



## Graduate Student Literature Review: Current perspectives on whole-plant sorghum silage production and utilization by lactating dairy cows\*

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### ABSTRACT

The purpose of this literature review is to evaluate current research into and understanding of whole-plant sorghum silage production and the effect of feeding whole-plant sorghum silage on lactation performance of dairy cows. Sorghum's drought tolerance, water efficiency, and low cost of production make it an intriguing crop in areas where whole-plant corn silage production may be limited. Currently, urban land encroachment and reduced water availability have increased social and economic pressures on farms to improve crop production efficiency. As these challenges become more prevalent, greater reliance on sorghum can be expected because of its ability to produce high dry matter yields while maintaining nutritive value, even under less-than-ideal growing conditions. Moreover, whole-plant sorghum silage provides both physically effective fiber and energy through fiber and grain fractions. Advancements in sorghum genetics and mechanical processing have the potential to alleviate common challenges associated with whole-plant sorghum silage supplementation, such as increased neutral detergent fiber and decreased neutral detergent fiber digestibility, starch concentration, and starch digestibility. These nutritive challenges must be overcome for whole-plant sorghum silage to be a viable alternative to whole-plant corn silage.

**Key words:** berry processing score, brown midrib, ensiling, harvest maturity

### INTRODUCTION

In 2018, approximately 2.5 million hectares of whole-plant corn silage (WPCS) was harvested in the United

States (USDA-NASS, 2018). Despite the widespread use of WPCS, many regions are threatened with low water availability or conditions that may not be ideal for its growth. Negative consequences of these issues include loss of nutritive value and reduced whole-plant yields, which affect farm productivity and profitability. In this context, whole-plant sorghum silage (WPSS) has received interest because of its ability to be drought-tolerant and more water efficient than corn (Staggenborg et al., 2008). A 3-yr summary of sorghum production in the United States is shown in Table 1. In the 2018 growing season, over 100,000 ha of WPSS was harvested in the United States (USDA-NASS, 2018). Much of the harvested area of WPSS was in regions where WPCS growth may be limited. Generally, sorghum is adapted to dry climates such as that in the southwestern United States, but it has also been successfully grown in more moist and humid conditions such as the southeastern United States. The ability of sorghum to be grown across a wide variety of conditions may improve its potential use in the future. Several varieties of sorghum are available, including grain, forage, biomass, and sweet sorghum. Variation can be observed both physically and chemically between sorghum varieties and hybrids. Table 2 highlights some of the variation that can be observed in nutritive value depending upon the variety and hybrid selected. Careful variety and hybrid selection must occur to avoid selecting a variety or hybrid that may produce unexpected results at the time of harvest. Several challenges exist in supplementing WPSS to lactating dairy cows, including increased NDF and lignin concentrations and reduced starch concentration and starch digestibility. However, current research indicates that improvements through plant genetic advancement or mechanical processing may be able to alleviate some of these drawbacks. The purpose of this review is to provide current insights surrounding WPSS production and the effect of feeding WPSS on the lactation performance of dairy cows. As water availability issues continue and pressure is applied to the dairy industry to become more water efficient, sorghum could play an important role as a potential solution.

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**Table 1.** Summary of whole-plant sorghum silage production in the United States over a 3-yr period<sup>1</sup>

Item	2016	2017	2018
Area harvested, ha	120,596	114,121	106,837
Production, Mg as-fed	3,783,872	3,421,905	2,957,426
Yield, Mg/ha as-fed	5.3	4.9	4.6

<sup>1</sup>USDA-NASS (2018).

## WHOLE-PLANT SORGHUM SILAGE FRACTIONS

Whole-plant sorghum silage is unique in that it contains a grain and a fiber fraction. We will discuss these fractions separately to evaluate the current knowledge related to improving each of their respective nutritive values.

### Grain Fraction

Sorghum grain comprises 3 separate units—the pericarp, endosperm, and germ. The pericarp surrounds the outside of the seed and acts as a physical barrier to digestion of nutrients contained within the endosperm and germ layers.

The endosperm can be further divided into 2 sections: (1) floury, and (2) vitreous endosperm. Differences between the floury and vitreous endosperm are associated with protein concentration differences. In the vitreous endosperm, more storage proteins are intertwined with starch, which contrasts with the floury endosperm's lower concentrations of storage proteins (Shull et al., 1990). This gives the vitreous endosperm a glossy yellow appearance, whereas the floury endosperm is opaque.

These storage proteins, called kafirin proteins (Johns and Brewster, 1916), are defined as prolamin proteins. Kafirin proteins make up 60 to 70% of the total protein in sorghum grain and are the main storage protein, much like zein proteins in corn kernels (Duodu et al., 2003). However, kafirin proteins are more hydrophobic in nature and less digestible (Herrera-Saldana et al., 1990), and account for a greater percentage of the total protein of the grain than zein proteins in corn kernels (sorghum grain true protein contains 68.1–72.9% of true kafirin vs. corn grain true protein, which contains 50.4–56.2% of true prolamin, respectively; Hamaker et al., 1995). The binding and encapsulation ability of kafirin protein often acts as a physiochemical impediment to starch digestion in ruminants (Owens et al., 1986).

Overall, the majority of starch in sorghum grain resides in the endosperm. Starch concentrations are approximately 70% of DM of grain, with approximately 24% of starch being amylose (Sang et al., 2008). Amylose is characterized by a linear chain of D-glucose units linked by  $\alpha(1-4)$  glycosidic bonds, and amylopectin consists of D-glucose units linked with  $\alpha(1-4)$  glycosidic bonds and  $\alpha(1-6)$  glycosidic bond branching points. Degradability of sorghum grain starch is generally accepted as being less than that of other grain sources, such as corn, barley, and wheat. Herrera-Saldana et al. (1990) quantified the in vitro starch degradation rates of corn, sorghum, wheat, barley, and oats and recorded rates of 6.4, 3.1, 23.5, 8.8, and 15.1% h<sup>-1</sup>, respectively. McAllister et al. (1990) quantified ruminal in situ DM degradability and fractions A, B, and C of DM after manually cut-

**Table 2.** Nutritive value of whole-plant sorghum silage samples submitted to a commercial laboratory<sup>1</sup> in 2015

Item <sup>2</sup>	Average	Minimum	Maximum	No. of samples
Moisture	67.1	36.6	89.5	1,741
CP, % of DM	10.5	3.88	17.1	1,677
ADICP, % of CP	1.08	0.52	1.64	1,650
Soluble CP, % of CP	42.7	17.9	67.4	1,208
ADF, % of DM	38.9	28.7	49.3	1,672
aNDF, % of DM	57.7	43.7	71.7	1,680
Lignin, % of DM	5.72	3.28	8.17	1,296
NDFD30, % of NDF	51.6	30.9	72.3	879
NDFD240, % of NDF	72.6	55.5	89.7	967
uNDFom240, % of DM	16.8	3.87	29.7	1,273
WSC, % of DM	7.23	0.09	25.1	1,288
Starch, % of DM	5.97	NR <sup>3</sup>	21.7	1,636
Ether extract, % of DM	2.85	1.45	4.25	1,300
Ash, % of DM	10.8	2.20	19.5	1,303

<sup>1</sup>Dairyland Laboratories Inc. (Arcadia, WI).<sup>2</sup>ADICP = acid detergent insoluble CP; aNDF = concentration of NDF determined in the presence of heat-stable  $\alpha$ -amylase, sodium sulfite, and inclusive of residual ash; NDFD30 = digestible NDF determined after 30 h of incubation in rumen fluid; NDFD240 = digestible NDF determined after 240 h of incubation in rumen fluid; uNDFom240 = undigestible NDF corrected for OM determined after 240 h of incubation in rumen fluid; WSC = water-soluble carbohydrates.<sup>3</sup>Not reported.

ting barley, corn, wheat, and sorghum grains in half or leaving grains whole. The authors observed that when barley, corn, sorghum, and wheat grain were left whole and incubated in the rumen for 48 h, whole grains were nearly indigestible (11, 14, 19, and 23% ruminal in situ DM degradability, respectively, after 48 h of incubation in the rumen). These results can be explained by the inability of rumen microbial populations to efficiently penetrate the pericarp. When McAllister et al. (1990) cut wheat, barley, sorghum, and corn in half, greater ruminal in situ DM degradability was observed ( $P < 0.01$ ; 50, 31, 25, and 13% ruminal in situ DM degradability after 12 h of incubation in the rumen, respectively). These results underscore that sorghum grain must be broken to disrupt barriers, such as the pericarp and the starch-protein matrix, which inhibit DM degradation. Aggressive processing of sorghum grain increases the surface area available to digestive processes (McAllister et al., 1990; Johnson, 2017). However, mechanical processing of sorghum grain contained within WPSS is often difficult under field conditions. Therefore, further research is needed to quantify the relationship between grain processing, starch digestibility, and lactation performance. Finally, the germ is of lesser importance in terms of grain protection; however, it contains fatty acids and minerals important for dairy cattle.

Sorghum grain also contains polyphenols, specifically phenolic acids, flavonoids, and tannins (Duodu et al., 2003), which can have negative effects on animal intake and performance. Dykes et al. (2005) analyzed 13 sorghum varieties and observed that physical traits such as plant color, pericarp thickness, and the presence or absence of a pigmented testa were related to phenol concentrations. Among polyphenolic compounds, tannins have been shown to bind protein and starch and can lower starch digestibility (Barros et al., 2012). Hence, hybrids containing tannin must be managed to mitigate reductions of starch digestibility and subsequently negative effects on lactation performance.

### Fiber Fraction

A widespread critique of WPSS is that it contains greater NDF, ADF, and lignin concentrations compared with WPCS (Aydin et al., 1999; Bernard and Tao, 2015). Subsequently, reduced digestibility of NDF (**NDFD**) has been observed when comparing conventional WPSS with WPCS (56.4 vs. 59.1% of NDF for conventional WPSS vs. conventional WPCS, respectively; Oliver et al., 2004). However, improvements of NDFD in WPSS have been made through genetic selection for the brown midrib (**BMR**) trait (Porter et al., 1978). Sorghum can exhibit the *bmr* gene at locus number 6, 12, or 18, commonly referred to in the literature as BMR-6,

BMR-12, or BMR-18, respectively (McCollum et al., 2005). Although BMR types reduce lignin concentrations, different mechanisms have been postulated. Sattler et al. (2010) explained that BMR-12 lowers caffeic *o*-methyltransferases activity, which is needed in the final step of the production of syringyl lignin, whereas BMR-6 reduces cinnamyl alcohol dehydrogenase, which produces coniferyl, coumaryl, and sinapyl alcohols, later used to produce *p*-hydroxyl lignin, guaiacyl lignin, and syringyl lignin. The mechanism of BMR-18 may be similar to that of BMR-12 because loci 12 and 18 are thought to be allelic (Oliver et al., 2004). Overall, BMR varieties are possibly the best example of how nutritive value can be improved through genetic advancement.

Aydin et al. (1999) compared BMR-6 WPSS with conventional WPSS, alfalfa silage, and conventional WPCS. The authors observed a 10.3% increase in NDFD with BMR-6 compared with conventional WPSS after 30 h of in situ incubation. Furthermore, ruminal NDF digestion kinetics were estimated. The fractional rates of NDF digestion were 3.3, 4.9, 10.3, and 3.1% h<sup>-1</sup> for conventional WPSS, BMR-6 WPSS, alfalfa silage, and conventional WPCS, respectively. The potential extent of NDF digestion at 96 h was 56.5, 64.6, 48, and 68.6% for conventional WPSS, BMR-6 WPSS, alfalfa silage, and conventional WPCS. Similarly, Oliver et al. (2004) observed that in situ NDFD was increased by 13.6% with BMR-6 and by 7.1% with BMR-18 compared with conventional WPSS after ruminal incubation for 48 h, when comparing a conventional WPSS, BMR-6 WPSS, BMR-18 WPSS, and a conventional WPCS. Rates of NDF digestion were 2.3, 3.7, 3.4, and 3.6% h<sup>-1</sup> for conventional WPSS, BMR-6 WPSS, BMR-18 WPSS, and a conventional WPCS, respectively. The potential extent of NDF digestion at 96 h was 70.4, 76.4, 73.1, and 79.0% for the same lines, respectively. The improvements in NDFD and NDF digestion kinetics presented by Aydin et al. (1999) and Oliver et al. (2004), imply that nutritive value and digestibility of whole-plant sorghum silage fiber are improved by the BMR trait compared with that of conventional WPSS, and that fiber nutritive value and digestibility may be equal to that of conventional WPCS. Recently, Sánchez-Duarte et al. (2019) used a meta-analytical approach and suggested that BMR WPSS hybrids have the potential to reach NDFD values similar to those of conventional WPCS hybrids.

### PREHARVEST FACTORS AFFECTING NUTRITIVE VALUE AND YIELD

Many important decisions affecting the nutritive value and yield of a crop are made before harvest season begins. The following discussion aims to provide cur-

rent knowledge of considerations that should be made before harvest.

### Planting Density and Plant Population

Sorghum can tolerate wide varieties of planting populations. M'Khaitir and Vanderlip (1992) observed that planting densities of 15,000, 45,000, and 135,000 plants ha<sup>-1</sup> had no effect on plant yield (kg/ha), although sorghum plants increased the number of seed heads per plant, compensating for any possible losses at lower planting densities. Conley et al. (2005) observed the ability of sorghum to adapt physiologically with plant populations of 74,131, 148,263, 222,394, 296,526, and 370,657 plants ha<sup>-1</sup> over 2 yr. The authors observed differences in grain yield (bu/ha) between 74,131 and 148,263 plants ha<sup>-1</sup> in both years ( $P \leq 0.05$ ; 278.9 vs. 319.9 bu/ha for year 1, and 259.4 vs. 284.9 bu/ha for year 2, respectively). No differences were observed between any other plant populations. Similar to the study of M'Khaitir and Vanderlip (1992), Conley et al. (2005) concluded that the ability of sorghum to adjust the number of seed heads per plant influenced the lack of significant difference between grain yields of different plant populations.

Limited published research is available elucidating the effects of plant population on WPSS nutritive value and yield. Marsalis et al. (2010) quantified the effect of planting population and N application rate on DM yield and nutritive value of a conventional corn, conventional forage sorghum, and BMR forage sorghum hybrids over 2 yr in New Mexico. Sorghum was planted at rates of 185,185, 214,815, and 249,383 plants ha<sup>-1</sup>. The authors concluded that planting density and nitrogen application can be reduced without detrimental effects on DM yield. However, a combination of high planting rate and reduced N application could lead to lower CP concentrations.

Sorghum genetics are continually improving and, therefore, consistent reassessment of optimal planting rates to maximize yield and nutrient value is justified. Previously recommended planting density and plant population may be rendered obsolete as hybrid characteristics and tolerances adapt due to plant genetic advancement.

### Plant Maturity

Sorghum grains can proceed from milk stage to soft dough to hard dough to physiological maturity over a 25- to 45-d period after flowering, depending upon the hybrid and climate (Gerik et al., 2003). The timing of harvest within this window is critical to capturing the desired nutrient value. Sonon and Bolsen (1996)

observed that as sorghum plants matured from late-milk to late-dough to hard-grain (25.4, 30.0, and 38.0% of DM, respectively), DM yield increased (11.2, 12.3, and 13.5 Mg of DM ha<sup>-1</sup>, respectively) and the proportion of the silage that was grain increased as well (1.3, 3.5, and 4.1 Mg of DM ha<sup>-1</sup>, respectively). Because sorghum grain comprises primarily starch, the concentration of NDF in WPSS decreased from late-milk to late-dough to hard-grain (60.2, 54.1, and 53.9% of DM, respectively). Lower NDF concentration is attributed to a dilution of NDF by increasing concentrations of starch with advancing plant maturity.

Recently, Lyons et al. (2019) evaluated the timing of harvest of BMR WPSS to maximize yield and nutritive value. Seven field trials across 2 locations in the northeastern United States were used. Harvests at each location were targeted at the boot, flower, milk, and soft dough stages. The authors concluded that harvest could take place at any of the tested harvest stages, depending upon the forage quality parameter desired. Early growth stages produced a crop with greater NDFD at 30 h (70, 68.1, 63, and 60.7% of NDF for boot, flower, milk, and soft dough, respectively) and CP concentration (104, 94, 82, and 80 kg/g, respectively), whereas later stages maximized DM yield (10.7, 13.4, 15.2, and 15.8 Mg of DM/ha for boot, flower, milk, and soft dough, respectively) and starch concentration (66.3, 82.7, 130.0, and 172.5 g/kg of DM, respectively). Last, the effect of substituting BMR WPSS for conventional WPCS was evaluated. The authors predicted ME-allowable milk and MP-allowable milk of the diet with the Cornell Net Carbohydrate and Protein System (v. 6.55; Van Amburgh et al., 2015) while replacing conventional WPCS with BMR WPSS. Inclusion amounts of BMR WPSS were 0, 25, 50, 75, and 100% of the conventional WPCS in the diet. Overall, substitution of BMR WPSS for conventional WPCS varied by the growth stage harvested and, on average, the predicted ME-allowable milk decreased from 41.9 kg/d (100% conventional WPCS) to 39.5, 40.1, 40.3, and 41.1 kg/d (100% BMR WPSS) for the boot, flower, milk, and soft dough stages, respectively. The authors suggested that the similar values for ME-allowable milk could be due to the greater NDFD when comparing the conventional WPCS used in the study with BMR WPSS. Results for MP-allowable milk were more variable among the 7 trials performed. However, on average across all trials, MP-allowable milk was 43 kg/d when only conventional WPCS was included in the diet, and as conventional WPCS was replaced with BMR WPSS, MP-allowable milk values of 42, 43, 42, and 43 kg/d for boot, flower, milk, and soft dough stages were observed, respectively. Based on these results, the authors concluded that replacement of conventional WPCS with BMR WPSS



protein may be sufficient, but additional energy supplementation may be necessary.

### THE SILAGE-MAKING PROCESS

Forage quality can have a significant effect on potential of milk yield from dairy cows and it is paramount to preserve the quality of forages throughout the harvest season. Waldo (1977) observed that the total efficiency of any preservation method is a function of several major factors, including recovery from the field, recovery from storage, intake, digestibility, efficiency of utilization, daily production, and production per hectare. Rotz et al. (2003) reviewed the use of silages in farming and observed that silage production and preservation methods can reduce harvest losses by reducing drying time in the field, providing more consistency in nutrient composition and increasing the ease of handling at mixing and feeding of total mixed rations. As average farm size increases, further emphasis will be put on efficient harvesting practices, storage of large amounts of feed, and consistency of nutrient content which can all be provided through the silage making process.

#### Roll Gap and Theoretical Length of Cut Settings

Historically, reduced theoretical lengths of cut were used to break the grain fraction of whole-plant cereal silages (Johnson et al., 1999). Currently, on-board grain processors are widely accepted as an effective tool to increase kernel breakage, starch digestibility, and milk yield of WPCS for dairy cows (Ferraretto and Shaver, 2012). The improvements in starch digestibility and subsequent milk yield are facilitated by the disruption of the pericarp and starch-protein matrix, a reduction in mean particle size, and an increase in available surface area for microbial attachment. Few published studies have evaluated the effects of varying theoretical length of cut or roll gap settings on WPSS grain breakage and starch digestibility. Johnson (2017) collected 72 samples of WPSS across 6 farms in Kansas, and samples were either unprocessed or processed with a roller mill at roll gap settings of 1.5, 1.0, or 0.5 mm. Samples were analyzed for berry processing score, defined as the percentage of total starch passing through a 1.70-mm sieve, and 7-h starch digestibility. Berry processing score and 7-h starch digestibility increased as the roll gap setting was reduced. Berry processing scores of 26.28, 34.64, 40.30, and 55.05 were observed for unprocessed, 1.5-, 1.0-, and 0.5-mm roll gap spacings, respectively. Similarly, 7-h starch digestibility values were 50.54, 66.76, 68.95, and 82.07 for the same settings, respectively. The unique agronomic characteristics of sorghum (i.e., drought tolerance,

water efficiency, and low cost of production) and the efficiency of modern forage harvesting equipment at breaking corn kernels justify further investigation into the ability of forage harvesters to break sorghum grain.

Further research should focus on designing experiments that quantify the relationships among grain breakage, starch digestibility, and lactation performance of dairy cows.

#### Fermentation of Sorghum Silage

The silage-making process is divided into 4 phases: (1) aerobic phase, (2) fermentation phase, (3) storage phase, and (4) feed-out phase (Wilkinson and Davies, 2013). During the fermentation phase, lactic acid (the strongest acid produced in the silo with an acid dissociation constant,  $pK_a$ , of 3.86; Rooke and Hatfield, 2003) becomes the prevalent acid in WPSS. Throughout the storage phase, the acidic environment degrades kafirin proteins, increasing the starch digestibility of the WPSS. A prolonged storage phase is recommended for certain sorghum hybrids that are suspected to contain increased concentrations of tannins or prussic acid. Although the exact mechanism is not known, tannins have been shown to be reduced with increased storage time (Cummins, 1971). Likewise, prussic acid can be reduced during the storage phase of WPSS. Recently, Driehuis et al. (2018) reviewed several published studies and observed lower prussic acid concentrations with increased storage time; however, the majority of prussic acid is removed through gaseous release during its exposure to air, although these losses have not been quantified.

### SUPPLEMENTATION OF WPSS AND LACTATION PERFORMANCE

Most WPSS harvested in the United States is fed to cattle with reduced energy requirements (i.e., dry cows and heifers) because of its higher NDF concentration, lower NDFD, and lower starch concentration and digestibility. However, the effects of supplementing WPSS to lactating dairy cows continue to be evaluated. Aydin et al. (1999) evaluated the effects of supplementing BMR WPSS to lactating dairy cows in 2 experiments. In experiment 1, cows were supplemented either conventional WPSS, BMR WPSS, alfalfa silage, or conventional WPCS at 65% of diet DM in a  $4 \times 4$  Latin square design with 4 wk-periods (Table 3). Dry matter intake (% of BW) was greatest for animals fed a conventional WPCS diet, intermediate for alfalfa silage and BMR WPSS, and lowest for conventional WPSS (4.2, 4.0, 3.7, and 3.5% of BW, respectively). Likewise, milk yield was greatest for cows fed conventional WPCS, in-

intermediate for those fed alfalfa silage and BMR WPSS, and lowest for cows fed conventional WPSS. Milk yield was increased by 13% with BMR WPSS compared with cows fed conventional WPSS. No effects on milk fat percentage were observed; however, milk fat yield was greater for conventional WPCS, intermediate for alfalfa silage and BMR WPSS, and lowest for conventional WPSS fed cows (1.12, 0.95, 0.89, and 0.79 kg/d, respectively). Similarly, milk protein yield was greatest for cows fed conventional WPCS, intermediate for those fed alfalfa silage and BMR WPSS, and lowest for those fed conventional WPSS (0.99, 0.79, 0.78, and 0.68 kg/d, respectively). Based on these results, BMR WPSS has a greater milk yield potential than conventional WPSS when fed to cows at an inclusion rate of 65% of diet DM (Aydin et al., 1999).

Experiment 2 (Aydin et al., 1999) elucidated the effects of long-term supplementation of WPSS in a 10-wk continuous lactation trial. Cows were supplemented with either conventional WPSS, BMR WPCS, or conventional WPCS at an inclusion rate of 35.3% of diet DM (Table 3). No differences were observed in DMI or milk composition among diets. Milk yield was greater with BMR WPSS than with conventional WPSS (36.0 and 33.8 kg/d), whereas cows fed conventional WPCS had milk yields similar to those of other treatments (34.6 kg/d). Fat-corrected milk (4%) was greatest with BMR WPSS (33.8 kg/d) and lowest with conventional WPSS (31.4 kg/d); that of conventional WPCS (32.4 kg/d) did not differ from the other treatments. Based on the results of that study, BMR WPSS has the potential to produce similar milk yields to conventional WPCS when included at 35.3% of diet DM. Similar findings were observed by Oliver et al. (2004), who fed BMR-6 WPSS, BMR-18 WPSS, conventional WPSS, and conventional WPCS to 16 lactating Holstein dairy cows in a replicated Latin square design with 28-d periods (Table 3). An inclusion rate of 40% of diet DM was used for the 4 forage sources. The BMR-6 WPSS and conventional WPCS had the greatest milk yield, conventional WPSS had the lowest, and BMR-18 WPSS was similar to that of all treatments (34.1, 33.8, 32.2, and 31.0 kg/d milk for BMR-6 WPSS, conventional WPCS, BMR-18 WPSS, and conventional WPSS, respectively). The authors observed a similar trend for milk fat yield (1.34, 1.32, 1.22, and 1.11 kg/d for cows fed BMR-6 WPSS, conventional WPCS, BMR-18 WPSS, and conventional WPSS). In a recent meta-analysis, Sánchez-Duarte et al. (2019) observed that BMR WPSS had similar milk yield potential to conventional WPCS in an evaluation of 9 published studies from 1987 to 2015. These results suggest that with further genetic advancement of sorghum, there is potential for greater supplementation of WPSS to lactating dairy cows.

**Table 3.** Summary of 3 experiments that compared lactation performance of dairy cows fed conventional whole-plant sorghum silage (WPSS) or brown midrib (BMR) WPSS or other forage sources

Study and trait <sup>1</sup>	Inclusion rate, % of diet DM	DMI, kg/d	DMI, % of BW	Milk, kg/d	Milk fat, %	Milk fat, kg/d	Milk protein, %	Milk protein, kg/d	Lactose, %	Lactose, kg/d	4% FCM, kg/d
Aydin et al., 1999 (1)											
WPSS	65	21.5	3.5 <sup>c</sup>	21.5 <sup>c</sup>	3.73	0.79 <sup>c</sup>	3.21 <sup>b</sup>	0.38 <sup>c</sup>	4.85	1.04 <sup>c</sup>	20.7 <sup>c</sup>
BMR WPSS	65	22.7	3.7 <sup>b</sup>	24.3 <sup>b</sup>	3.73	0.80 <sup>b</sup>	3.23 <sup>b</sup>	0.78 <sup>b</sup>	4.88	1.19 <sup>b</sup>	23.7 <sup>b</sup>
AS	65	24.0	4.0 <sup>ab</sup>	25.2 <sup>b</sup>	3.78	0.98 <sup>b</sup>	3.14 <sup>b</sup>	0.79 <sup>b</sup>	4.86	1.22 <sup>b</sup>	24.5 <sup>b</sup>
WPCS	65	25.3	4.2 <sup>a</sup>	29.5 <sup>a</sup>	3.82	1.12 <sup>a</sup>	3.36 <sup>a</sup>	0.99 <sup>a</sup>	4.90	1.44 <sup>a</sup>	29.0 <sup>a</sup>
SE		0.4	0.1	0.5	0.08	0.03	0.03	0.01	0.02	0.01	0.6
Aydin et al., 1999 (2) <sup>2</sup>											
WPSS	35.3	23.7	4.1	33.8 <sup>b</sup>	3.54		2.99		4.97		31.4 <sup>b</sup>
BMR WPSS	35.3	25.1	4.2	36.0 <sup>a</sup>	3.59		3.09		5.04		33.8 <sup>a</sup>
WPCS	35.3	24.8	4.3	34.6 <sup>ab</sup>	3.57		3.01		5.04		34.4 <sup>ab</sup>
SE		1.0	0.08	0.7	0.14		0.04		0.05		0.7
Oliver et al., 2004											
WPSS	40	23.2	3.67	31.0 <sup>b</sup>	3.57 <sup>b</sup>	1.11 <sup>b</sup>	2.89	0.91	4.84	1.53	29.1 <sup>b</sup>
BMR-6 WPSS	40	25.2	3.79	34.1 <sup>a</sup>	3.89 <sup>a</sup>	1.34 <sup>a</sup>	2.89	0.99	4.88	1.68	33.7 <sup>a</sup>
BMR-18 WPSS	40	23.4	3.65	32.2 <sup>ab</sup>	3.77 <sup>ab</sup>	1.22 <sup>ab</sup>	2.98	0.96	4.90	1.58	31.2 <sup>ab</sup>
WPCS	40	24.3	3.81	33.8 <sup>a</sup>	3.88 <sup>a</sup>	1.32 <sup>a</sup>	2.97	1.00	4.78	1.62	33.3 <sup>a</sup>
SE		1.1	0.19	1.6	0.21	0.11	0.14	0.08	0.34	0.17	2.3

<sup>a-c</sup>Means with different superscripts within a column and study differ significantly ( $P < 0.05$ ).

<sup>1</sup>AS = alfalfa silage; WPCS = conventional whole-plant corn silage; BMR-6 WPSS = WPSS with the brown midrib gene (*bmr*) at locus 6; BMR-18 WPSS = WPSS with *bmr* at locus 18.

<sup>2</sup>Milk fat (kg/d), milk protein (kg/d), and lactose (kg/d) were not reported.

Although great progress has been made to improve the NDFD of WPSS through the BMR trait, careful replacement of WPCS with WPSS is still recommended. Starch concentration and starch digestibility have consistently been lower for WPSS than for WPCS. As discussed earlier, harvesting sorghum at later maturity would allow for greater starch deposition (Lyons et al., 2019); however, digestibility of starch is negatively affected by formation of a more pronounced starch–protein matrix. Early harvesting of sorghum increases starch digestibility but does not allow for adequate starch deposition, resulting in reduced concentrations of starch (Harper et al., 2017). Perhaps the most feasible solution to improve WPSS starch concentration and digestibility is harvesting at a maturity that allows for greater starch deposition and aggressively mechanically processing the grain fraction.

### CONCLUDING REMARKS

Complete substitution of WPSS for WPCS has not been recommended due to increased NDF concentrations, as well as reduced NDFD, starch concentration, and starch digestibility. Recent published literature suggests that genetic improvements via the BMR trait allow BMR WPSS to achieve milk yields similar to that conventional WPCS. The maturity of the crop at harvest can be used to increase starch concentration, and starch digestibility challenges may be alleviated through mechanical processing of the grain fraction of WPSS in a forage harvester. Further research is needed to quantify the effects of forage harvester settings on grain breakage, starch digestibility, and lactation performance. Additionally, the adoption of a berry processing score could aid in quantifying the adequacy of processing. Contemporary sorghum varieties offer vast options of potentially high-yielding and nutrient-dense feed sources. Careful hybrid selection, proper silo management, and continued advancement in agronomic and harvesting practices will continue to add value to WPSS as a forage source to dairy cattle.

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