 m by 0.89 m by 1.52 m) of corn stover were dried artificially. A pilot-scale dryer demonstrated the feasibility of removing moisture from these bales. A one-layer batch of 9 bales dried from an average 56% moisture to 19% moisture in 52 h with air heated at 45˚C on average. A two-layer batch of 18 bales dried from an average 56% moisture to 18% moisture in 90 h with air heated at 61˚C on average.
3. Initial moisture content ranged from 49 to 66% between bales prior to artificial drying. The moisture content difference between the driest bale and the wettest bale increased after drying. Final moisture content ranged from 7 to 30% in the one-layer batch and from 8 to 38% in the two-layer batch.
4. Energy efficiency for water evaporation was 13% in the one-layer batch and 16% in the two-layer batch. Minor improvements such as air pipe insulation could improve energy efficiency to 30%.
5. Total cost to artificially dry corn stover bales to a final moisture content of 12% was estimated at $20/t DM for stover harvested at 20% moisture and $35/t DM for stover harvested at 30% moisture. In climatic zones where field wilting does not allow natural drying of corn stover to less than 30% moisture because of frequent rain or cool weather, wet storage is likely to be the preferred method of conservation.

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