Nutritive value, fermentation characteristics, and in situ disappearance kinetics of sorghum silage treated with inoculants

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ABSTRACT

Fibrolitic enzymes and microbial inoculants have the potential to improve the value of sorghum feedstuff and feedstock. An experiment was conducted to determine nutritive value, ensiling characteristics, and in situ disappearance kinetics of 4 sorghum (*Sorghum bicolor* L.) silage varieties: Dairy Master BMR (DBMR; brown midrib; Richardson Seed, Vega, TX), PS 747 (PS; photoperiod sensitive; Pogue Seed, Kenedy, TX), Silo 700D (S700D; conventional forage type; Richardson Seed), and MMR 381/73 (MMR; conventional forage type; Richardson Seed) pretreated with fibrolitic enzyme (xylanase plus cellulase, XC; 50:50 mixture of Cellulase Plus and Xylanase Plus; Dyadic, Juniper, FL) or microbial [Promote ASB (*Lactobacillus buchneri* and *Lactobacillus plantarum*); Cargill Animal Nutrition, Indianapolis, IN; PRO] inoculants. The greatest yield was for cultivar PS and the least for MMR. Neutral detergent fiber (NDF) concentration was least for XC-treated silage, and acid detergent fiber (ADF) concentration was least for XC- and PRO-treated silage. When silage was treated with XC, concentrations of NDF concentrations decreased, on average, 4.81% across all cultivars and ADF concentrations decreased, on average, 3.23% in all cultivars except MMR. Inoculant PRO reduced the NDF concentration of DBMR by 6.47%. The ADF concentrations of DBMR and PS treated with PRO were decreased by 3.25%. Treating sorghum silage with XC or PRO reduced the NDF and ADF fractions, which increased cell wall degradability. In vitro true digestibility was greatest for PRO-treated DBMR, whereas acid detergent lignin was least for PRO-treated DBMR. Aerobic stability was not improved by PRO; however, aerobic stability of XC-treated MMR was 63 h greater than that of the control. Acetate concentrations were greatest for XC-treated MMR, which explains the 63-h improvement in aerobic stability due to the inhibition of fungi. However, inoculant PRO did not improve yeast

and mold counts or aerobic stability of sorghum silage compared with the control, which may be due to the lesser acetate concentrations, especially of PRO-treated S700D silage. Generally, in situ disappearance kinetics were improved with the application of XC and PRO, and XC had the greatest effect on silage with greater NDF and ADF concentrations.

Key words: sorghum, silage, fibrolitic enzyme, microbial inoculant

INTRODUCTION

Sorghum silage can be fed to livestock or used as biomass for biofuel production. In 2010, 13,102 ha were harvested for silage production in Texas (USDA, 2011). Sorghum is well adapted to the climate, has a high yield, and is drought tolerant, making it an excellent crop to meet the grain or forage needs of the livestock industry (Prostko et al., 1998). However, acceptance of sorghum silage for livestock feed has been limited because of its greater ADF and ADL levels compared with corn silage (Prostko et al., 1998). The greater fiber levels found in sorghum reduce forage digestibility and may compromise milk production (Prostko et al., 1998). Bolsen et al. (1989) reported that grain sorghum silage can be substituted for corn silage in mid-lactation dairy cattle diets with no adverse effects on milk production, whereas others have reported that silage from brown midrib (BMR) sorghum supports milk production similar to that of corn silages (Lusk et al., 1984; Grant et al., 1995; Oliver et al., 2004).

During the ensiling process, DM is lost if fermentation does not occur immediately and aerobic stability is not maintained during storage and feedout (McDonald et al., 1991; Jones, 2012). Therefore, limitations to sorghum silage use include storage constraints and fiber degradation, and both may be improved by the application of fibrolitic enzyme or bacterial inoculant, thereby, increasing the value of sorghum silage. Treating silage with fibrolitic enzymes breaks bonds between hemicelluloses and lignin so that sugars can be extracted from hemicelluloses (Han et al., 2007). Elwakeel et al. (2007) found that the in vitro DM digestibility of 4 fibrous

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dairy feedstuffs was improved by addition of a fibrolytic enzyme mixture containing β -glucanase, xylanase, and cellulase. Bacterial inoculants containing lactic acid bacteria (**LAB**) increase aerobic stability by inhibiting aerobic spoilage (Kung and Charley, 2010). Inoculation of biofuel crops with biological silage additives and ensiling prolongs crop storage and improves methane yields up to 11% (Herrmann et al., 2011).

Forage sorghum has been bred to favor improved nutritive value and yield. Photoperiod-sensitive (**PPS**) varieties have high yields and use water efficiently; however, their reduced digestibility and greater fiber than conventional forage sorghum cultivars limits their broad application (McCollum et al., 2012). Increased fiber concentrations and reduced digestibility of PPS silage may reduce its feedstock and feedstuff value because fiber degradation is one of the major limitations to value. However, Murray et al. (2008) suggested that yield traits be selected over composition traits for maximizing energy yield of sorghum biomass. This suggestion is similar to the conclusion of McCuiston et al. (2011) that PPS varieties fed more cattle than varieties with greater nutritive value. Varieties selected for BMR traits have less ADL and may be 10 to 30% more digestible; however, DM yield may be 15 to 20% less and lodge and bend more easily (Ball et al., 2007).

Despite the large acreage of sorghum grown in the United States, limited information is available on the ensiling characteristics, nutritive value, and in situ kinetics of sorghum silage pretreated with fibrolytic enzymes or bacterial inoculants. The lack of information is especially apparent regarding genetically improved PPS and BMR types. Thus, the goal of this study was to determine nutritive value, fermentation characteristics, aerobic stability, and in situ ruminal disappearance kinetics of conventional, PPS, and BMR sorghum silages pretreated with fibrolytic enzymes (cellulase:xylanase) or bacterial inoculant.

MATERIALS AND METHODS

Forage Production and Ensiling

Sorghum cultivars Dairy Master BMR (**DBMR**; brown midrib; Richardson Seed, Vega, TX), PS 747 (**PS**; photoperiod sensitive; Pogue Seed, Kenedy, TX), Silo 700D (**S700D**; conventional forage type; Richardson Seed), and MMR 381/73 (**MMR**; conventional forage type; Richardson Seed) were grown at the Texas A&M AgriLife Research Station in Beeville (28°N, 98°W) and the Texas A&M University Agriculture Research Farm in College Station (30°N, 96°W), Texas. At planting, sorghum was sprayed with a tank mix of 0.575 L/ha of atrazine + 0.339 L/ha of metolachlor, and no

fertilizer was applied. Sorghum was harvested during the mid-dough stage, at which time 4 random height measurements were recorded; 7.3 m of sorghum was cut from the 2 center rows to a 10-cm stubble height, and a subsample (3.66 m row length) was weighed to calculate yield. Material was chopped into at least 13-mm particle size using a chopper shredder (Earthquake, Cumberland, WI). A 1-kg subsample of forage was dried at 65°C until weight loss ceased. Samples were ground to 4 mm and subsamples used for nutritive value analysis of pre-ensiled sorghum were ground to pass through a 2-mm screen in a Wiley mill (Arthur H. Thomas Company, Philadelphia, PA).

Chopped sorghum (5 kg) was sprayed with 200 mL of distilled water (control), 1.34 mL of fibrolytic enzymes (**XC**), or 16.5 mg of bacterial inoculant (**PRO**; Promote ASB, *Lactobacillus buchneri*, *Pediococcus acidilactici*, *Pediococcus pentosaceus*, *Lactobacillus plantarum*, *Enterococcus faecium*; Cargill Animal Nutrition, Indianapolis, IN) mixed in 200 mL of distilled water. Bacterial inoculant PRO is marketed as a water-soluble forage inoculant and instructions for its use indicate that is to be mixed with water before spray application. Enzyme activity was approximately 35,000 units of XC/g for XC-treated silage and approximately 100,000 cfu/g for PRO-treated silage. The fibrolytic enzyme mixture was a 50:50 mixture of Cellulase Plus (Dyadic, Juniper, FL), which is a liquid acid cellulose enzyme produced by the fermentation of non-genetically modified *Trichoderma longibrachiatum* and Xylanase Plus (Dyadic), which is a liquid acid-neutral endo-1,4- β -D-xylanase produced by the fermentation of non-genetically modified *T. longibrachiatum*. Additional enzyme activities in the XC product included β -glucanase, pectinase, mannanase, xyloglucanase, laminarase, β -glucosidase, β -xylosidase, α -L-arabinofuranosidase, amylase, and protease. Inoculant type and dose were determined based on results of application to corn silage in previous studies of other research groups and the label-recommended application rate. Silage was hand mixed and packed into mini-silos, which were 17.6-L containers with lids and were lined with 38.1 $\times$ 22.9 $\times$ 61 cm polyethylene bags and sealed for at least 120 d.

Laboratory Analyses

After 120 d, silos were opened and 4 separate subsamples were taken. The first subsample was dried at 65°C and ground to pass through a 4-mm screen and then a subsample ground to pass through a 2-mm screen in a Wiley mill for nutritive value analysis. The second silage subsample was sent to Dairy One (Ithaca, NY) for analyses of water-soluble carbohydrate (**WSC**), ammonia- N ($\text{NH}_3\text{-N}$), pH, and VFA. Water-soluble

carbohydrates were determined by incubation in water (40°C) followed by acid hydrolysis with sulfuric acid and colorimetric reaction with potassium ferricyanide (Hall et al., 1999). Ammonia-N was analyzed with a Timberline TL-2800 analyzer (Timberline Instruments, Boulder, CO) after the method described by Liu (1998). Silage pH was analyzed by placing wet samples into a beaker with deionized water and analyzed using a Thermo Orion Posi-pHlo SympHony Electrode and Thermo Orion 410A meter (Thermo Fisher Scientific, Waltham, MA). Acetate, propionate, butyrate, and isobutyrate were measured with a Perkin Elmer Autosystem XL Gas Chromatograph (Perkin Elmer, Waltham, MA) containing a Supelco packed column (Sigma Aldrich, St. Louis, MO) with procedures adapted from Supelco (1990). Lactate was determined by analyzing silage extract for L-lactate using a YSI 2700 Select Biochemistry Analyzer (YSI Inc., Yellow Springs, OH). The third silage subsample was sent to Ag Source Laboratories (Bonduel, WI) for yeast and mold counts (Tournas et al., 1998). The last silage subsample was used to measure aerobic stability by placing type-k thermocouple wires (Omega Engineering, Stamford, CT) at the center of approximately 800 g of silage stored in a polyethylene bag within an open-top polystyrene box covered with 2 layers of cheesecloth to prevent drying. Thermocouple wires were connected to a DT80 series 2 data taker (Scoresby, Victoria, Australia) that recorded temperature readings every 15 min until the silage reached 2°C above ambient temperature (18–25°C; Foster et al., 2011).

Fresh subsamples previously ground to 2 mm were dried at 135°C for 8 h, and ensiled subsamples were dried at 104°C for 3 h for DM determination (AOAC, 1990; Thiex and Van Erem, 1999). Concentrations of NDF and ADF were sequentially measured using the methods of Van Soest et al. (1991) and AOAC (1990; method 973.18) in an Ankom 200 Fiber Analyzer (Ankom Technologies, Macedon, NY) with α -amylase and without ashing. Lignin was measured sequentially following ADF, using the Ankom (2011) procedure based on the Van Soest, 1967) procedure, whereby samples in Ankom bags were incubated in 72% sulfuric acid. The Van Soest et al. (1966) method and an Ankom DaisyII Incubator (Ankom Technologies) followed by NDF as previously described were used to determine in vitro true digestibility (IVTD). Nitrogen was determined by rapid combustion using a Macro Elemental N analyzer (Elementar Americas, Mt. Laurel, NJ), and CP was calculated as $N \times 6.25$. The N in ADF residue was measured using methods described previously and ADIN reported, and the laboratory subsample was separate from that used for previous fiber analyses.

In Situ Incubation Procedures

Because of a limited quantity of samples for incubation, only the sorghum silage cultivars exhibiting the greatest (S700D) and least (MMR) NDF and ADF concentrations were milled to pass through a 4-mm screen and used for in situ incubation. Approximately 4.5 g (as fed) of sample was weighed into 10 × 20 cm polyester bags (53 ± 10 µm pore size; Bar Diamond Inc., Parma, ID) in triplicate. Bags were incubated in the ventral rumen of 3 Angus cross steers (453 ± 25 kg of BW) and removed after 0, 4, 8, 16, 24, 48, and 72 h. The trial began after a 10-d adaptation to 8 kg/head per day of sorgho-sudan (*Sorghum* spp.) hay (6.4% CP, 55.8% NDF, and 32.7% ADF; DM basis) along with 1.7 kg/head per day of cotton (*Gossypium hirsutum* L.) seed meal (42.4% CP, 24.6% NDF, 15.2% ADF; DM basis). Water and a trace mineralized salt block (minimum 1.8% Ca, 90.0% NaCl, 1.0% S, 25 mg/kg of Co, 150 mg/kg of Cu, 90 mg/kg of I, 1,500 mg/kg of Fe, 3,000 mg/kg of Mn, 10 mg/kg of Se, and 2,500 mg/kg of Zn) were provided ad libitum. Animal care and use regulations set by the animal welfare committee at Texas A&M University-Kingsville were followed. Immediately after removal from the steers, bags were placed in ice water, rinsed with tap water (39°C), placed in plastic bags, and frozen (−20°C) until all bags were incubated. All bags were washed with one cycle in a commercial washing machine and dried at 55°C to a constant weight. Dried residues were analyzed for DM, CP, NDF, ADF, and NDIN. The NDIN was determined by measuring the N in NDF residues and RUP was calculated from NDIN according to Haugen et al. (2006). In situ rumen DM, NDF, and ADF degradation data were fitted to the first-order exponential model with discrete lag (Mertens, 1977) using the iterative Marquardt method and the NLIN procedure of SAS (SAS Institute, Cary, NC). The model is of the form

$$R_{(t)} = B \times (e^{-K_d(t-L)}) + C,$$

where $R_{(t)}$ = total indigested residue at any time t , B = insoluble potentially digestible fraction, K_d = fractional rate of digestion of B , t = time incubated in the rumen in h, L = discrete lag time (h), and C = fraction not digested after 96 h of incubation. The wash fraction A was the percentage of substrate washed out of the bag at 0 h. The derivative model statement for K_d is of the form

$$K_d = A \times (e^{-k(t-L)}) \times (L - t),$$

where k is the rate of degradation. The derivative model statement for L is of the form

$$L = A \times (e^{-k(t-L)}) \times k,$$

with abbreviations as previously defined. In situ rumen CP degradation data were fit to a similar model that excluded the discrete lag time (Mertens, 1977). Effective ruminal degradability (**ERD**; extent of digestion) was calculated using the model of Ørskov and McDonald (1979):

$$\text{ERD} = A + \{B \times [K_d / (K_d + K_p)]\},$$

where K_p = assumed ruminal passage rate of 0.05.

Statistical Analyses

Results were analyzed as a factorial arrangement with GLIMMIX procedure of SAS (SAS Institute Inc.) and the model included cultivar, location, treatment, and their interactions. When significant ($P < 0.05$) effects were observed among treatments, least squares means were compared with Fisher's least significant difference test for multiple comparisons.

RESULTS

Yield and Chemical Composition of Pre-Ensiled Sorghum

We found no interaction ($P > 0.41$) between cultivar and location for DM yield; therefore, data are presented

as means across locations. We did find an interaction ($P < 0.01$) between location and cultivar for height. The height of DBMR was greater ($P < 0.01$) than that of MMR at both locations, whereas PS and S700D were intermediate (Figure 1). Dry matter yield of PS was greater ($P < 0.05$) than that of MMR, the lowest yielding cultivar at both locations, and was not different ($P > 0.76$) between locations.

No interaction ($P > 0.07$) was observed between cultivar and location for chemical composition of pre-ensiled sorghum; therefore, data are presented as means across location. Among pre-ensiled sorghum, DM concentration was not different ($P > 0.17$) among cultivars (Table 1). Crude protein concentration was least ($P < 0.03$) in S700D and not different ($P > 0.06$) among the other cultivars. The NDF and ADF concentrations were greatest ($P < 0.03$) in MMR. The PS cultivar had the least ($P < 0.03$) NDF concentration and the other cultivars were intermediate. The DBMR and PS cultivars had the lowest ($P < 0.03$) ADF concentrations and S700D was intermediate. The concentration of WSC was greater ($P < 0.02$) in DBMR and PS than MMR. The cultivar DBMR had greater ($P < 0.01$) IVTD than did S700D or MMR. The concentration of ADL was greater ($P < 0.01$) in S700D and MMR than in DBMR. The ADIN concentration of S700D was lower ($P < 0.04$) than that of other cultivars.

Figure 1. Dry matter yield and height of 4 sorghum cultivars in Beeville and College Station, Texas. Cultivars: DBMR = Dairy Master BMR (Richardson Seed, Vega, TX); PS = PS 747 (Pogue Seed, Kenedy, TX); S700D = Silo 700 (Richardson Seed); MMR = MMR 381/73 (Richardson Seed).

Table 1. Chemical composition of pre-ensiled sorghum cultivars

Item	Cultivar ¹				
	DBMR	PS	S700D	MMR	SEM
CP, % of DM	6.36 ^a	6.32 ^a	5.59 ^b	6.94 ^a	0.29
NDF, % of DM	53.85 ^b	50.55 ^c	52.90 ^{bc}	57.66 ^a	1.49
ADF, % of DM	30.32 ^b	30.57 ^b	31.53 ^{ab}	32.99 ^a	0.99
WSC, ² % of DM	21.33 ^a	19.92 ^a	17.2 ^{ab}	13.32 ^b	3.11
IVTD, ³ % of DM	65.45 ^a	63.15 ^{ab}	62.05 ^{bc}	59.82 ^c	1.18
ADL, % of DM	4.61 ^b	5.84 ^{ab}	5.87 ^a	6.43 ^a	0.58
ADIN, % of DM	2.99 ^a	2.52 ^a	2.06 ^b	3.12 ^a	0.42

^{a-c}Within a row, means without a common superscript letter differ ($P < 0.05$).

¹DBMR = Dairy Master BMR (Richardson Seed, Vega, TX); PS = PS 747 (Pogue Seed, Kenedy, TX); S700D = Silo 700 (Richardson Seed); MMR = MMR 381/73 (Richardson Seed). ²WSC = water-soluble carbohydrates.

³IVTD = in vitro true digestibility.

Chemical Composition of Ensiled Sorghum

No cultivar by inoculant interactions ($P > 0.22$) were observed for ensiled sorghum chemical composition parameters. The DM of PS silage was greater ($P < 0.01$) than that of DBMR and MMR silages and inoculant treatment did not affect ($P > 0.08$) any of the cultivars (Table 2). The CP concentration of MMR silage was greater ($P < 0.01$) than that of other cultivars, and was not affected ($P > 0.05$) by treatment. Neutral detergent fiber concentration was less ($P < 0.01$) for MMR silage than for S700D and DBMR silages, and treatment with XC decreased ($P < 0.04$) the NDF concentration compared with control for all cultivars. Application of PRO to DBMR resulted in a decreased ($P < 0.01$) NDF concentration of silage. Among cultivars, S700D silage had the greatest ($P < 0.03$) ADF concentration and MMR silage the least ($P < 0.02$). The ADF concentration was lesser ($P < 0.01$) for all cultivars except MMR silage treated with XC compared with control. Treatment with PRO decreased ($P < 0.01$) the ADF concentrations of DBMR and PS silages compared with control. The WSC concentration of PS silage was greater ($P < 0.04$) than that of DBMR or MMR silages, and treatment with XC increased ($P < 0.02$) the WSC of PS and S700D silages compared with control. Treatment with PRO increased ($P < 0.02$) the WSC concentration of DBMR, PS, and S700D silages. The IVTD was not different ($P > 0.25$) among cultivars, and treatment with PRO increased ($P < 0.05$) the IVTD of DBMR silage compared with control. The ADL concentrations of PS and S700D silages were greater ($P < 0.03$) than that of DBMR silage and was not affected ($P > 0.17$) by treatment for any cultivar. Concentration of ADIN in PS silage was greater ($P < 0.04$) than MMR and DBMR silages, and was not different ($P > 0.09$) between treatments within cultivars. The RUP did not differ ($P > 0.06$) between S700D and MMR silages and did not differ ($P > 0.64$) between S700D treatments;

however, treatment with XC reduced ($P < 0.01$) the RUP of MMR silage compared with PRO and control.

Fermentation Indices and Aerobic Stability

We observed no interactions ($P > 0.05$) between cultivar and inoculant for silage fermentation indices and aerobic stability except ($P < 0.01$) for pH and propionate. The pH of MMR silage was greater ($P < 0.01$) than that of other cultivars, and treatment of MMR silage with XC or PRO decreased ($P < 0.01$) silage pH compared with control (Table 3). Treatment of DBMR silage with PRO also decreased ($P < 0.01$) silage pH compared with control. Ammonia-N concentration was lower ($P < 0.03$) for PS silage than for the other cultivars. The MMR control and XC-treated silages had the greatest ($P < 0.02$) $\text{NH}_3\text{-N}$ concentration, and treatment did not affect ($P < 0.09$) $\text{NH}_3\text{-N}$ concentration of any cultivar. Lactate concentration was least ($P < 0.01$) and acetate concentration greatest ($P < 0.04$) for MMR silage. Treatment of DBMR silage with PRO increased ($P < 0.02$) lactate concentration, whereas treatment of MMR silage with XC and S700D silage with PRO decreased ($P < 0.01$) acetate concentration versus control. Propionate concentrations were below measurable limits for most samples. Propionate concentration was greater ($P < 0.01$) in MMR silage than in the other cultivars, and treatment of MMR silage with either inoculant decreased ($P < 0.01$) propionate concentration compared with control. Isobutyrate concentration was greater ($P < 0.03$) in S700D silage than the other cultivars, and treatment of S700D silage with PRO decreased ($P < 0.01$) the isobutyrate concentration compared with control. Similarly, treatment of PS silage with PRO decreased ($P < 0.03$) the isobutyrate concentration compared with control. Butyrate concentrations were not different ($P > 0.34$) among cultivars or affected ($P > 0.46$) by treatment

with inoculant. Total VFA concentration was greatest ($P < 0.04$) for S700D and was decreased ($P < 0.01$) when S700D silage was treated with PRO. When MMR silage was treated with XC, the total VFA concentration increased ($P < 0.01$) compared with control. Yeast counts were not different ($P > 0.55$) among cultivars or affected by inoculant treatment. Mold counts were not different ($P > 1.0$) among cultivars and were increased ($P < 0.02$) in DBMR silage treated with XC. Aerobic stability was not different ($P > 0.12$) among cultivars and was improved ($P < 0.02$) by more than 62 h when MMR silage was treated with XC.

Disappearance Kinetics

No interactions ($P > 0.06$) were found between cultivar and inoculant for in situ DM disappearance parameters except ($P < 0.01$) the potentially degradable fractions. The wash DM fraction was greater ($P < 0.01$) for S700D silage than for MMR silage and both inoculants decreased ($P < 0.04$) wash DM fraction of S700D compared with control (Table 4). The potentially degradable DM fraction was greater ($P < 0.01$) for MMR silage than S700D silage, and treatment of MMR silage with XC decreased ($P < 0.01$) the potentially degradable DM fraction. The undegradable DM fraction was greater ($P < 0.01$) for S700D silage than MMR silage and was reduced ($P < 0.04$) when S700D silage was treated with PRO. The ERD for DM decreased ($P < 0.01$) when XC was applied to S700D silage. The lag before DM degradation was greater ($P < 0.01$) for S700D silage than for MMR silage and decreased ($P < 0.04$) when S700D silage was treated with XC compared with control. Rate of DM degradation was faster ($P < 0.01$) for S700D control silage than for XC-treated S700D silage and was not affected by PRO.

We found no interactions ($P > 0.06$) between cultivar and inoculant for in situ NDF disappearance parameters except ($P < 0.01$) the potentially degradable fractions. The wash NDF fraction was greater ($P < 0.01$) for S700D silage than for MMR silage (Table 5). Treatment of S700D silage with XC increased ($P < 0.04$) the wash NDF fraction compared with control. The potentially degradable NDF fraction was greater ($P < 0.03$) for XC-treated S700D silage than for control. The undegraded NDF fraction was greater ($P < 0.01$) for S700D silage than for MMR silage, and treatment of S700D silage with PRO decreased ($P < 0.04$) the undegraded NDF fraction compared with control. The ERD for NDF fraction was greater ($P < 0.05$) for S700D silage than for MMR silage, and when S700D silage was treated with XC, the ERD of NDF decreased ($P < 0.02$). Lag time of NDF degradation was not different ($P > 0.29$) between cultivars and was not affected by

treatment. Rate of NDF digestion was not different ($P > 0.18$) between cultivars, and treatment with XC decreased ($P < 0.04$) the rate of NDF digestion of S700D silage.

No interactions ($P > 0.06$) were found between cultivar and inoculant for in situ ADF disappearance parameters. The wash ADF fraction was greater ($P < 0.01$) for S700D silage than for MMR silage and not affected ($P > 0.12$) by either inoculant treatment (Table 6). The potentially degradable ADF fraction was greater ($P < 0.04$) for MMR than S700D silage, and treatment with XC increased ($P < 0.04$) the potentially degradable ADF fraction of S700D silage compared with control. The undegradable ADF fraction was greater ($P < 0.01$) for S700D silage than for MMR silage, and addition of PRO to S700D silage decreased ($P < 0.04$) the undegradable ADF fraction. The ERD, lag time, and digestion rate of ADF were not different ($P > 0.05$) between cultivars or affected by treatment with either inoculant. We found a cultivar by inoculant interaction ($P < 0.01$) for all in situ CP disappearance parameters except ($P > 0.13$) the potentially degradable fraction and rate. The washed CP fraction was greater ($P < 0.01$) for MMR silage than S700D silage and increased ($P < 0.01$) when XC was applied (Table 7). The potentially degradable CP fraction was not different ($P > 0.37$) between cultivars. Treatment of S700D silage with PRO increased ($P < 0.02$) the potentially degradable CP fraction. The undegradable CP fraction was greater ($P < 0.01$) for S700D silage than MMR silage. Treatment of MMR silage with XC or S700D silage with either inoculant decreased ($P < 0.01$) the undegradable CP fraction. Crude protein ERD was greater ($P < 0.01$) for MMR silage than for S700D silage, and MMR silage treated with XC had greater ($P < 0.01$) ERD for CP than control. The rate of CP digestion did not differ ($P > 0.81$) between cultivars, and was greater ($P < 0.02$) for MMR silage treated with XC than for control.

DISCUSSION

Yield and Chemical Composition of Pre-Ensiled Sorghum

The PS cultivar is a PPS forage variety and had a greater yield than MMR at both locations. This is consistent with previous reports, where yield of PPS varieties was greater than other types of sorghums (Bean et al., 2009). The cultivar with the greatest height was the DBMR forage cultivar, which was taller at both locations than MMR. These results agree with results from a forage sorghum trial in the Texas Panhandle (Bean et al., 2009).

Table 2. Chemical composition of sorghum silages¹ and sorghum silage treated with inoculants² after 120 d of conservation

Item	DBMR			PS			S700D			MMR			SEM
	C	XC	PRO	C	XC	PRO	C	XC	PRO	C	XC	PRO	
CP, % of DM	6.03 ^{de}	6.73 ^{bcd}	5.70 ^e	6.22 ^{cde}	6.53 ^{bcd}	6.22 ^{cde}	6.12 ^{de}	6.27 ^{cde}	5.82 ^e	7.22 ^{ab}	7.57 ^a	6.88 ^{abc}	0.35
NDF, % of DM	61.28 ^a	54.30 ^{cd}	54.81 ^{cd}	59.00 ^{ab}	54.58 ^{cd}	56.34 ^{bcd}	61.18 ^a	57.21 ^{bc}	59.32 ^{ab}	56.76 ^{bc}	52.91 ^d	56.05 ^{bcd}	1.74
ADF, % of DM	36.06 ^{bc}	32.51 ^{ef}	32.54 ^{ef}	37.04 ^{ab}	34.00 ^{cdef}	34.06 ^{cde}	38.40 ^a	35.29 ^{bcd}	36.65 ^{ab}	33.48 ^{def}	31.72 ^f	33.34 ^{def}	1.07
WSC, ³ % of DM	4.80 ^{de}	7.03 ^{cd}	8.25 ^{bc}	7.72 ^c	10.95 ^{ab}	11.3 ^a	6.22 ^{cde}	10.55 ^{ab}	11.23 ^a	3.53 ^e	3.88 ^e	4.90 ^{de}	1.38
IVTD, ⁴ % of DM	57.62 ^{bc}	59.25 ^{abc}	61.24 ^a	58.29 ^{abc}	59.29 ^{abc}	59.58 ^{abc}	56.26 ^c	56.75 ^{bc}	59.44 ^{abc}	58.45 ^{abc}	57.85 ^{abc}	60.10 ^{ab}	1.90
ADL, % of DM	5.21 ^{bc}	5.25 ^{bc}	4.08 ^c	7.04 ^a	6.98 ^a	5.94 ^{ab}	6.80 ^a	6.93 ^a	6.55 ^{ab}	5.73 ^{ab}	6.66 ^{ab}	5.67 ^{ab}	0.71
ADIN, % of DM	2.97 ^d	3.49 ^{cd}	3.75 ^{bcd}	4.79 ^a	4.02 ^{abc}	4.01 ^{abc}	4.64 ^{ab}	4.77 ^a	4.21 ^{abc}	3.84 ^{bcd}	4.03 ^{abc}	3.57 ^{cd}	0.32
RUP, % of DM	—	—	—	—	—	—	1.77 ^a	1.75 ^a	1.74 ^a	1.64 ^{ab}	1.33 ^c	1.57 ^b	0.64

^{a-f}Within a row, means without a common superscript letter differ ($P < 0.05$).

¹DBMR = Dairy Master BMR (Richardson Seed, Vega, TX); PS = PS 747 (Pogue Seed, Kenedy, TX); S700D = Silo 700 (Richardson Seed); MMR = MMR 381/73 (Richardson Seed). ²C = control (distilled water); XC = xylanase and cellulase (50:50 mixture of Cellulase Plus and Xylanase Plus; Dyadic, Juniper, FL); PRO = Promote ASB (Cargill Animal Nutrition, Indianapolis, IN).

³WSC = water-soluble carbohydrates.

⁴IVTD = in vitro true digestibility.

Table 3. Fermentation characteristics of sorghum silages¹ and sorghum silage treated with inoculants² after 120 d of conservation

Item	DBMR			PS			S700D			MMR			SEM
	C	XC	PRO	C	XC	PRO	C	XC	PRO	C	XC	PRO	
pH	3.83 ^{cd}	3.77 ^{de}	3.67 ^e	3.83 ^{cd}	3.78 ^d	3.78 ^d	3.83 ^{cd}	3.8 ^d	3.83 ^{cd}	4.23 ^a	4.00 ^b	3.92 ^{bc}	0.05
NH ₃ -N, % of total N	2.67 ^{a-d}	2.67 ^{a-d}	2.0 ^{b-e}	1.0 ^e	1.33 ^{de}	1.67 ^{cde}	3.0 ^{abc}	2.25 ^{a-e}	1.67 ^{cde}	3.5 ^{ab}	3.67 ^a	2.67 ^{a-d}	0.76
Lactate, % of DM	4.03 ^{bcd}	5.09 ^{ab}	5.53 ^a	4.31 ^{abc}	4.49 ^{ab}	5.53 ^a	4.75 ^{ab}	4.97 ^{ab}	4.92 ^{ab}	2.06 ^e	2.89 ^{de}	3.17 ^{cde}	0.61
Acetate, % of DM	2.42 ^{de}	2.25 ^{de}	2.09 ^{de}	2.635 ^{cde}	2.76 ^{cde}	1.64 ^e	4.51 ^{bc}	3.73 ^{bcd}	1.26 ^e	5.02 ^b	7.68 ^a	5.01 ^b	0.97
Propionate, % of DM	0.002 ^b	0.000 ^b	0.000 ^b	0.000 ^b	0.000 ^b	0.000 ^b	0.000 ^b	0.000 ^b	0.000 ^b	0.350 ^a	0.005 ^b	0.000 ^b	0.01
Isobutyrate, % of DM	0.16 ^{ef}	0.19 ^{def}	0.07 ^f	0.69 ^{bc}	0.56 ^{bcd}	0.25 ^{def}	1.10 ^a	0.96 ^{ab}	0.36 ^{cdef}	0.52 ^{cde}	0.51 ^{cde}	0.18 ^{def}	0.20
Butyrate, % of DM	0.01 ^a	0.003 ^a	0.01 ^a	0.01 ^a	0.02 ^a	0.01 ^a	0.02 ^a	0.03 ^a	0.01 ^a	0.02 ^a	0.05 ^a	0.002 ^a	0.02
Total VFA, % of DM	6.63 ^d	7.53 ^{cd}	7.71 ^{cd}	7.64 ^{cd}	7.83 ^{bcd}	7.44 ^{cd}	10.38 ^{ab}	9.69 ^{abc}	6.54 ^d	7.65 ^{cd}	11.14 ^a	8.36 ^{bcd}	1.28
Yeasts, log cfu/g	7.07 ^{ab}	6.70 ^{ab}	6.77 ^{ab}	7.01 ^{ab}	6.76 ^{ab}	7.16 ^a	6.51 ^{ab}	5.98 ^{ab}	6.97 ^{ab}	8.76 ^{ab}	5.76 ^b	6.79 ^{ab}	6.69
Molds, log cfu/g	1.00 ^b	2.24 ^a	1.00 ^b	1.00 ^b	1.00 ^b	1.00 ^b	1.00 ^b	1.00 ^b	1.00 ^b	1.00 ^b	1.00 ^b	1.00 ^b	1.68
Aerobic stability, h	25.37 ^b	22.41 ^b	24.72 ^b	26.47 ^b	32.90 ^b	41.25 ^b	59.56 ^{ab}	54.81 ^{ab}	17.97 ^b	34.46 ^b	97.27 ^a	44.97 ^{ab}	26.25

^{a-f}Within a row, means without a common superscript letter differ ($P < 0.05$).

¹DBMR = Dairy Master BMR (Richardson Seed, Vega, TX); PS = PS 747 (Pogue Seed, Kenedy, TX); S700D = Silo 700 (Richardson Seed); MMR = MMR 381/73 (Richardson Seed). ²C = control (distilled water); XC = xylanase and cellulase (50:50 mixture of Cellulase Plus and Xylanase Plus; Dyadic, Juniper, FL); PRO = Promote ASB (Cargill Animal Nutrition, Indianapolis, IN).

Table 4. In situ DM disappearance kinetics of 2 sorghum silage cultivars¹ treated with inoculants² before ensiling

Item	S700D			MMR			SEM
	C	XC	PRO	C	XC	PRO	
Wash fraction (A), %	37.78 ^a	28.19 ^{cb}	32.31 ^b	29.45 ^{bc}	27.23 ^c	29.11 ^{bc}	1.64
Potentially degradable fraction (B), %	34.99 ^c	40.22 ^{bc}	38.29 ^c	45.61 ^{ab}	37.77 ^c	48.45 ^a	1.92
Undegradable fraction (C), %	38.03 ^a	35.97 ^{ab}	35.43 ^b	31.75 ^c	29.39 ^c	31.24 ^c	0.8
Extent of digestion, %	57.24 ^a	41.17 ^c	49.90 ^{ab}	50.51 ^{ab}	44.41 ^{bc}	52.39 ^a	2.41
Lag time, h	9.10 ^a	0.24 ^b	4.50 ^{ab}	0.00 ^b	0.00 ^b	0.65 ^b	2.08
K _d ³ per h	0.07 ^a	0.02 ^b	0.05 ^{ab}	0.04 ^{ab}	0.04 ^{ab}	0.05 ^{ab}	0.01

^{a-c}Within a row, means without a common superscript letter differ ($P < 0.05$).

¹S700D = Silo 700 (Richardson Seed, Vega, TX); MMR = MMR 381/73 (Richardson Seed). ²C = control (distilled water); XC = xylanase and cellulase (50:50 mixture of Cellulase Plus and Xylanase Plus; Dyadic, Juniper, FL); PRO = Promote ASB (Cargill Animal Nutrition, Indianapolis, IN).

³Fractional rate of digestion.

Concentrations of NDF and ADF were greatest in the MMR cultivar, which is consistent with previously reported values for non-BMR cultivars (Bean and Marsalis, 2012). The structural carbohydrate concentrations of MMR were greater than those of DBMR and PS, making the BMR and PSS varieties in this study more degradable pre-ensiling. The concentration of WSC was greater in DBMR than in MMR, whereas all cultivars showed greater values than those for freshly chopped sorghum in Tabacco et al. (2011). The lower ADL concentration in DBMR than in S700D and MMR and greater the WSC concentration in DBMR than in MMR contributed to the greater IVTD, which agrees with Bean et al. (2009). Here, the genetically improved BMR and PSS forage sorghum varieties showed favorable results for yield and nutritive value, thus improving their usefulness as feedstuff or feedstock.

Chemical Composition of Ensiled Sorghum

Concentrations of NDF decreased on average 4.81% in all cultivars treated with XC, and ADF concentrations decreased on average 3.23% in all cultivars except

MMR, which is consistent with previous experiments and indicates the ability of XC to reduce the fibrous fraction of corn silage (Colombatto et al., 2004 b,c; Arriola et al., 2011). Inoculant PRO reduced the NDF concentration of DBMR by 6.47%, likely because it is a BMR, which has lesser NDF concentration and less undegradable components (Bean et al., 2009). The ADF concentrations of DBMR and PS treated with PRO were reduced by 3.25%, which is consistent with previously published reports that indicated a reduced ADF concentration of corn silage inoculated with similar bacterial inoculants (Arriola et al., 2011).

The WSC was greater in DBMR, PS, and S700D inoculated with PRO and in PS and S700D treated with XC; therefore, both inoculants were effective at increasing the availability of fermentation substrates, which is consistent with Colombatto et al. (2004b) but inconsistent with Colombatto et al. (2004c), which found lower WSC after treatment with fibrolytic enzymes on corn silage. Kleinschmit and Kung (2006) found no difference in WSC after inoculation of corn silage with bacterial inoculants. Pre-ensiled MMR had the least amount of WSC and was the only cultivar unaffected

Table 5. In situ NDF disappearance kinetics of 2 sorghum silage cultivars¹ treated with inoculants² before ensiling

Item	S700D			MMR			SEM
	C	XC	PRO	C	XC	PRO	
Wash fraction (A), %	48.78 ^a	40.32 ^{bc}	44.53 ^{ab}	37.35 ^{bc}	36.47 ^c	34.4 ^c	2.61
Potentially degradable fraction (B), %	48.14 ^{bc}	57.28 ^a	46.53 ^c	56.08 ^{ab}	52.38 ^{abc}	57.79 ^a	2.68
Undegradable fraction (C), %	38.03 ^a	35.97 ^{ab}	35.43 ^b	31.75 ^c	29.39 ^c	31.24 ^c	0.8
Extent of digestion, %	74.49 ^a	60.00 ^b	67.34 ^{ab}	61.96 ^b	57.09 ^b	59.28 ^b	3.96
Lag time, h	8.39 ^a	4.40 ^a	8.21 ^a	5.22 ^a	6.35 ^a	4.92 ^a	2.01
K _d ³ per h	0.06 ^a	0.03 ^b	0.05 ^{ab}	0.04 ^{ab}	0.03 ^{ab}	0.04 ^{ab}	0.01

^{a-c}Within a row, means without a common superscript letter differ ($P < 0.05$).

¹S700D = Silo 700 (Richardson Seed, Vega, TX); MMR = MMR 381/73 (Richardson Seed).

²C = control (distilled water); XC = xylanase and cellulase (50:50 mixture of Cellulase Plus and Xylanase Plus; Dyadic, Juniper, FL); PRO = Promote ASB (Cargill Animal Nutrition, Indianapolis, IN).

³Fractional rate of digestion.

Table 6. In situ ADF disappearance kinetics of 2 sorghum silage cultivars¹ treated with inoculants² before ensiling

Item	S700D			MMR			SEM
	C	XC	PRO	C	XC	PRO	
Wash fraction (A), %	50.48 ^a	42.98 ^{ab}	45.21 ^{ab}	36.74 ^b	37.80 ^b	37.84 ^b	3.15
Potentially degradable fraction (B), %	44.02 ^b	55.21 ^a	44.11 ^b	55.76 ^a	49.58 ^{ab}	53.40 ^{ab}	3.51
Undegradable fraction (C), %	38.03 ^a	35.97 ^{ab}	35.43 ^b	31.75 ^c	29.39 ^c	31.24 ^c	0.8
Extent of digestion, %	75.67 ^a	62.70 ^a	66.96 ^a	59.66 ^a	60.78 ^a	63.54 ^a	5.14
Lag time, h	9.67 ^a	5.61 ^a	13.41 ^a	6.22 ^a	12.16 ^a	8.71 ^a	3.79
K _d ³ per h	0.07 ^a	0.03 ^a	0.05 ^a	0.04 ^a	0.07 ^a	0.05 ^a	0.02

^{a-c}Within a row, means without a common superscript letter differ ($P < 0.05$).

¹S700D = Silo 700 (Richardson Seed, Vega, TX); MMR = MMR 381/73 (Richardson Seed). ²C = control (distilled water); XC = xylanase and cellulase (50:50 mixture of Cellulase Plus and Xylanase Plus; Dyadic, Juniper, FL); PRO = Promote ASB (Cargill Animal Nutrition, Indianapolis, IN).

³Fractional rate of digestion.

by inoculant treatment, indicating that silage bacteria may have had difficulty accessing substrates because of the decreased polysaccharides (Williams and Shinnors, 2012).

The IVTD was greatest for DBMR silage treated with PRO, which is reasonable because ADL for DBMR treated with PRO was least among all similarly treated cultivars. Previous studies did not measure ADL or IVTD for comparison with these results. Treating sorghum silage with XC or PRO reduced the NDF and ADF fractions, which increased cell wall degradability. Past biogas research reported that reduced NDF and ADF content of forage feedstock silage is correlated with greater methane yields (Klimiuk et al., 2010). Treatment of DBMR silage with PRO reduced ADL, causing an increase of IVTD. The RUP was reduced when MMR silage was treated with XC, but no studies could be found to compare the effect of inoculant on silage RUP. Likewise, no studies were found to compare effects of enzyme or bacterial inoculation of non-BMR and BMR sorghum silage.

Fermentation Indices and Aerobic Stability

Silage pH was reduced by XC in MMR silage and by PRO in DBMR and MMR silages. This is likely because

of the increased lactate concentration in XC-treated DBMR silage. Treatment of MMR silage with either inoculant only tended to increase lactate concentration of silage. Decreased pH and improved lactate production has been seen in previous studies of sorghum silage treated with bacterial inoculant (Filya, 2003; Williams and Shinnors, 2012). Similar to these results, previously reported literature indicates that inoculation with fibrolytic enzymes or bacterial inoculants does not affect NH₃-N concentration of corn silage (Shepard and Kung, 1996; Kleinschmit and Kung, 2006).

Acetate concentrations were greatest for XC-treated MMR, which explains the 62-h improvement in aerobic stability, because acetate is known to inhibit fungi (Moon, 1983). However, bacterial inoculant PRO did not improve yeast and mold counts or aerobic stability of sorghum silage compared with the control, which may be due to the lesser acetate concentrations, especially of PRO-treated S700D silage. Jones (2012) suggested that the use of *Lactobacillus buchneri* on corn silage with a DM content of 32% or less produces inactive acetic acid, causing an energy loss without providing significant improvement in aerobic stability. This likely occurred for MMR silage treated with PRO in this experiment. The application of bacterial inoculants to corn and sorghum silage has been successful at improv-

Table 7. In situ CP disappearance kinetics of 2 sorghum silages¹ treated with inoculants² before ensiling

Item	S700D			MMR			SEM
	C	XC	PRO	C	XC	PRO	
Wash fraction (A), %	61.44 ^d	66.69 ^b	61.49 ^d	63.89 ^c	69.10 ^a	56.01 ^e	0.35
Potentially degradable fraction (B), %	22.21 ^{bc}	21.90 ^{bc}	24.63 ^a	23.08 ^{abc}	21.24 ^c	23.83 ^{ab}	0.66
Undegradable fraction (C), %	18.06 ^a	10.22 ^c	14.56 ^b	12.88 ^b	9.87 ^c	19.20 ^a	0.66
Extent of digestion, %	69.18 ^c	73.14 ^{bc}	72.73 ^{bc}	75.05 ^b	86.06 ^a	71.78 ^{bc}	1.33
Lag time, h	0.03 ^b	0.02 ^b	0.04 ^b	0.05 ^b	0.29 ^a	0.10 ^b	0.06

^{a-e}Within a row, means without a common superscript letter differ ($P < 0.05$).

¹S700D = Silo 700 (Richardson Seed, Vega, TX); MMR = MMR 381/73 (Richardson Seed). ²C = control (distilled water); XC = xylanase and cellulase (50:50 mixture of Cellulase Plus and Xylanase Plus; Dyadic, Juniper, FL); PRO = Promote ASB (Cargill Animal Nutrition, Indianapolis, IN).

ing fermentation products in fewer than half of the reported studies (Muck and Bolsen, 1991). Williams and Shinnars (2012) found that sorghum silage that had a greater DM concentration and greater amount of bacterial inoculant (38.5–57.9% and 500,000 cfu/g of silage, respectively) than in this experiment (25.5% average of control silage and 100,000 cfu/g of silage, respectively) exhibited increased production of fermentation products, which lowered yeast and mold populations during aerobic exposure and improved aerobic stability; thus, little heating occurred in inoculated sorghum silage.

Disappearance Kinetics

Sorghum silage disappearance kinetics are a function of their nutritive value, morphology, and physiology. Silages exhibiting a greater wash fraction have a reduced potentially degradable fraction. The wash DM, NDF, and ADF fractions were greater and wash CP fraction lesser for S700D silage than for MMR silage. This is likely due to the tendency of greater WSC concentration and greater total VFA of S700D silage compared with MMR silage. Treating S700D silage with XC decreased the wash DM and NDF fractions. The potentially degradable DM and ADF fractions were greater for MMR silage than for S700D silage because of lesser NDF and ADF of MMR silage. Treatment of MMR silage with XC decreased the potentially degradable DM fraction, which is consistent with decreased NDF concentration of XC-treated MMR silage versus control. The S700D cultivar had greater NDF and ADF concentrations than MMR, and treatment with XC was not successful in increasing potentially degradable DM fraction, but the potentially degradable NDF and ADF fractions were increased.

These disappearance kinetics are consistent with *in vitro* results from corn silage showing increased soluble losses compared with controls, indicating that the fibrolytic enzymes solubilized material that contributed to the increase in initial OM degradation, suggesting that enzymes also enhanced accessibility of the insoluble yet potentially degradable OM (Colombatto et al., 2004a,b,c). The extent of DM and NDF digestion for S700D decreased due to the reduced rate of digestion of DM and NDF, which was caused by decreased structural carbohydrate concentration of XC-treated silage. The lower structural carbohydrate concentration also resulted in a reduced lag time for DM degradation. Because XC reduced total and less digestible fiber fractions, it could increase intake and digestibility of sorghum silage fed to cattle. Treatment with XC may also reduce structural carbohydrates binding soluble carbohydrates used for ethanol production, thus im-

proving the efficiency of ethanol production from feedstock (Han et al., 2007).

The undegraded DM, NDF, and ADF fractions were greater for S700D than for MMR, and greater in untreated sorghum silage than in PRO-treated silage. Treatment with PRO also increased the wash DM fraction and potentially degradable ADF fraction of S700D silage, indicating that PRO may be more effective at reducing the undegradable fraction of sorghum silage cultivars having a greater fiber fraction due to greater hemicellulose and lignin bonds (Álvarez et al., 2009; Bean et al., 2009). Part of the cell wall contents can be lost due to the acidic conditions as well as microbial activity during the ensiling process (Morrison, 1979). An *in vivo* digestibility trial that fed bacterial inoculated corn silage showed similar reductions in NDF and ADF fractions; however, feed efficiency was not affected by treatment (Arriola et al., 2011). Sorghum silage harvested at hard dough stage, which is a later maturity than the sorghum silage in this experiment, did not exhibit decreased cell wall content due to bacterial inoculant (Williams and Shinnars, 2012).

The wash CP fraction was greater for MMR silage than for S700D silage because the CP concentration of MMR silage was greater. When S700D silage was treated with PRO, the potentially degradable CP fraction was increased, likely because of the reduced undegradable DM and NDF fractions that released bound protein, indicated by the ADIN concentrations of silage. Treatment of S700D silage with PRO decreased the undegradable CP fraction, whereas treatment of MMR silage with PRO increased the undegradable CP fraction. Treatment with XC consistently decreased undegradable CP fraction of both cultivars. Generally, inoculants facilitate degradation of cell wall bound proteins, which reduces the fiber, releasing available CP (Kohn and Allen, 1992). The extent of CP digestion was increased by XC in MMR silage, likely due to the faster rate of CP digestion. The rate of CP digestion was faster when treated with XC because of the increase of wash CP fraction and decrease of undegradable CP fraction.

CONCLUSIONS

Fibrolytic enzyme XC reduced the NDF concentrations of all cultivars and improved the DM, NDF, ADF, and CP disappearance kinetics of both MMR and S700D silages, but especially of S700D, the cultivar with the greatest structural carbohydrate concentration. More research is recommended to determine whether the improved nutritive value of sorghum silage treated with XC inoculation translates into enhanced

forage quality and biogas production. In addition, XC increased the aerobic stability in MMR silage due to the greater amount of acetate. Bacterial inoculant PRO only reduced the NDF and ADF concentrations of DBMR and PS silages, the cultivars with moderate ADF concentrations. The undegradable DM, NDF, ADF, and CP fractions of S700D silage were decreased when treated with PRO. Treatment with PRO did not improve ensiling characteristics enough to increase aerobic stability; therefore, it is not recommended for improving aerobic stability of sorghum silage. It is most efficient to apply inoculants to sorghum silage with greater structural carbohydrate concentrations, such as those that are harvested at a more advanced stage of maturity. Treatment with fibrolytic enzyme XC had more benefit on fermentation characteristics and in situ disappearance kinetics than treatment with the bacterial inoculant used in this experiment.

REFERENCES

- Álvarez, G., J. M. Pinos-Rodríguez, J. G. Herrera, J. C. García, S. S. Gonzalez, and R. Bárcena. 2009. Effects of exogenous fibrolytic enzymes on ruminal digestibility in steers fed high fiber rations. *Livest. Sci.* 121:150–154.
- Ankom. 2011. Method for determining acid detergent lignin in beakers. Accessed Oct. 15, 2012. http://www.ankom.com/media/documents/Method_8_Lignin_in_beakers_4-13-11.pdf.
- AOAC. 1990. Official Methods of Analysis. 15th ed. Assoc. Off. Anal. Chem., Arlington, VA.
- Arriola, K. G., S. C. Kim, C. R. Staples, and A. T. Adesogan. 2011. Effect of applying bacterial inoculants containing different types of bacteria to corn silage on the performance of dairy cattle. *J. Dairy Sci.* 94:3973–3979.
- Ball, D. M., C. S. Hoveland, and G. D. Lacefield. 2007. Southern Forages. 4th ed. International Plant Nutrition Institute, Norcross, GA.
- Bean, B., and M. Marsalis. 2012. Corn and sorghum silage production considerations. The High Plains Dairy Conference, Texas Animal Nutrition Council, Amarillo. Accessed Oct. 1, 2012. http://www.highplainsdairy.org/2012/18_Bean_Corn%20and%20Sorghum%20Silage%20Production%20Considerations_2012%20HPDC_Final.pdf.
- Bean, B., T. McCollum, B. Villarreal, J. Blumenthal, J. Robinson, R. Brandon, E. Buttrey, R. Van Meter, and D. Pietsch. 2009. Texas panhandle forage sorghum silage trial. AgriLife Research and Extension Center at Amarillo. Accessed May 1, 2012. <http://amarillo-tamu.edu/wpengine.netdna-cdn.com/files/2010/11/Forage-Sorghum-2009-Variety-Report-Final.pdf>.
- Bolsen, K. K., J. E. Sherley, A. Laytimi, and J. Dickerson. 1989. Whole-plant grain sorghum and inoculated corn silages in mid-lactation dairy cows diets. Pages 32–37 in Annual Kansas State Dairy Day Proc. Agric. Exp. Stn., Kansas State University, Manhattan. Accessed May 1, 2012. <http://krex.k-state.edu/dspace/bitstream/handle/2097/14666/Dairy89pg32-37.pdf?sequence=1>.
- Colombatto, D., F. L. Mould, M. K. Bhat, R. H. Phipps, and E. Owen. 2004a. *In vitro* evaluation of fibrolytic enzymes as additives for maize (*Zea mays* L.) silage: I. Effects of ensiling temperature, enzyme source and addition level. *Anim. Feed Sci. Technol.* 111:111–128.
- Colombatto, D., F. L. Mould, M. K. Bhat, R. H. Phipps, and E. Owen. 2004b. *In vitro* evaluation of fibrolytic enzymes as additives for maize (*Zea mays* L.) silage: II. Effects on rate of acidification, fibre degradation during ensiling and rumen fermentation. *Anim. Feed Sci. Technol.* 111:129–143.
- Colombatto, D., F. L. Mould, M. K. Bhat, R. H. Phipps, and E. Owen. 2004c. *In vitro* evaluation of fibrolytic enzymes as additives for maize (*Zea mays* L.) silage: III. Comparison of enzymes as derived from psychrophilic, mesophilic or thermophilic sources. *Anim. Feed Sci. Technol.* 111:145–159.
- Elwakeel, E. A., E. C. Titgemeyer, B. J. Johnson, C. K. Armendariz, and J. E. Shirley. 2007. Fibrolytic enzymes to increase the nutritive value of dairy feedstuffs. *J. Dairy Sci.* 90:5226–5236.
- Filya, I. 2003. The effect of *Lactobacillus buchneri*, with or without homofermentative lactic acid bacteria, on the fermentation, aerobic stability and ruminal degradability of wheat, sorghum, and maize silage. *J. Appl. Microbiol.* 95:1080–1086.
- Foster, J. L., J. N. Carter, L. E. Sollenberger, A. R. Blount, R. O. Myer, M. K. Maddox, S. C. Phatak, and A. T. Adesogan. 2011. Nutritive value, fermentation characteristics, and in situ disappearance kinetics of ensiled warm-season legumes and bahiagrass. *J. Dairy Sci.* 94:2042–2050.
- Grant, R. J., S. G. Haddad, K. J. Moore, and J. F. Pedersen. 1995. Brown midrib sorghum silage for midlactation dairy cows. *J. Dairy Sci.* 78:1970–1980.
- Hall, M. B., W. H. Hoover, J. P. Jennings, and T. K. Miller Webster. 1999. A method for partitioning neutral detergent soluble carbohydrates. *J. Sci. Food Agric.* 79:2079–2086.
- Han, K.-H., J.-H. Ko, and S. H. Yang. 2007. Optimizing lignocellulosic feedstock for improved biofuel productivity and processing. *Biofuels Bioprod. Biorefin.* 1:135–146.
- Haugen, H. L., M. J. Lamonte, T. J. Klopfenstein, D. C. Adams, and M. D. Ullrich. 2006. Estimation of undegradable intake protein in forages using neutral detergent insoluble nitrogen at a single in situ incubation time point. *J. Anim. Sci.* 84:651–659.
- Herrmann, C., M. Heiermann, and C. Idler. 2011. Effects of ensiling, silage additives and storage period on methane formation of biogas crops. *Bioresour. Technol.* 102:5153–5161.
- Jones, L. 2012. Inoculants: Insurance or strategy? Accessed Aug. 1, 2012. http://www.progressiveforage.com/index.php?option=com_content&view=article&id=4572:inoculants-insurance-or-strategy&catid=81:silage&Itemid=135.
- Kleinschmit, D. H., and L. Kung Jr. 2006. A meta-analysis of the effects of *Lactobacillus buchneri* on the fermentation and aerobic stability of corn and grass and small-grain silages. *J. Dairy Sci.* 89:4005–4013.
- Klimiuk, E., T. Pokój, B. Wojciech, and B. Dubis. 2010. Theoretical and observed biogas production from plant biomass of different fibre contents. *Bioresour. Technol.* 101:9527–9535.
- Kohn, R. A., and M. S. Allen. 1992. Storage of fresh and ensiled forages by freezing affects fibre and crude protein fractions. *J. Sci. Food Agric.* 58:215–220.
- Kung, L., and R. Charley. 2010. Forage inoculants: Key silage management topics. Accessed June 18, 2010. http://www.qualitysilage.com/inoculants/PDF/Forage_Inoculants.pdf.
- Liu, L. 1998. Determination of ammonium-nitrogen in plant tissue. Pages 89–92 in Handbook of Reference Methods for Plant Analysis. Y. P. Kalra, ed. Soil and Plant Analysis Council Inc., CRC Press, Boca Raton, FL.
- Lusk, J. W., P. K. Karau, D. O. Balogu, and L. M. Gourley. 1984. Brown midrib sorghum or silage for milk production. *J. Dairy Sci.* 67:1739–1744.
- McCollum, T., III, K. McCuiston, and B. Bean. 2012. Brown midrib and photoperiod-sensitive forage sorghums. Texas Agricultural Research and Extension Center Amarillo, Texas A&M University System. Accessed Apr. 5, 2012. <http://amarillo.tamu.edu/files/2010/11/brownmidrib.pdf>.
- McCuiston, K. C., F. T. McCollum, L. W. Greene, J. MacDonald, and B. Bean. 2011. Performance of stocker cattle grazing 2 sorghum-sudangrass hybrids under various stocking rates. *Prof. Anim. Sci.* 27:92–100.
- McDonald, P., A. R. Henderson, and S. J. E. Heron. 1991. Biochemistry of Silage. 2nd ed. Chalcombe Publication, Marlow, UK.
- Mertens, D. R. 1977. Dietary fiber components: Relationship to the rate and extent of ruminal digestion. *Fed. Proc.* 36:187–192.

- Moon, N. J. 1983. Inhibition of the growth of acid tolerant yeasts by acetate, lactate and propionate, and their synergistic mixture. *J. Appl. Bacteriol.* 55:453–460.
- Morrison, I. M. 1979. Change in the cell wall components of laboratory silages and the effect of various additives on these changes. *J. Agric. Sci.* 93:581–586.
- Muck, R. E., and K. K. Bolsen. 1991. Silage preservation and silage additive products. Pages 105–126 in *Field Guide for Hay and Silage Management in North America*. K. K. Bolsen, ed. NFIA, Des Moines, IA.
- Murray, S., W. L. Rooney, S. E. Mitchell, A. Sharma, P. E. Klein, J. E. Mullet, and S. Kresovich. 2008. Genetic improvement of sorghum as a biofuel feedstock: II. QTL for stem and leaf structural carbohydrates. *Crop Sci.* 48:2180–2193.
- Oliver, A. L., R. J. Grant, J. F. Pedersen, and J. O. Rear. 2004. Comparison of brown midrib-6 and -18 forage sorghum with conventional sorghum and corn silage in diets of lactating dairy cows. *J. Dairy Sci.* 87:637–644.
- Ørskov, E. R., and I. McDonald. 1979. The estimation of protein degradability in the rumen from incubation measurements weighted according to rate of passage. *J. Agric. Sci.* 92:499–503.
- Prostko, E. P., J. P. Muir, and S. R. Stokes. 1998. The influence of harvest timing on forage sorghum silage yield and quality. *Texas Agric. Exp. Stn.*, Stephenville, TX. Accessed Jun. 15, 2012. <http://articlesearchdatabase.tamu.edu/article.cfm?WhichArticle=1394>.
- Sheperd, A. C., and L. Kung Jr. 1996. Effects of an enzyme additive on composition of corn silage ensiled at various stages of maturity. *J. Dairy Sci.* 79:1767–1773.
- Supelco. 1990. Analyzing fatty acids by packed column gas chromatography. Supelco GC Bulletin 856A. Supelco Inc., Bellefonte, PA.
- Tabacco, E., F. Righi, A. Quarantelli, and G. Borreani. 2011. Dry matter nutritional losses during aerobic deterioration of corn and sorghum silages influenced by different lactic acid bacteria inocula. *J. Dairy Sci.* 94:1409–1419.
- Thiex, N., and T. Van Erem. 1999. Comparisons of Karl Fischer method with oven methods for determination of water in forages and animal feeds. *J. AOAC Int.* 82:799–808.
- Tournas, V., M. E. Stack, P. B. Mislivec, H. A. Koch, and R. Bandler. 1998. Yeasts, molds and mycotoxins. Pages 18.01–18.11 in *Food and Drug Administration Bacteriological Analytical Manual*. AOAC Int., Gaithersburg, MD.
- USDA-NASS (US Department of Agriculture-National Agricultural Statistics Service). 2011. 2011 State Agriculture Overview: Texas. Accessed Jun. 24, 2011. http://www.nass.usda.gov/Statistics_by_State/Ag_Overview/AgOverview_TX.pdf.
- Van Soest, P. J. 1967. Development of a comprehensive system of feed analyses and its application to forages. *J. Anim. Sci.* 26:119–128.
- Van Soest, P. J., J. B. Robertson, and B. A. Lewis. 1991. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. *J. Dairy Sci.* 74:3583–3597.
- Van Soest, P. J., R. H. Wine, and L. A. Moore. 1966. Estimation of the free digestibility of forages by the in vitro digestion of cell walls. Pages 438–411 in *Proc. 10th Intl. Grassl. Congr.*, Helsinki, Finland. University of Helsinki, Finland.
- Williams, S. D., and K. J. Shinnars. 2012. Farm-scale anaerobic storage and aerobic stability of high dry matter sorghum as a biomass feedstock. *Biomass Bioenerg.* 46:309–316. <http://dx.doi.org/10.1016/j.biombioe.2012.08.010>.