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Hydrodynamic Separation of Grain and Stover Components in Corn Silage

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Abstract

Mixing fresh silage in water resulted in partial segregation of grain from stover. Grain concentration was 75% in the sunk material when silage was relatively dry (64% moisture content [MC]) and 41% when silage was relatively wet (74% MC). Partial drying to remove 20 percentage units of moisture prior to water separation increased grain concentration to 92%, and complete drying increased grain concentration to 99%. Sieving without drying followed by water separation resulted in a grain concentration of 79%. A byproduct of water separation is a large amount of soluble and deposited fine particles in the effluent: 18% of original dry matter after one separation, and between 21 and 26% after eight separations. In an industrial setting, hydrodynamic separation of silage with minimal pretreatment could provide a feedstock with a high concentration of grain (75–80%). In a laboratory setting, hydrodynamic separation with prior oven drying could provide a method to separate grain from stover in corn silage by reaching a grain concentration higher than 99%.

Index Entries: Corn; stover; grain; separation; silage.

Introduction

Various methods for separating corn grain from stover have been proposed. One approach is to shell the grain with a combine and subsequently to harvest the residual stover with either a forage harvester or a baler *(1)*. Another approach is to harvest, chop, and ensile the whole crop, and to separate components at removal from storage *(2)*. Advantages of separation after storage include fast and efficient harvest in a single stream;

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low-cost storage in high-capacity bunker silos without the need for grain drying; and separation throughout the year at relatively low work rates, with small size equipment, compared with the high rates handled during the short harvest season.

After ensiling, grain has been sorted from stover, at least partially, by mechanical sieving *(3)* or aerodynamic separation *(4)*. Hydrodynamic separation has not previously been used for corn silage, but it is used industrially to separate heavier particles such as phosphatides from corn oil in the wet-milling process *(5)*.

Hydrodynamic separation of grain from stover could be feasible if components exhibit significant differences in specific gravity or buoyancy. The specific gravity of corn grain has been observed to range from 1278 to 1380 kg/m^3 *(6)*. The specific gravity of corn stover components (stalk, cob, leaf, husk) is less well documented. Meanwhile, the specific gravity of forage particles is in the order of 1500 kg/m^3 *(7)*. This would suggest poor hydrodynamic separation of grain from stover in water because both components would sink. However, empirical evidence shows that grain sinks more rapidly than stover, which tends to float because of buoyancy.

The objective of the present work was to evaluate the potential of hydrodynamic separation with water to sort grain from stover after ensiling. New data are presented on the specific gravity of corn grain and stover components after coarse chopping or grinding. Factors considered include harvest conditions (chop length and processing) and pretreatment of the silage (partial drying, sieving) prior to hydrodynamic separation.

Materials and Methods

Experiment 1: Specific Gravity of Corn Components

Several stalks of whole-plant corn were cut with a scythe at 10 cm from the ground at full maturity (early December 2002) near Madison, WI. Plants were separated manually into five components: grain, stalk, leaf, husk, and cob. The components were oven-dried at 103°C for 24 h *(8)* to estimate moisture content and the respective proportions of dry matter (DM). Specific gravity was estimated with a PMI Automated Gas Pycnometer (Porous Materials, Ithaca, NY), which measured the pressure change in helium gas as it surrounded the crop component in an enclosed volume *(9)*. Three iterations were done for each sample in the pycnometer, and three replications were done for each component in two states: intact grain or coarsely chopped stover, and ground components. Chopping was done with a laboratory chopper set at 13-mm theoretical length of cut. Grinding was carried out with a Model 4 Thomas Wiley Mill using a 1-mm screen (Thomas Scientific). The specific gravity was corrected to a dry basis by mass balance:

$$\rho_{DM} = \frac{\rho_{WM}\,\rho_{H_2O}\left(100 - MC\right)}{100\,\rho_{H_2O} - \rho_{WM}\,MC} \qquad (1)$$

in which ρ_{DM} is the corrected specific gravity on a dry matter basis, ρ_{WM} is the wet matter specific gravity as measured experimentally, ρ_{H2O} is the specific gravity of water (1000 kg/m^3), and MC is the moisture content on a wet basis (%).

Experiment 2: Sequential Water Separation

Four silages harvested in fall 2002 were retrieved from the silo in March 2003 for the sequential water separation. The silages were selected to represent four mechanical harvest treatments: short chop and unprocessed, long chop and unprocessed, short chop and processed, and long chop and processed. Processing involved crushing and shearing the chopped whole plant through a pair of toothed rolls operating at small clearance and differential speed *(10)*. Silages came from two experimental farms (Arlington, Prairie-du-Sac) and two commercial farms (Binversie, Ziegler) in Wisconsin. A measured mass of 1 kg of fresh silage was placed in a water basin containing initially 7 L of water. After 1 min of manual gentle mixing, the material still floating on the water surface was removed by hand. The rest of the basin contents was poured gently over a screen made of 0.40-mm (1/64-in.) thick wire spaced 1.59 mm (1/16 in.) center to center in a square grid with about 50% open area. The screen separated material into two components, the effluent water and the suspended solids, and a third component was the sunk material that remained at the bottom of the basin after pouring. The latter two components were spread onto separate paper cloths to partially dry in ambient air. The floating material was then deposited again in the water basin with the same effluent water. After 1 min, the floating and suspended solids were set aside for the next water separation and the sunk material was put on a cloth to dry. This process was repeated until eight water separations had been completed. The eight-step sequential separation was replicated three times for each of the four silages.

The sunk material from each of the eight separations, the suspended solids from the first separation, and the residual floating material after the eighth separation (i.e., 10 components) were oven-dried at 103°C for 24 h to estimate the proportions of DM at each step. A well-mixed amount of 2 kg of water effluent was also measured after the eighth separation and oven-dried to estimate the total DM in the effluent.

For each replication (four silages × three replications), the 10 dried components were hand sorted to separate grain from stover. Sorted grain included full and broken grains, grain hull, and grain endosperm pieces that were large enough (1 to 2 mm) to be clearly identified as starch. The rest was considered to be stover. Because sorting occurred over a period of several weeks after oven-drying, rehydration occurred and component masses were corrected to a DM basis. Grain concentration was estimated as the proportion of sunk grain over the total of sunk grain and sunk stover.

Experiment 3: Separation After Drying or Sieving

Six pretreatments were done to compare the effect of drying or sieving on subsequent grain and stover separation:

1. A fresh untreated silage.
2. Silage that was partially dried until it lost 10 percentage units of moisture.
3. Silage that was partially dried until it lost 20 percentage units of moisture content.
4. Silage that was oven-dried to approx 0% moisture.
5. Silage that was sieved by a standard method *(11)* and whose material from only screen no. 3 was hydrodynamically separated (particle size between 9.0 and 18.0 mm).
6. The same sieved material as in item 5 that was also partially dried to lose 10 percentage units of moisture.

The silage for all six pretreatments was unprocessed and came from a commercial farm (Manthe) in south-central Wisconsin.

A single water separation was done with these treated silages. Using the same amounts of silage (1 kg) and water (7 L) as in the second experiment, the material was separated into three components: sunk, suspended, and floating material. DM in the effluent was estimated by mass balance. The three measured components were further subdivided into grain and stover by hand sorting after oven-drying. The water separation was replicated three times for each of the six silage treatments. In the case of sieved material, 1 kg was placed in the separator, and only the fraction retained on screen no. 3 was separated by water.

MC, Particle Length, and Statistical Analyses

As indicated previously, moisture was measured by oven-drying at 103°C for 24 h *(8)*. Three samples from each of the five silages were taken for moisture measurement. Mean particle length (MPL) was measured by the standard separator method using five screens and a pan *(11)*. Three samples of about 2 kg each were taken to measure MPL for each of the five silages.

Statistical analyses were done using analysis of variance (ANOVA) with a single factor. The single factor in the first experiment was corn component at five levels: grain, stalk, leaf, husk, and cob. The single factor in the second experiment was silage source at four levels: Binversie Farm (unprocessed, short), Prairie-du-Sac Farm (unprocessed, long), Ziegler Farm (processed, short), and Arlington Farm (processed, long). The single factor in the third experiment was treatment at six levels: fresh silage, partially dried to lose 10 percentage units of moisture, partially dried to lose 20 percentage units of moisture, completely dried in the oven, sieved and fresh, sieved and partially dried to lose 10 percentage units of moisture. ANOVA was used to determine significant differences. The least significant difference method was used to rank results *(12)*.

Table 1
Specific Gravity of Corn Components Either Coarsely Chopped or Ground on DM Basis

	Specific gravity (kg DM/m^3)	
Component	Chopped	Ground
Grain	1305 [a]	1486 [a]
Stalk	606 [c]	1625 [a]
Husk	814 [b]	1606 [a]
Cob	837 [b]	1504 [a]
Leaf	664 [c]	1510 [a]
SEM	38	67
LSD	86	149

[a]Average of three replications. Values with the same superscript letter in a given column indicate no significant difference ($p < 0.05$). SEM, standard error of means; LSD, least significant difference.

Chemical Analyses

The following components were selected for chemical analyses: five corn components from the first experiment (grain, stalk, leaf, husk, and cob), five whole-plant corn silages from the second experiment, four effluent DMs obtained from the four corn silages in the second experiment, four components from the third experiment (sunk grain, sunk stover, suspended stover, and floating stover). Three replications of each component were analyzed by the UW Soil and Plant Analysis Lab in Marshfield, WI, using wet chemistry for acid detergent fiber (ADF), neutral detergent fiber (NDF), crude protein (CP), minerals (P, Ca, K, Mg), and starch.

Results

Experiment 1: Specific Gravity of Corn Components

Table 1 presents the specific gravity of corn components as measured by the gas pycnometer. All components were oven-dried prior to measurements. Because of ambient rehydration, the MC of components varied between 2 and 8% at the time of measurements. The data presented in Table 1 were corrected on a DM basis using Eq. 1. Intact grain was significantly denser (1305 kg of DM/m^3) than chopped stalk and leaf (average of 635 kg of DM/m^3) or chopped husk and cob (average of 826 kg of DM/m^3). However, when all material was ground through a 1-mm screen, there was no significant difference among the five components (average of 1546 kg of DM/m^3). The corn used to measure specific gravity was very mature, being harvested in December, and had DM fractions of grain, stalk, husk, cob, and leaf of 65, 18, 4, 10, and 3%, respectively. Measures might be different for earlier maturity corn. However, the data show a remarkable homogeneity in specific gravity when material becomes very fine.

Table 2
Characteristics of Corn Silages Used for Hydrodynamic Separation of Grain and Stover in Eight Stages in Experiment 2[a]

Silage source	MC (% wet basis)			Processed	MPL (mm)	Geometric SD (mm)
	Silage	Grain	Stover			
Ziegler Farm	67.3	50.3	69.5	Yes	12.9	1.70
Prairie-du-Sac Farm	73.8	52.8	75.8	No	17.4	1.81
Arlington Farm	63.8	45.8	67.6	Yes	13.6	1.97
Binversie Farm	66.0	46.8	70.7	No	8.1	1.66

[a]Average of three replications.

Experiment 2: Sequential Water Separation

Table 2 presents the physical characteristics of the four silages used for the sequential water separation experiment. The two processed silages (Ziegler Farm and Arlington Farm) had very similar MPL (13 and 14 mm, respectively). They also had a relatively low MC; the Arlington silage had the highest DM content (36% DM). The Prairie-du-Sac Farm silage was unprocessed and had a long particle size (17 mm), whereas the Binversie Farm silage was unprocessed and had a short particle size (8 mm). The moisture reported for grain and stover in Table 2 may slightly underestimate the actual values because components were exposed to natural air-drying for about 1 h during manual sorting prior to oven-drying.

Table 3 shows the proportion of grain and stover in the sunk material from the four silages. After the first separation, the grain concentration in the sunk material was 75% and highest for the Arlington silage, which also was the driest. The grain concentration was only 41% and lowest for the Prairie-du-Sac silage, which was the wettest. The Binversie silage was different from the other three silages because it produced a higher amount of sunk grain (31% of total DM) than the three other silages (19% of total DM). This might be the result of a later maturity harvest; a greater presence of fully formed kernels; and no used of a processor, thereby leaving more intact grain.

After the eighth separation, grain concentrations ranged from 27 to 46% and were lower than after the first separation. At each separation, more stover sank and mixed with the corn grain. Only the Arlington silage released more than 1.5% of total DM as grain beyond the first separation. The actual concentration of DM in the effluent ranged from 0.71 to 1.22%, with an average of 1.01%. DM in the effluent reported in Table 3 represents the DM as a proportion of the original DM in the silage.

Figures 1 and 2 illustrate the curves of sunk grain, sunk stover, DM in the effluent, and floating material over the course of the eight water separations for two contrasting cases: the Arlington Farm silage with a low MC and the Prairie-du-Sac Farm silage with a high MC. The sunk grain and sunk stover reported in Figs. 1 and 2 were measured at each separation.

Table 3
Grain and Stover Proportions After the First and Eighth Separations of Fresh Silage in Water in Experiment 3

Silage source	After first separation			After eighth separation				
	DM (%)		Grain concentration in sunk material (%)	DM (%)				Grain concentration in sunk material (%)
	Sunk grain	Sunk stover		Sunk grain	Sunk stover	Floating stover	DM in effluent	
Ziegler Farm	18.5^{b}	11.4^{bc}	62.0^{b}	20.0^{c}	36.3^{b}	17.6^{b}	26.0^{a}	35.6^{b}
Prairie-du-Sac Farm	19.1^{b}	27.1^{a}	41.3^{c}	19.5^{c}	53.2^{a}	6.7^{c}	20.7^{b}	26.8^{c}
Arlington Farm	19.3^{b}	6.6^{c}	75.2^{a}	25.2^{b}	29.6^{c}	23.8^{a}	21.6^{b}	45.9^{a}
Binversie Farm	30.7^{a}	14.7^{b}	67.7^{ab}	31.6^{a}	37.2^{b}	10.2^{c}	21.0^{b}	45.9^{a}
SEM	1.7	2.3	4.9	2.1	2.1	1.7	0.4	3.5
LSD	3.9	5.3	11.2	4.9	4.9	3.9	1.2	7.5

[a] Average of three replications. Values with the same superscript letter in a given column indicate no significant difference ($p < 0.05$). SEM, standard error of means; LSD, least significant difference.

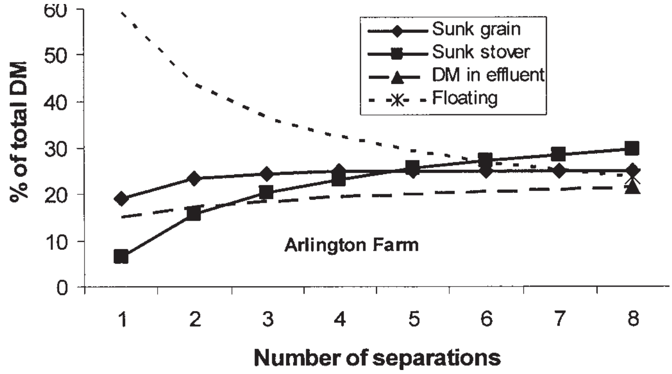

Fig. 1. Corn silage components after eight successive water separations: Arlington Farm. Silage was processed and had an MPL of 13.6 mm and an MC of 63.8%.

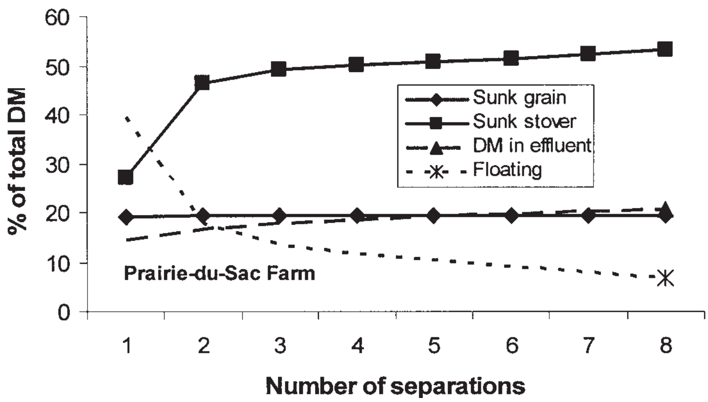

Fig. 2. Corn silage components after eight successive water separations: Prairie-du-Sac Farm. Silage was not processed and had an MPL of 17.4 mm and an MC of 73.9%.

The floating material and the effluent DM were measured only after the eighth separation. The curve for DM in the effluent was inferred by assuming that 70% of DM in the effluent was released after the first separation (*see* experiment 3 for a justification) and by assuming that the release followed a logarithmic curve. The curve for floating material was obtained by mass balance. The suspended stover recovered after the first separation was considered to be part of the floating material.

Experiment 3: Separation After Drying or Sieving

Table 4 presents fractions of sunk, suspended, and floating material after a single separation. The residual grain represents grain that was hand sorted from either the suspended or floating material. The DM in the effluent was obtained by mass balance after other components had been dried and separated.

Table 4
Grain and Stover Proportions After One Water Separation and Various Pretreatments

Pretreatment	Silage used (%)	MC (%)	DM after one separation (%) Sunk grain	Sunk stover	Suspended stover	Floating stover	Residual grain	DM in effluent	Grain concentration in sunk material (%)
1. Untreated silage	100	64.6	21.3 ^{c}	8.4 ^{a}	7.1 ^{b}	44.1 ^{cd}	1.5 ^{b}	17.6 ^{a}	71.8 ^{d}
2. Partially dried to lose 10% units of MC	100	54.8	22.9 ^{c}	9.5 ^{a}	5.2 ^{c}	45.4 ^{c}	0.5 ^{c}	16.5 ^{ab}	70.6 ^{d}
3. Partially dried to lose 20% units of MC	100	45.3	25.8 ^{b}	2.2 ^{c}	2.1 ^{d}	54.6 ^{b}	1.0 ^{bc}	14.3 ^{bc}	92.3 ^{b}
4. Oven-dried	100	0.0	23.8 ^{bc}	0.1 ^{c}	0.6 ^{d}	62.3 ^{a}	2.5 ^{a}	10.8 ^{d}	99.4 ^{a}
5. Sieved and fresh	50.3	64.6	37.0 ^{a}	9.8 ^{a}	9.5 ^{a}	29.5 ^{e}	0.6 ^{c}	13.6 ^{cd}	79.1 ^{c}
6. Sieved, partially dried to lose 10% units of MC	50.3	55.5	34.6 ^{a}	4.7 ^{b}	5.1 ^{c}	41.1 ^{d}	1.7 ^{ab}	12.8 ^{cd}	88.0 ^{b}
SEM			1.4	1.0	0.8	1.8	0.4	1.3	2.7
LSD			3.1	2.2	1.7	3.9	0.9	2.8	5.8

[a] Experiment 3 with silage from Manthe Farm: 64.6% MC, unprocressed and 10.3mm MPL; average of three replications. Values with the same superscript letter in a given column indicate no significant difference ($p < 0.05$). SEM, standard error of means; LSD, least significant difference.

Sieving increased the proportion of grain collected (37 vs 21%, without drying), and improved the grain concentration in the sunk material (79 vs 72%). However, the total amount of grain obtained in the sunk material was lower after sieving (18.6 vs 21.3%) because about half the silage remained in the other sieves that were not used for the water separation. The smaller-size sieves would contain a significant amount of broken grain.

The proportion of sunk stover decreased significantly with partial drying (20 percentage units of moisture loss) and with complete drying in the oven. The grain concentration was enhanced as high as 99.4% for bone-dry material. The proportion of suspended stover was highest for sieved and fresh pretreatment. This material was of relatively uniform length (between 9 and 18 mm), so grain could sink rapidly in the absence of long stover pieces that tended to float and hinder the descent of smaller grain. The proportion of floating material was significantly higher for dry material. Residual grain was highest also in dry material. The proportion of DM in the effluent decreased as the silage was dried. The reduction in soluble and fine particles after drying might be owing to a loss of volatile organic acids.

In experiment 3, effluent contained an average of 17.6% of fresh silage DM after one separation. In experiment 2, in which eight successive water separations occurred, the effluent water contained between 20.7 and 26.0% of the fresh silage DM. A large proportion of the soluble and fine particles mixed rapidly in the effluent water. These values suggest a range between 68 and 85% for the ratio between DM in the effluent after one separation and DM in the effluent after eight separations. A ratio of 70% was assumed in Figs. 1 and 2 to illustrate initial DM in effluent and is within the experimental range of 68 to 85%.

Chemical Composition

Table 5 reports the chemical composition of five components from corn. The level of starch in grain was not as high as expected (50–60% is typical), perhaps because of the crop's late maturity. Fiber concentrations, either ADF or NDF, are good indicators to estimate the proportion of grain and stover in a whole-plant mix.

Table 6 shows the chemical composition of components after water separation. The sunk grain had a level of starch as expected but more fiber than expected. The sunk stover probably contained small fractions of grain that could not be separated manually. The suspended and floating materials also probably contained some small grain particles that had not sunk after the first water separation. The effluent DM containing soluble and very fine particles had on average 26% starch and 3% ADF, indicating a larger proportion of grain than stover components. Prior to water separation, silages in experiment 2 had an average composition of 8.5% CP, 19.1% starch, 23.6% ADF, and 40.3% NDF.

Table 5
Chemical Composition on DM Basis of Mature Whole-Plant Corn Components*

Component	CP (%)	P (%)	Ca (%)	K (%)	Mg (%)	Starch (%)	ADF (%)	NDF (%)
Grain	4.9^{b}	0.25^{a}	0.03^{d}	0.31^{d}	0.11^{d}	42.5^{a}	2.5^{d}	21.0^{d}
Stalk	3.3^{c}	0.10^{bc}	0.16^{b}	1.04^{a}	0.17^{b}	0.4^{b}	45.5^{b}	78.3^{c}
Husk	3.9^{c}	0.07^{cd}	0.13^{c}	0.74^{b}	0.16^{c}	1.3^{b}	42.2^{c}	84.4^{b}
Cob	2.8^{d}	0.05^{d}	0.05^{d}	0.60^{c}	0.08^{e}	0.1^{b}	44.5^{b}	90.6^{a}
Leaf	5.7^{a}	0.13^{b}	0.44^{a}	0.23^{d}	0.25^{a}	1.3^{b}	46.8^{a}	77.8^{c}
SEM	0.3	0.02	0.01	0.05	0.01	2.3	0.8	2.7
LSD	0.7	0.03	0.02	0.12	0.01	5.2	1.8	6.1

*Average of three replications. Values with the same superscript letter in a given column indicate no significant difference ($p < 0.05$). SEM, standard error of means; LSD, least significant difference.

Table 6
Chemical Composition on DM Basis of Corn Silage Components After One or Eight Water Separations*

Component	CP (%)	P (%)	Ca (%)	K (%)	Mg (%)	Starch (%)	ADF (%)	NDF (%)
After one water separation (experiment 3)								
Sunk grain	1.9^{d}	0.06^{c}	0.02^{c}	0.15^{c}	0.03^{d}	55.0^{a}	5.3^{c}	16.9^{c}
Sunk stover	4.0^{c}	0.10^{b}	0.07^{b}	0.22^{b}	0.07^{c}	16.7^{b}	29.7^{b}	50.9^{b}
Suspended stover	5.1^{b}	0.11^{b}	0.18^{a}	0.23^{b}	0.09^{b}	6.8^{d}	39.0^{a}	63.4^{a}
Floating material	6.0^{a}	0.16^{a}	0.18^{a}	0.38^{a}	0.14^{a}	9.5^{c}	36.5^{a}	61.5^{a}
SEM	0.1	0.01	0.01	0.01	0.00	1.2	1.6	2.2
LSD	0.3	0.02	0.02	0.03	0.01	2.7	3.6	5.1
After eighth water separation (experiment 2)								
Effluent DM	15.5	0.64	0.95	3.13	0.73	25.9	3.2	5.0

*Average of three replications after one separation, average of 12 replications after eighth separation. Values with the same superscript letter in a given column indicate no significant difference ($p < 0.05$). SEM, standard error of means; LSD, least significant difference.

Discussion

The specific gravity of particles changed with their size. Intact grain was much denser than coarsely chopped stover components. However, when material was finely ground, the density of all components increased and no further difference in density was observed. The results suggest that stalk and leaf have more micropores than husk and cob while grain had the least micropores. In principle, fine chopping and processing would contribute to an increase in the density of all components and the proportion of stover that sinks with grain in a water separation process.

In experiment 2, most of the corn grain sunk rapidly. Between the first and the eighth water separation, the amount of sunk grain increased by only 0.4% for the Prairie-du-Sac silage, 0.9% for the Binversie silage, 1.5% for the Ziegler silage, and 5.9% for the Arlington silage. Therefore, only one or two water separations would be needed to separate most grain.

When fresh silage was separated in water, the highest grain concentration achieved in the sunk material was 75%; this was observed with processed and relatively dry corn silage (64% MC). Short chopped material (8 mm) actually had a higher grain concentration (68%) than long material (17 mm), whose grain concentration was only 41% largely because of a high initial MC (74%). The moisture content had a greater impact than the physical form in the range that was observed (8- to 17-mm MPL, processed or not processed).

The effect of MC was even more apparent in experiment 3 when fresh material was compared with material partially dried (10 or 20 percentage units of moisture removal) or completely dried prior to water separation. Greater than 99% grain concentration was observed with bone-dry material. As corn silage becomes drier, stover pieces are likely to become more buoyant because of their large area compared to grain. Oven-drying is therefore a good pretreatment followed by water separation to concentrate grain from corn silage. Because of the large amount of water in silage and the high cost to dry this material, the procedure could be used for small samples in the laboratory but would not likely be feasible in an industrial setting.

Without any pretreatment, hydrodynamic separation could allow the production of a concentrate of about 75% grain and 25% stover. It is difficult to achieve a higher grain concentration without having to partially dry or sieve the silage. Sieving increased the grain concentration in the sunk material to 79%. From an industrial point of view, water separation would require recuperation of considerable amounts of soluble and deposited fine particles (18% of original DM after one separation, and between 21 and 26% after eight separations). Hydrodynamic separation could provide a feedstock with a high concentration in grain (75–80%), but it could not provide a stover-free feedstock without drying. Compared to pneumatic separation and sieving alone, hydrodynamic separation is likely to require less energy when drying is not used. If pure corn components are needed, the traditional combine thresher is more suitable for providing pure grain than any poststorage separation method applied to silage. Various harvest devices can be designed to collect the stover either simultaneously with threshing or afterward with another pass machine.

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