PROCESSING WHOLE-PLANT CORN SILAGE WITH CROP PROCESSING ROLLS ON A PULL-TYPE FORAGE HARVESTER

K. J. Shinners, A. G. Jirovec, R. D. Shaver, M. Bal

ABSTRACT. *Whole-plant corn silage (WPCS) was harvested with a pull-type forage harvester equipped with crop processing rolls. Variables considered were crop maturity, theoretical length-of-cut (TLC), processor roll speed difference and roll clearance. Whole-plant particle size, whole cob and coarse fiber fractions, level of kernel breakage, and kernel fraction particle-size were used to quantify crop physical properties. Compared to unprocessed WPCS cut at 9.5 mm TLC, WPCS cut at 19 mm TLC and then processed had greater whole-plant particle size, less whole cob fraction, fewer unbroken kernels, smaller kernel fraction particle size, and greater estimated surface area of the kernel fraction. The processed treatments at 19 mm TLC and 3 or 5 mm roll clearance required similar specific energy and produced similar harvesting rates compared to the control unprocessed treatment at 9.5 mm TLC. Feeding dairy cattle WPCS (~33% of DMI) increased fat-corrected milk yield by about 4% and fat yield by about 2%. Compared to unprocessed WPCS cut at 9.5 mm TLC, WPCS cut at 19 mm TLC and processed with 1 mm roll clearance increased in situ DM disappearance by seven percentage units. Based on crop physical properties, harvester energy requirements and dairy cattle lactation performance, the recommended settings when harvesting WPCS with an on-board crop processor would be 19 mm TLC and 1 to 3 mm roll clearance.*

Keywords. *Forage harvester, Processing rolls, Corn silage.*

North American dairy farmers are showing increasing interest in processing whole-plant corn silage (WPCS) with roll processors onboard the forage harvester. Although commonly utilized in Europe for years, the practice was virtually ignored in North America. This lack of interest could be traced to the following causes. First, nutritional research in North America with beef and dairy animals had not shown improved animal performance with processed corn silage diets (Miller et al., 1969; Rojas-Bourrillon et al., 1987). These researchers harvested both the control and processed crop at a theoretical length-of-cut (TLC) of 3 to 10 mm. By cutting at a short TLC and then processing, the quantity of fine material in the diet was increased such that depressed fiber digestion may have counteracted any improvement in starch digestion. Second, there was a decade long decline in the total North American production of corn silage (Shinners, 1997). Third, there was a lack of availability of processing systems on pull-type forage harvesters, the most common machine used to harvest WPCS in North America. Finally, dairy producers typically used a short TLC to eliminate whole cob sections and to be compatible with upright silo unloaders. This short TLC caused considerable kernel breakage, so the concern about incomplete kernel utilization was less.

Recently, there has been unprecedented interest in processed WPCS. This reversal in opinion can be traced to the following causes. First, new nutritional research has shown that increased TLC (12 to 20 mm) with processing WPCS has led to improved animal performance compared to control diets comprised of short TLC unprocessed WPCS (Straub et al., 1996; Johnson et al., 1999; Bal et al., 1998). Second, production of WPCS is increasing because many dairy producers are expanding their herd size on a limited land base and they need to maximize dry matter (DM) yield per unit area. Third, there is a greater understanding by dairy producers of the nutritional benefits of coarse dietary fiber. Processed corn silage cut at a long TLC is one way to produce a feed with sufficient kernel breakage while still maintaining desired fiber length. Finally, there is greater use of bunker and bag silos in North America that are compatible with a longer TLC silage because both silo types are typically unloaded with front-end loaders.

As more producers become aware of crop processing on the forage harvester, questions have arisen concerning the appropriate machine setting for the TLC and the processor roll clearance. Concerns have also surfaced about the harvesting rate and the power requirements of a forage harvester when equipped with crop processing rolls. The overall objective of this work was to answer these concerns and questions regarding processed WPCS. The specific objectives of the research were to: (1) measure physical properties of processed WPCS at a variety of stages of

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The authors are **Kevin J. Shinners**, Professor of Agricultural Engineering, and **Andrew G. Jirovec**, former Graduate Research Assistant, Department of Biological Systems Engineering, and **Randy D. Shaver**, Professor, and **Mehmet Bal**, Graduate Research Assistant, Department of Dairy Science, College of Agriculture and Life Sciences at the University of Wisconsin-Madison. **Corresponding author:** Kevin J. Shinners, University of Wisconsin, College of Agriculture & Life Sciences, 460 Henry Mall, Madison, WI 53706, phone: 608.263.0756, fax: 608.262.1228, e-mail: <kjshinne@facstaff.wisc.edu>.

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maturity and machine variables such as TLC, roll-speed difference, and roll clearance; (2) determine the specific energy requirements and harvester capacities when processing WPCS; (3) process sufficient WPCS at a variety of TLC to conduct full-scale lactation and digestion trials with Holstein dairy cows; and (4) investigate maturity and processing effects on ruminal *in situ* degradation of a variety of WPCS hybrids.

Description of Crop Processor and Harvesters

A set of grooved counter-rotating rolls was placed after the cutterhead of an experimental forage harvester (fig. 1). With a simple field adjustment, it was possible to direct the crop from the cutterhead toward either the processing rolls (processed treatment) or directly toward the cross-auger (unprocessed treatment). Thus, it was possible to use the same machine to produce both the control and experimental treatments.

The processing roll diameter was about 150 mm, the tooth pitch 6.4 mm and the tooth depth 5.4 mm. The processing rolls were hardened to Rockwell "C" 56 after fabrication and had a 60° angular tooth profile. In 1997, the rolls were powered via four "A" section v-belts from a sheave driven by the cutterhead. The high-speed roll was driven off the backside of the v-belts via a pulley, thus causing this roll to counter-rotate relative to the lower-speed roll. By changing sheave and pulley combinations, no load speed difference (difference of fast and slow roll rotational speed divided by rotational speed of slow roll, expressed as a percent) between the processing rolls of 17 and 50% were obtained. In 1998, four "A" section v-belts were used to drive a countershaft. This shaft drove a second countershaft through another series of four "A" section v-belts and finally, one processing roll was driven from the left and right end of this shaft, respectively. This arrangement allowed variable pitch sheaves to be used to drive each roll independently, which allowed a speed difference range from 10 to 69%. The harvester was equipped with a two-row harvesting unit and was operated with a Case IH model 7140 tractor with about 150 kW PTO

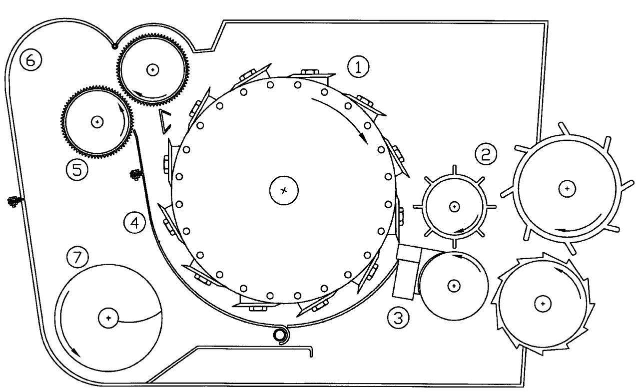

Figure 1–Schematic right-side view of crop processing rolls on the experimental pull-type forage harvester, including ① cutterhead, ② feed rolls, ③ shearbar, ④ removable crop deflector, ⑤ crop processing rolls, ⑥ crop deflector and access panel, and ⑦ cross-auger.

power. Harvesting ground speed typically was between 4 and 5 km/h.

In 1998, two additional commercially available harvesters equipped with optional crop processors were used. A Gehl model 1275 pull-type harvester was equipped with processing rolls between the cutterhead with four knives and the cross-auger. The rolls were about 215 mm in diameter, had longitudinal teeth with a 6.4 mm/tooth pitch, 5.4 mm tooth depth, a 60° angular tooth profile, and a roll speed difference of 13%. The harvester was equipped with a three-row, row-crop harvesting unit and was operated with a John Deere model 7400 tractor with about 80 kW pto power. Harvesting ground speed typically was between 3.0 and 3.5 km/h.

A John Deere model 6750 self-propelled forage harvester equipped with processing rolls between the cutterhead with six rows of knives and the cylindrical blower was also used. The rolls were about 215 mm in diameter, had longitudinal teeth with a 6.4 mm/tooth pitch, 5.4 mm tooth depth, a 60° angular tooth profile, and a roll speed difference of 21%. The harvester was equipped with a six-row, non-row sensitive row-crop harvesting unit and a rated engine power of 270 kW. Harvesting ground speed typically was between 4.0 and 4.5 km/h.

Procedures

Analysis of Physical Characteristics

At harvest, stage of maturity was determined by visual observation of the milk line progression. The kernel milk line is the visual line that separates the solid from the liquid endosperm as the kernel reaches physiological maturity. For each experimental condition, three sub-samples were oven dried at 103°C for 24 h as per ASAE Standard S358.2 to determine dry matter (DM) content (ASAE, 1998). Whole-plant particle size was quantified from three separate sub-samples per experimental condition using the apparatus and procedure described in ASAE Standard S424.1 (ASAE, 1998). The coarse fiber fraction was defined as the fraction of the total particle size sub-sample remaining on the top two sieves of the particle separator (square hole diagonal > 18 mm), expressed as a percent of total mass. Whole, intact cob sections (with or without kernels attached) located on the top sieve were collected, weighed and quantified as a percent of the total mass on that sieve.

A simple hand separation technique was used in 1997 to determine the fraction of kernels damaged. For each experimental condition, a 1/2 L sub-sample was collected and spread on a white surface. Identifiable whole or partial kernels were removed by hand and segregated as either damaged or undamaged. Each fraction was weighed and expressed as a percent of the total kernel mass collected. Kernel breakage was determined on three sub-samples for each experimental condition.

A modified technique based on some features of ASAE Standard S319.3 (ASAE, 1998) was developed in 1998 to more thoroughly quantify the physical properties of the kernel fraction. A 100 g sub-sample was placed in a Tyler Ro-Tap shaker with a cascade of sieves with 12.7, 9.5, 5.9, 4.0, and 2.0 mm openings. The sieve shaker was operated for 2 min. The contents of each of the five sieves and the pan were then separated into five fractions: stalk and broken cobs, whole cobs, undamaged kernels, cracked kernels, and broken kernels. Undamaged kernels were defined as those that were whole, intact, and clearly had no physical damage. Cracked kernels were defined as those that were basically intact, but had a small nick or cut, possibly from the cutterhead rather than the processing rolls. Broken kernels were defined as those whose physical shape was clearly disrupted from the shearing and crushing of the processing rolls.

The elapsed time per sub-sample caused some fractions to dry at differential rates, so all fractions were oven dried at 103°C for 24 h and all subsequent analysis conducted on a DM basis. The physical characteristics of the kernel fraction were quantified by fraction of kernel mass undamaged, cracked, and broken; geometric mean size of the kernel fraction, and estimated surface area of the kernel fraction. The latter two parameters were determined using the procedures in ASAE Standard S319.3. To estimate the surface area of the kernel fraction using ASAE Standard S319.3, shape factors β_s and β_v were assumed to be 3.14 and 0.52, respectively, and particle density was assumed to be 1.4 gm/cm^3. The fraction of the sub-sample found as whole, intact cob was expressed as a percent of the total sub-sample DM.

Analysis of Machine Variables

In 1997, tests were conducted with the experimental harvester at the University of Wisconsin West Madison Experimental Research Station, harvesting Pioneer 3563 hybrid corn (105 day maturity, planted 10 May) on 23 September, 2 October, and 7 October. For these three dates, the stage of maturity was about one-third, one-half, and two-thirds milk line and the moisture was 71, 64, and 61% wet basis (w.b.), respectively. Variables considered were 1 and 3 mm roll clearance (9/23 and 10/2 only) and 17 and 50% no-load roll speed difference (10/7 only). All processed treatments were harvested at 19 mm TLC. Two unprocessed control treatments were harvested at 9.5 and 19 mm TLC.

In 1998, tests were conducted with the experimental harvester at the University of Wisconsin West Madison Experimental Research Station harvesting Pioneer 3563 hybrid corn (105 day maturity, planted 11 May) on 4, 11 and 18 September. For these three dates, stage of maturity was about one-third, one-half, and three-fourths milk line and moisture was 69, 63, and 60% w.b., respectively. Variables were 1, 3, and 5 mm roll clearance and 25 and 55% no-load roll speed difference. All processed treatments were harvested at 19 mm TLC. Two unprocessed control treatments were harvested at 9.5 and 19 mm TLC.

In addition, on 18 September 1998, the commercial pull-type and self-propelled harvesters described above were operated along side the experimental harvester. The commercial pull-type harvester was operated at 19 mm TLC with the processor's roll clearance at 1, 3, and 5 mm. The self-propelled harvester was operated at 21 mm TLC with a roll clearance at 1, 3, and 5 mm. The 21 mm TLC setting was used because it offered the closest setting to the 19 mm TLC setting used on the other harvesters. Finally, the commercial pull-type harvester was operated on 25 September 1998 at three TLC (12.7, 19, and 25.4 mm) and three roll clearances (1, 2, and 3 mm), values typical of practice in Wisconsin at the time. The Pioneer 3563 hybrid was then at black layer maturity.

Analysis of Harvester Specific Energy

Field measurement of the experimental forage harvester's specific energy requirement was made on 4, 11, and 18 September 1998 using the experimental conditions described above. During field tests, all the chopped material from the forage harvester was collected in a side-dumping forage box with a weighed container (Kraus et al., 1993). The machine feed rate was determined by dividing the material mass collected during a test run by the test duration. The feed rate chosen was the maximum possible without plugging the harvester at the crop processor. After each test, samples for moisture and particle-size determination were taken (ASAE Standards S328.2 and S424.1, respectively). The feed rate of each test run was adjusted using a moisture adjustment factor (ASAE Standard EP 503; ASAE, 1998). The moisture adjusted feed rate compensates for the effect of conducting individual tests with crop of different moisture contents and reduces the data scatter associated with data on a wet or dry matter basis.

Two torque transducers were used; one mounted between the tractor's pto and the drive shaft of the forage harvester, and another in the drive to the processing rolls. The former transducer allowed determination of the total machine power requirements and the latter the power required by the processing rolls alone. The shaft torque and speed were measured and stored with a portable, programmable datalogger every 0.1 s. After each test, an average of the collected data was stored by the datalogger. Power requirements were then determined from these data. A typical test run lasted about 70 s while harvesting about 600 kg of crop. Specific energy was determined by dividing the required power by the moisture adjusted feed rate. Four replicates per experimental condition were conducted. Speed sensors on the processing rolls were used to independently measure the rotational speed of both rolls during harvest so that actual speed difference could be calculated.

Analysis of Dairy Cattle Performance

In 1997, about 35 t DM per treatment was harvested with the experimental harvester using four machine configurations: unprocessed at 9.5 mm TLC, and processed at 9.5, 14, and 19 mm TLC (17% speed difference, 1 mm roll clearance). The Pioneer hybrid 3563 was harvested as WPCS at the one-half milk line stage of maturity. Experimental silages were stored in four separate silo bags, and averaged 33% whole-plant DM with little variation across treatments at feed-out.

Twenty-four mature Holstein cows at about 50 to 100 days in milk at the start of the feeding trial were used in a replicated 4 × 4 Latin Square design with 28 day periods. Four of the cows were ruminally fistulated to facilitate measurement of rumen pH, fiber-mat formation, and digestion measurements. All diets were fed as total mixed rations (TMR) containing 50% forage of which two-thirds was treatment corn silage and one-third was alfalfa silage on a DM basis. All diets were formulated to 18% crude protein (DM basis) using a corn-soybean meal based concentrate. Greater detail concerning particulars of this feeding trial can be found in Bal et al., 1999.

Analysis of Hybrid, Maturity, and Processing on *In Situ* Degradation

An experiment was conducted to analyze maturity and processing effects on ruminal *in situ* degradation of a variety of WPCS hybrids. Nine hybrids of corn were planted at the University of Wisconsin West Madison Research Station on 11 May 1998 (table 1). Each hybrid was harvested with the experimental harvester at approximately early dent, one-half milk line, and black layer maturity on 28 August, 9 September, and 23 September 1998, respectively. Each hybrid and maturity were harvested at 9.5 mm TLC unprocessed and at 19 mm processed (1 mm clearance and 25% roll speed difference). For each experimental condition, about 25 kg of crop was collected, sealed in a plastic bag and transported to the laboratory. To accommodate the *in situ* work, samples were placed in mini-silos of about 100 mm diameter and 370 mm height. Each mini-silo was hand packed with approximately 1.3 kg of DM, and then compacted with about 16 kN force using a hydraulic press and finally capped with rubber end cap affixed with a plastic hose barb. A rubber balloon was connected to a plastic hose barb to allow for gas expansion. The fermentation period for all treatments was 28 days. After 28 days, all treatments were removed from the silos and immediately frozen so all maturities could be analyzed together at a later date. *In situ* ruminant digestion studies were undertaken using the “macro-bag” technique. Typically, *in situ* digestibility tests are conducted using dried and ground forage to produce sample uniformity and to allow many replicates to be placed into the rumen at once. Because the goal of this test was to determine the 24-h ruminal DM disappearance based on physical differences between treatments, samples were placed in the rumen bags in their “as-fed” physical form. This procedure is similar to that successfully used by Harrison et al. (1997). About 25 g of DM were placed in 250 × 350 mm polyester bags (52 μm pore size) and sealed. Two fistulated Holstein dairy cows in mid-lactation and with similar milk production were used. Tests were conducted over nine days, with one of nine hybrids randomly selected each day. Twelve bags were placed in each cow’s rumen consisting of two replicates of six treatments (two processing levels × three harvest dates).

Statistical Analysis

All data collected in the machine operating variables and power requirement studies were analyzed using analysis of variance. If tests were conducted on different days, a two-way analysis of variance was conducted to remove confounding effects. Statistical differences were determined using a least-square-difference (LSD) at the 95% probability level. The data collected in the *in situ* digestion and dairy cattle performance studies were analyzed using the general linear model procedure of SAS (SAS, 1989).

Table 1. Characteristics of WPCS hybrids used for *in situ* study

Brand	Relative Maturity Estimate (days)	Characteristics	Hybrid
Mycogen	108-112	Leafy	TMF-106
Mycogen	110-115	Leafy	TMF-108
Cargill	110-115	Brown mid-rib	F657
Pioneer	105-110	General variety	P3563
Pioneer	105-110	Bt version of P3563	P35N05
Pioneer	100-105	Waxy	P3578E
Pioneer	110-115	General variety	P3489
Pioneer	110-115	Bt version of P3489	P34R06
Pioneer	110-115	High oil	P34K77

Results

Analysis of Machine Variables

Processing of WPCS was initially conducted in 1997 with the no-load roll speed difference at 17% and roll clearance either at 1 or 3 mm. Two replicate experiments were conducted with the crop maturity at about one-third and one-half milk line, respectively. Processing caused significantly more kernel breakage and left fewer whole, intact cob sections than control treatments (table 2). Processing with either roll clearance produced a high level of kernel breakage, while still providing a longer whole-plant particle size than the 9.5 mm TLC control (table 2).

Table 2. Physical properties of processed and unprocessed WPCS. (processed with 17% no-load roll speed difference)

	Whole-Plant Geometric Mean Particle Size (mm)	Broken and Cracked Kernels (% of total kernel mass)	Whole, Intact Cob Fraction (% of mass on top screen)
One-third Milk Line, 71% (w.b.) Moisture			
Unprocessed — 19 mm TLC	15.2_d	45_a	20
Unprocessed — 9.5 mm TLC	10.1_a	61_b	12
Processed — 19 mm TLC 1 mm clearance	11.9_b	99_c	0
Processed — 19 mm TLC 3 mm clearance	13.5_c	90_c	12
LSD (P = 0.05)	1.1	10	
One-half Milk Line, (64% w.b.) Moisture			
Unprocessed — 19 mm TLC	17.4_c	55_a	50
Unprocessed — 9.5 mm TLC	10.4_a	64_b	29
Processed — 19 mm TLC 1 mm clearance	11.3_a	100_d	0
Processed — 19 mm TLC 3 mm clearance	13.3_b	92_c	0
LSD (P = 0.05)	1.1	5	

Table 3. Physical properties of processed and unprocessed WPCS at two-thirds milk line and 61% (w.b.) moisture (processed with 1 mm roll clearance)

	Whole-Plant Geometric Mean Particle Size (mm)	Broken and Cracked Kernels (% of total kernel mass)	Whole, Intact Cob Fraction (% of mass on top screen)
Unprocessed — 19 mm TLC	15.4_b	44_a	20
Unprocessed — 9.5 mm TLC	10.2_a	51_b	35
Processed — 19 mm TLC 17% speed difference	11.2_a	100_c	0
Processed — 19 mm TLC 50% speed difference	10.4_a	100_c	0
LSD (P = 0.05)	1.3	4	

Decreasing the roll clearance from 3 to 1 mm increased the fraction of cracked and broken kernels to near 100% and reduced the whole-plant particle size a small amount (about 2 mm). The effect of roll speed difference could not be determined because the extent of damage was already 100% at 17% speed difference (table 3).

A more complete, factorial analysis of the effects of machine variables on crop physical properties was conducted in 1998 (tables 4 and 5). Smaller clearance between the processing rolls caused greater drive belt slippage, which slightly reduced the roll speed difference as clearance decreased (table 4). Whole-plant corn silage cut at 19 mm TLC and processed at 1 mm roll clearance resulted in similar whole-plant particle size to that of the unprocessed material cut at 9.5 mm TLC. However, the former treatment had greater coarse fiber fraction than the latter treatment. This long dietary fiber is an important constituent of the dairy cattle ration. Insufficient fiber length can lead to such problems as reduced milk fat content, displaced abomasum, laminitis and acidosis (Sudweeks et al., 1981). All processed treatments had a significantly greater coarse fiber fraction (two to three times) compared to the 9.5 mm TLC control treatment.

Table 4. Average whole-plant physical properties of WPCS harvested on 4, 11, and 18 September 1998

Treatment — TLC	Roll Clear-ance (mm)	Speed Diff. (%)	Whole-Plant Geo-metric Mean Particle Size (mm)	Whole, Intact Cob Fraction (% of total mass)	Coarse Fiber Fraction* (% of total mass)
Unprocessed — 19mm	-	-	19.6_{e}	8_{c}	55.1_{f}
Unprocessed — 9.5mm	-	-	11.4_{a}	4_{b}	15.1_{a}
Processed — 19 mm	1	21	12.0_{ab}	0_{a}	36.4_{b}
Processed — 19 mm	1	42	11.5_{a}	0_{a}	37.1_{b}
Processed — 19 mm	3	26	12.5_{b}	0_{a}	40.0_{c}
Processed — 19 mm	3	45	12.3_{b}	0_{a}	40.1_{c}
Processed — 19 mm	5	26	14.5_{d}	0_{a}	46.4_{e}
Processed — 19 mm	5	49	13.5_{c}	0_{a}	43.9_{d}
LSD (P = 0.05)			0.7	3	1.6

* Particles remaining on top two sieves (square hole diagonal ≥ 18.0 mm).

Table 5. Average physical properties of the kernel fraction of WPCS harvested on 4, 11, and 18 September 1998

Treatment — TLC	Roll Clearance (mm)	Speed Diff. (%)	Kernel Fraction Geometric Mean Particle Size (mm)	Undam-aged % of ker-nel mass)	Cracked (% of ker-nel mass)	Broken (% of ker-nel mass)	Estimated Surface Area (cm²/kg DM)
Unprocessed 19 mm	-	-	6.4_{e}	41.6_{e}	19.7_{d}	38.7_{a}	$7{,}412_{a}$
Unprocessed 9.5 mm	-	-	6.3_{e}	33.3_{d}	19.6_{d}	47.2_{b}	$7{,}445_{a}$
Processed 19 mm	1	21	4.6_{b}	0.2_{a}	3.5_{a}	96.3_{f}	$10{,}685_{d}$
Processed 19 mm	1	42	4.1_{a}	0.0_{a}	1.9_{a}	98.1_{f}	$11{,}829_{e}$
Processed 19 mm	3	26	4.9_{c}	3.8_{b}	10.0_{b}	86.2_{e}	$9{,}892_{c}$
Processed 19 mm	3	45	4.6_{b}	1.0_{ab}	3.0_{a}	96.1_{f}	$10{,}548_{d}$
Processed 19 mm	5	26	5.1_{d}	12.0_{c}	15.3_{c}	72.8_{c}	$9{,}567_{b}$
Processed 19 mm	5	49	5.1_{d}	10.3_{c}	10.0_{b}	79.7_{d}	$9{,}568_{b}$
LSD (P = 0.05)			0.1	3.0	2.8	3.8	309

Processing effectively eliminated the whole, intact cob fraction that is often segregated and refused by dairy cattle.

After separation of the kernel from the stalk and cob fractions, it was determined that the average overall kernel mass fraction for the two control treatments was about 33%; whereas, the kernel mass fraction for all processed treatments averaged 27%. The unidentified kernel fraction in the processed treatments was probably due to the very small size of many of the kernel particles, which made collection difficult. Therefore, the physical properties of the processed treatments presented in table 5 are probably conservative measures the degree of kernel processing.

Processing significantly reduced the particle size and increased the specific surface area of the kernel fraction compared to control treatments (table 5). The 9.5 mm TLC unprocessed treatment had about 33% of the kernels undamaged after harvest. Processing resulted in undamaged kernel fractions of 0.1, 2.4, and 11.1% for 1, 3, and 5 mm roll clearance, respectively. Less than half of the kernel fraction of the 9.5 mm TLC treatment were broken, while the processed treatments had about 97, 91, and 76% broken for 1, 3, and 5 mm roll clearance, respectively. Roll clearance had a greater effect on the subsequent physical properties of the kernel fraction than did roll speed difference (table 5). Greater roll clearance resulted in less kernel breakage, more undamaged kernels and less specific surface area. Greater roll speed difference numerically reduced the fraction of undamaged kernels and created greater specific surface area of the kernel fraction for all roll clearances. However, the effect of greater speed difference on specific surface area was larger at smaller roll clearances. Roberge et al. (1998, 1999) also found that roll clearance and roll speed difference had a significant effect on level of kernel processing. They reported that roll speed difference had greater effect on the level of kernel processing than roll clearance. However, their experiments were conducted using a larger range of speed difference (8 to 93%), larger roll clearance (4 and 6 mm) and much lower feed rates (9 to 18 Mg/h) than reported here (25 to 35 Mg/h).

Independent of clearance or speed ratio, the level of processing of WPCS appeared to increase as the plant matured (table 6). Generally, there were small differences in the processed crop physical properties between one-third and one-half milk line maturity. However, the processed crop at three-fourths milk line had smaller

Table 6. Average physical properties of processed WPCS as affected by crop maturity independent of roll clearance or speed difference

Physical Properties	1/3 Milk Line	1/2 Milk Line	3/4 Milk Line	LSD (P = 0.05)
Whole-plant geometric mean particle size (mm)	13.2_{b}	13.1_{b}	11.9_{a}	0.9
Coarse fiber fraction (% of total mass)	44.1_{c}	41.5_{b}	36.2_{a}	0.9
Kernel fraction geometric mean particle size (mm)	4.8_{b}	4.9_{b}	4.6_{a}	0.1
Undamaged kernels (% of kernel mass)	6.4_{b}	4.3_{a}	3.0_{a}	1.4
Cracked kernels (% of kernel mass)	8.1_{b}	7.7_{b}	5.9_{a}	1.7
Broken kernels (% of kernel mass)	85.5_{a}	88.0_{b}	91.1_{c}	2.1
Estimated surface area of kernel fraction (cm²/kg DM)	10249_{b}	10004_{a}	10792_{c}	200

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whole plant and kernel fraction particle size, fewer undamaged kernels and greater kernel fraction surface area than when the crop was less mature. It was observed that the unprocessed kernels and cobs were physically larger at three-fourths milk line than when the crop was less mature. These larger kernels and cobs were more likely to be damaged by the processing rolls at any given roll clearance. These results suggest that if roll clearance is initially set to provide a sufficient level of kernel processing, changes to roll clearance are unnecessary as the crop matures and clearance could even be increased slightly to achieve the same level of processing found when the crop was less mature.

For a given roll clearance, there were generally very few differences in crop physical properties between different machines when harvesting whole-plant corn silage at three-fourths milk line and 60% (w.b.) moisture (tables 7 and 8). At 1 mm roll clearance, all three machines produced a similar whole-plant and kernel fraction particle size and estimated surface area of the kernel fraction. The self-propelled harvester produced a greater change in kernel fraction physical properties than the two pull-type harvesters did as the clearance was increased from 1 to 5 mm. The self-propelled harvester was operated at over twice the feed rate of the pull-type harvesters. Its crop processor was about the same width, and its cutting frequency (cutterhead knives past the shearbar per unit time) was 18 to 50% greater than that of the two pull-type harvesters. Therefore, the thickness of the mat of material entering the crop processor was greater for the self-propelled harvester than the pull-type harvesters. At 5 mm roll clearance, this extra mat thickness might have cushioned some of the material from the roll forces and contributed to a slightly lower level of processing than the pull-type harvesters at this roll clearance. Self-propelled harvesters may be more sensitive to changes in processor roll clearance because of this phenomenon.

With a very mature, black layer crop, the 12.7, 19, and 25.4 mm TLC generally all produced a similar level of kernel processing (tables 9 and 10). However, the two longer TLC produced a crop that may be more beneficial to

Table 7. Whole-plant physical properties of WPCS harvested on 18 September 1998 with three different harvesters

Treatment	Roll Clearance (mm)	TLC (mm)	Whole-Plant Geometric Mean Particle Size (mm)	Whole, Intact Cob Fraction (% of total mass)	Coarse Fiber Fraction* (% of total mass)
Experimental pull-type	1	19	10.6_a	0	31.8_a
”	3	”	10.4_a	0	29.4_a
”	5	”	14.0_b	0	42.4_b
Commercial pull-type	1	”	11.0_d	0	27.4_d
”	3	”	12.3_e	0	34.9_e
”	5	”	12.8_e	0	32.7_e
Commercial self-propelled	1	21	11.0_g	0_g	28.7_g
”	3	”	12.7_{hi}	0_g	31.6_h
”	5	”	13.1_i	2_h	35.3_i
Average across machines	1	19.7	10.9_j	0	29.3_j
”	2	”	11.8_k	0	32.0_k
”	3	”	13.3_l	0.7	36.8_l

* Particles remaining on top two sieves (square hole diagonal ≥ 18.0 mm).
a, b, c Averages with significant differences for experimental pull-type harvester (p = 0.05).
d, e, f Averages with significant differences for commercial pull-type harvester (p = 0.05).
g, h, i Averages with significant differences for commercial self-propelled harvester (p = 0.05).
j, k, l Averages with significant differences across machines (p = 0.05).

Table 8. Physical properties of the kernel fraction of WPCS harvested on 18 September 1998 with three different harvesters

Treatment	Roll Clearance (mm)	TLC (mm)	Kernel Fraction Geometric Mean Particle Size (mm)	Undamaged (% of kernel)	Cracked (% of kernel mass)	Broken (% of kernel mass)	Estimated Surface Area (cm²/kg DM)
Exp. Pull-type	1	19	4.4_a	0.0_a	6.6_a	93.4_b	11154_b
”	3	”	4.8_b	1.6_a	6.9_a	91.5_b	10072_a
”	5	”	5.0_b	8.8_b	14.4_b	76.8_a	9928_a
Com. Pull-type	1	”	4.7_d	0.0_d	5.9_d	94.1_f	10485_f
”	3	”	5.2_e	0.0_d	14.7_e	85.3_e	9170_e
”	5	”	5.5_f	9.0_e	17.9_e	73.1_d	8714_d
Com. Self-propelled	1	21	4.5_g	0.0_g	0.0_a	100.0i	10524_h
”	3	”	5.6_h	0.0_g	17.4_h	82.6_h	8323_g
”	5	”	5.8_h	5.8_h	19.5_h	74.7_g	8015_g
Average across machines	1	19.7	4.5_j	0.0_j	4.1_j	95.9_l	10721_k
	3	”	5.2_k	0.5_j	13.0_k	86.5_k	9188_j
	5	”	5.4_k	7.9_k	17.3_l	74.9_j	8886_j

a, b, c Averages with significant differences for experimental pull-type harvester (p = 0.05).
d, e, f Averages with significant differences for commercial pull-type harvester (p = 0.05).
g, h, i Averages with significant differences for commercial self-propelled harvester (p = 0.05).
j, k, l Averages with significant differences across machines (p = 0.05).

Table 9. Whole-plant physical properties of WPCS harvested on 25 September 1998 with the commercial pull-type harvester

Roll Clear-ance (mm)	TLC (mm)	Whole-Plant Geometric Mean Particle Size (mm)	Whole, Intact Cob Fraction (% of total mass)	Coarse Fiber Fraction* (% of total mass)
1	12.7	11.0_b	0.7_b	15.0_a
2	”	11.0_b	0.0_a	15.5_a
3	”	10.2_a	0.0_a	15.2_a
1	19.0	11.7_c	0.0_a	34.5_b
2	”	13.3_d	0.0_a	35.2_b
3	”	12.3_c	0.0_a	32.9_b
1	25.4	13.4_d	0.0_a	38.8_c
2	”	13.1_d	0.0_a	39.3_c
3	”	13.1_d	0.0_a	39.9_c
LSD (P = 0.05)		0.6	0.5	2.3

* Particles remaining on top two sieves (square hole diagonal ≥ 18.0 mm).

Table 10. Physical properties of the kernel fraction of WPCS harvested on 25 September 1998 with commercial pull-type harvester

Roll Clearance (mm)	TLC (mm)	Kernel Fraction Geometric Mean Particle Size (mm)	Undamaged (% of kernel)	Cracked (% of kernel mass)	Broken (% of kernel mass)	Estimated Surface Area (cm²/kg DM)
1	12.7	5.0_{bc}	0.0_a	4.3_b	95.7_d	9428_{ab}
2	”	5.2_{cd}	1.6_c	8.5_c	89.9_{abc}	9225_{ab}
3	”	5.3_d	0.0_a	13.5_d	86.5_a	9147_a
1	19.0	4.7_a	0.0_a	0.0_a	100.0_e	10155_{cd}
2	”	5.2_{cd}	0.0_a	11.7_{cd}	88.3_{ab}	9258_{ab}
3	”	4.7_a	0.0_a	7.7_{bc}	92.3_{cd}	10444_d
1	25.4	4.8_{ab}	0.0_a	5.1_{bc}	94.9_d	9947_c
2	”	5.0_{bc}	0.0_a	9.3_{cd}	90.7_{bc}	9520_{ab}
3	”	5.1_{cd}	0.7_b	11.3_{cd}	88.0_{ab}	9551_b
LSD (P = 0.05)		0.2	0.3	4.0	3.9	393

ruminant health because of greater whole-plant particle size and coarser fiber fraction. The longer TLC could also save power at the cutterhead, which could be used at the processing rolls (see below).

Clearly, processing improved the physical characteristics of WPCS by increasing the feed surface area available to rumen microbes while maintaining a greater fraction of long, coarse fiber. Processing allows for a longer TLC to be used so that the processing rolls can utilize energy conserved at the cutterhead. Harvesting with longer TLC and processing resulted in a material with similar whole-plant particle-size, greater coarse fiber fraction, smaller kernel particle size, fewer whole kernels and whole cobs, and greater specific surface area of the kernel fraction than a control treatment that represented current practice (9.5 mm TLC).

Analysis of Harvester Specific Energy

Roll clearance had a significant effect on harvester specific energy requirements (table 11). Processor specific energy was reduced by 20 and 9% as clearance was increased from 1 to 3 mm and 3 to 5 mm, respectively, indicating that the effect on energy required was less as clearance increased. In all cases, greater roll speed difference increased specific energy requirements with an average increase of 22% as speed difference increased from 24 to 45%. The processed treatments at 19 mm TLC and 3 or 5 mm roll clearance required similar specific energy compared to the control unprocessed treatment at 9.5 mm TLC. The processed treatment at 1 mm clearance had numerically the lowest harvesting rate because frequent plugging at the rolls occurred at mass-flow-rates obtainable with other machine configurations (table 11). Roberge et al. (1998) reported processing WPCS increased harvester specific energy requirements by about 7%. In that work, the TLC was 12.7 mm for both processed and unprocessed treatments and processor roll clearance was 4.5 mm. Roberge et al. (1999) also found that power requirements for the crop processor increased with smaller roll clearance and greater speed difference, although these variables did not have a significant effect on overall machine specific energy requirements. However, these experiments were conducted in the laboratory where only very low mass-flow-rates were obtained (9 and 18 Mg/h), so the processor represented only a small part of the total harvester specific energy requirements.

Table 11. Average specific energy requirements for WPCS harvested on 4, 11, and 18 September 1998

Treatment — TLC	Roll Clear-ance (mm)	Speed Ratio (%)	Whole-Plant Geometric Mean Particle Size (mm)	Moisture Content (w.b.) (%)	Moisture Adjusted Feed Rate (Mg/h)	Total Harvester Specific Energy (kWh/Mg)	Processor Specific Energy (kWh/Mg)	Processor Specific Energy Diffe-rence* (kWh/Mg)
Unprocessed 19 mm	-	-	19.6_e	64.2_{bc}	34.9_b	1.76_a	-	-
Unprocessed 9.5 mm	-	-	11.4_a	63.8_b	34.1_b	2.21_b	-	-
Processed 19 mm	1	21	12.0_{ab}	62.4_a	32.4_b	2.46_c	0.83_c	1.63
Processed 19 mm	1	42	11.5_a	63.4_b	26.6_a	2.69_d	1.05_d	1.64
Processed 19 mm	3	26	12.5_b	64.3_{bc}	35.2_b	2.27_{bc}	0.66_{ab}	1.61
Processed 19 mm	3	45	12.3_b	64.9_{cd}	33.3_b	2.47_c	0.81_c	1.66
Processed 19 mm	5	26	14.5_d	65.4_d	35.4_b	2.22_b	0.61_a	1.61
Processed 19 mm	5	49	13.5_c	64.5_c	34.8_b	2.34_{bc}	0.72_b	1.62
LSD (P = 0.05)			0.7	0.6	3.4	0.21	0.07	0.15

* Difference between total and crop processor specific energy.

Table 12. Physical properties of processed and unprocessed WPCS* used for dairy cattle feeding trial

	Whole-Plant Geometric Mean Particle-Size (mm)	Coarse Fiber Fraction† (% of total mass)	Broken and Cracked Kernels (% of total kernel mass)	Whole, Intact Cob Fraction (% of mass on top screen)
Unprocessed — 9.5 mm TLC	11.3	17.4	68	9.9
Processed — 9.5 mm TLC	8.9	5.1	100	0
Processed — 14 mm TLC	10.5	24.7	100	0
Processed — 19 mm TLC	14.1	44.5	100	0.4

* WPCS harvested at one-half milk line and 67% (w.b.) moisture, and processed with roll speed difference of 17% and roll clearance of 1 mm.

† Particles remaining on top two sieves (square hole diagonal ≥ 18.0 mm).

Analysis of Dairy Cattle Performance

When applied at a short TLC (9.5 mm), processing reduced whole-plant particle size, fraction of coarse fibers and fraction of whole, intact cob slices, as well as increased kernel damage (table 12). The coarse fiber fraction in the unprocessed silage contained a high proportion of whole and half cobs that would be prone to sorting in the feed bunk. When applied at a long TLC (19 mm), processing successfully broke practically all cob material and produced primarily precision-cut stalk in the coarse fiber fraction. Cows fed the processed silage on average ate 0.7 kg more DM each day than cows fed unprocessed silage (table 13). Cows fed the processed silage diets on average produced 1.1 kg more milk and 1.6 kg more fat-corrected milk each day than cows fed unprocessed silage (table 13). Milk fat test was 0.06 percentage units higher on average for cows fed the processed silage. This improvement in milk fat test with processing was unexpected, but may have resulted from less sorting of the cob fiber in the bunk for the processed silage diets. There were generally no differences in DM intake, milk yield or milk composition among the processed silage diets with different TLC.

Rumen pH and rumination time did not differ among the four treatments (data not presented). Rumen fiber-mat formation was lower for the 9.5 mm TLC processed silage compared with the unprocessed silage (table 14). Cutting

Table 13. Holstein dairy cattle milk yield and composition as affected by processing and TLC

	Dry Matter Intake (kg/cow/day)	Milk Yield (kg/cow/day)	Fat Corrected (3.5%) Milk Yield (kg/cow/day)	Milk Fat (%)
Unprocessed — 9.5 mm TLC	25.1_a	44.7_a	38.0_a	3.05_a
Processed — 9.5 mm TLC	25.8_b	46.3_b	40.1_c	3.12_b
Processed — 14 mm TLC	25.8_b	45.2_{ab}	38.9_{ab}	3.10_b
Processed — 19 mm TLC	25.7_b	46.0_b	39.8_{bc}	3.13_b
LSD (P = 0.05)	0.5	1.2	1.0	0.04

Table 14. Holstein dairy cattle digestion parameters as affected by silage processing and TLC

Treatment — TLC	Macro Bag *in situ* DM Disappearance (%)	Rumen Mat Formation Time to Exit Rumen (min)
Unprocessed — 9.5 mm TLC	51.0_a	10
Processed — 9.5 mm TLC	58.3_b	7
Processed — 14 mm TLC	57.2_b	9
Processed — 19 mm TLC	52.9_a	11
LSD (P = 0.05)	4.0	

the processed silage at 19 mm TLC produced a similar rumen-mat to the unprocessed silage. It is unknown whether this would have proved beneficial for preventing digestive disorders in fresh cows or in a longer-term study. Ruminal 24-hour macro-bag DM digestion was higher on average for the processed silage (table 14). This parameter was lower for the 19 mm TLC processed silage than the 9.5 and 14 mm TLC processed silage, suggesting that 19 mm may be near the upper limit on processed corn silage TLC.

Analysis of Hybrid, Maturity, and Processing on *In Situ* Degradation

On average, processing WPCS hybrids (19 mm TLC and 1 mm roll clearance), at varying maturities, increased the 24 h macro *in situ* DM disappearance by seven percentage units when compared with WPCS hybrids harvested at 9.5 mm TLC without processing (table 15).

Table 15. Average physical properties and ruminal 24 h macro *in situ* DM disappearance of all WPCS hybrids

Treatment — TLC	Whole-Plant Geometric Mean Particle Size (mm)	Coarse Fiber Fraction (% of total mass)	24 h *in situ* DM Disappearance (% of total mass)
Unprocessed — 9.5 mm TLC	10.8_a	12.5_a	49.4_a
Processed — 19 mm TLC	11.6_b	34.7_b	56.4_b
LSD (P = 0.05)	0.4	1.4	1.2

Table 16. Average physical properties and ruminal 24 h macro *in situ* DM disappearance of WPCS hybrids harvested at early dent (ED), one-half milk line (ML), and black layer (BL)

Treatment — TLC	Maturity	Geometric Mean Particle Size (mm)	Coarse Fiber Fraction (% of total mass)	24 h *in situ* DM Disappear-ance (% of total mass)
Unprocessed 9.5 mm TLC	ED	12.2_b	15.5_d	55.9_b
Processed 19 mm TLC	ED	13.6_a	41.5_a	58.4_a
Unprocessed 9.5 mm TLC	1/2 ML	10.6_d	12.4_e	48.6_d
Processed 19 mm TLC	1/2 ML	11.2_c	33.6_b	58.5_a
Unprocessed 9.5 mm TLC	BL	9.7_f	9.7_f	43.6_e
Processed 19 mm TLC	BL	10.0_e	29.0_c	52.2_c
LSD (P = 0.05)	0.2	0.9	1.6	

The material was harvested on 28th August, 9th September, and 23 September 1998, at early dent, one-half milk line, and black layer maturity, respectively.

As the crop matured from early dent, to one-half milk line, and finally to black layer, both whole-plant particle-size and coarse fiber fraction decreased for both processed and unprocessed treatments (table 16). Averaged across all hybrids, processing WPCS increased the 24 h *in situ* DM disappearance over the unprocessed treatments by 2.5, 9.9, and 8.6 percentage units at early dent, one-half milk line, and black layer, respectively (table 16). Processing at early dent did not produce as great an increase in DM disappearances as that found at one-half milk line or black layer maturity. When the crop is at early dent, its seeds are smaller and may be more likely to pass through the rolls undamaged. Also, at early dent the kernels have a soft endosperm and embryo, which make it easier for rumen microbes to fully utilize the value of the kernel even when unprocessed. At early dent, the stalk has less fiber concentration, so the processed treatment may have shown less benefit from increased surface area of the stalk fraction. As the crop matures, the fiber concentration increases, the kernel and embryo harden, and the sugars change to starch. Processing may then become more effective in improving digestion parameters. Processing showed the ability to maintain DM disappearance at high levels, but it did not totally mitigate the negative effect of maturity on digestibility. For instance, DM disappearance was 52% for the processed treatment at black layer maturity but was 56% for the unprocessed treatment at early dent maturity.

Conclusions

Unprocessed WPCS cut at 9.5 mm TLC is a common harvesting configuration. Compared to this practice, WPCS cut at 19 mm TLC and processed had greater whole-plant particle size, less whole cob fraction, fewer unbroken kernels, smaller kernel fraction particle size, and greater estimated surface area of the kernel fraction.

Within the limits tested, the clearance between the processing rolls appeared to have greater effect on the level of kernel processing than roll speed difference.

Independent of clearance or roll speed difference, the level of processing of WPCS increased as the plant matured. As maturity increased, the kernels and cobs were observed to be larger, and thus were more likely to be damaged by the processing rolls.

The processed treatments at 19 mm TLC and 3 or 5 mm roll clearance required similar specific energy to the control unprocessed treatment at 9.5 mm TLC. Thus the physical property benefits of processing can be achieved without loss of harvesting rate or additional power requirements.

Processed WPCS harvested at one-half milk line with 67% (w.b.) whole-plant moisture increased fat-corrected milk yield by about 4% and fat yield by about 2%.

Based on crop physical properties, harvester energy requirements and dairy cattle lactation performance, recommended settings when harvesting processed WPCS would be 19 mm TLC and 1 to 3 mm processing roll clearance.

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