Rapidly drying sorghum biomass for potential biofuel production

A.C. Rocateli[1], R.L. Raper[2*], B. Olander[3], M. Pruitt[3], E.B. Schwab[4]

(1. *Dept. of Plant and Soil Science*, *Texas Tech University*, *Texas 79409 USA*;
2. *Field and Research Services Unit*, *Oklahoma State University*, *Oklahoma*, *74078 USA*;
3. *Hesston AGCO*, *Hesston*, *Kansas*, *67062 USA*;
4. *USDA-NRCS*, *Auburn*, *Alabama*, *36830 USA*)

Abstract: The Southern U.S. has an ideal climate that may aid in growing large amounts of biomass suitable for biofuel; however, droughts during the growing season may reduce yields. Sorghum (*Sorghum bicolor* L.) may have great potential as an energy crop, because it is capable of high biomass yields and is drought tolerant. However, sorghum biomass has relatively high moisture content and should be conditioned and dried before transported to reduce costs. Sorghum-sudan hybrid was harvested with two different headers on a self-propelled windrower: a Massey Ferguson 9145 (sickle) and a Massey Ferguson 9185 (disc). The disc header was comprised of two pairs (rear front) of metal conditioner rollers which compressed the biomass, thus improving the drying process. The roller pairs were used with three different pressures (0, 3500 and 7,000 kPa), and with different gaps (0 and 0.02 m). Sorghum biomass samples were collected after harvest and the percentage of moisture content wet basis evaluated daily until they remained constant. Results revealed that the higher pressures and smaller gaps resulted in faster drying of biomass. Thus, the best settings for the disc header were "7,000 kPa -0 m" or "7,000 kPa - 0.02 m" which showed, respectively, moisture content levels of 13.6% and 16.8% after 14 days. However, when the disc header was set to "0 kPa - 0.02 m", the moisture content was significantly higher (43.2%). These results indicate sorghum was adequately dried for bailing in Southeastern U.S. condition, when proper machinery and settings were applied.

Keywords: moisture, sorghum, baling, windrowers

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1 Introduction

Growing domestic biomass for bioenergy may help to reduce the amount of oil imported by the United States. The Southeastern U.S. has an ideal climate that may aid in growing large amounts of biomass; however, short-term droughts during the growing season over the last several years have dramatically reduced production. For these reasons, sorghum may be a reasonable alternative as an energy crop in this region, because it is considered drought resistant (Habyarimana et al., 2004). Sorghum can extract water from deep soil layers with most coming from depths of 0.45 - 1.35 m (Farré and Faci, 2006).

Sorghum has been considered a potential bioenergy crop, mostly from a cellulosic standpoint, providing a total maximum dry matter yield of 30.15 t ha^{-1} in a short time (120 days) and with a maximum mean daily growth rate of 22 g d^{-1} (Loomis and Williams, 1963). Furthermore, sorghum has higher biomass production potential at lower costs than other perennial bioenergy crops, e.g., switchgrass (*Panicum virgatum* L.) (Hallam et al., 2001).

Therefore, sorghum could be integrated into a conservation system as part of a crop rotation with typical cash crops where part of its biomass would be used as a soil cover and any additional amount of biomass would be harvested for potential biofuel production. While much emphasis has been placed on perennials for biofuel production, annual crops, such as sorghum would provide

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*** Corresponding author: R.L. Raper,** Senior Director of Field and Research Services Unit, Oklahoma State University, Oklahoma, 74078 USA. Email: randy.raper@okstate.edu.

a major source of biomass for cellulosic ethanol production. These annual crops for bioenergy production have largely been ignored in the Southeastern U.S.

However, sorghum biomass has thick stems which dry slowly when windrowed (Lardy and Anderson, 2003, pp. 5). Therefore, sorghum conditioning techniques must be improved in order to reduce timing, costs and quality losses regarding to biomass moisture. Cundiff and Worley (1992) found that freshly harvested sorghum stalks had 48 to 76% of fresh weight and contained 42 to 75% of whole-plant nonstructural carbohydrate. Thus, sorghum biomass needs to be dried to a moisture content of 15–20% for storage. Moisture content higher than 20% results in molds and bacteria growth that consumes biomass nutrients and decreases quantity and quality of the feedstock. On the other hand, moisture content lower than 15% results in leaf loss decreasing biomass quantity (Wilcke et al., 1999). According to Wall and Blessin (1970), forage sorghum such as sorghum-sudangrass contains higher lignin content than other sorghum types (sweet and grain sorghum). In addition, sorghum stalks contain higher lignin content than leaves for all types of sorghum (Tunger et al., 1973) Therefore, leaf loss during harvest due to biomass moisture content lower than 15% would increase the feedstock lignin content which is undesirable for biofuels production. Cellulosic materials with low lignin content are desirable for biofuel production, because high lignification requires higher costs and lower sugar yields from delignification pretreatment (Weng et al., 2008). Lignin is composed of different subunits (monolignols) rather than a composition of linear identical subunits found in cellulose; therefore, no single enzyme has sufficient chemical diversity to degrade lignin.

The objective of this study was: 1) Compare the drying of sorghum biomass under two different headers on a self-propelled windrower, 2) determine the best setting of the disc header including setting the pressures and gaps, 3) evaluate if adequate biomass moisture content levels (15-20%) could be obtained for baling sorghum within a relatively short time period in southeastern U.S. conditions.

2 Materials and methods

In order to compare the drying of sorghum biomass, an experiment was conducted at the E.V. Smith Research Station, Shorter, AL (85º:53’50” W, 32º:25’22” N) in April, 2008. The soil at the experimental field was classified as Lynchburg loamy sand (fine-loamy, siliceous, semiactive, thermic Aeric Paleaquults). The total field was previously used for corn (*Zea Mays* L.) silage before planting sorghum.

2.1 Crop

The sorghum evaluated in this experiment was the Sweet Graze BMR (Brown Midrib Sorghum Sudangrass). It is described as tolerant to drought (500 mm rainfall requirement during growing season), high sugar content, high forage quality, low lignin content, and with little cold tolerance (Pogue, 2011).

Conventional tillage was applied to the entire experimental area. Seeding rate of 28 kg ha^{-1} and N (urea) rate of 65 kg ha^{-1} was applied during planting. Other applications, such as nutrients and herbicides were obtained by following the Auburn University Extension recommendations (Adams and Mitchell, 2000). Only natural rainfall was used.

2.2 Self-propelled windrowers

Two different headers on a self-propelled windrower were compared: a Massey Ferguson 9145 and a Massey Ferguson 9185 (AGCO Company, Duluth, GA), which are a sickle and a disc header, respectively.

The disc header was comprised of two pairs (rear/front) of metal conditioner rollers which compressed the biomass, thus improving the drying process. The roller pairs were used with three different pressures (0,3500 and 7,000 kPa), and with different gaps (0 and 0.02 m) combined in seven different configurations (Figure 1). The pressures applied were through four hydraulic cylinders (2.54 cm diameter) which were used to apply forces onto the rollers and hold them together. The gap is the distance between the rolls when no crop is going through. However, the sickle header was also comprised of two pairs (rear/front) of conditioners, the front pair being metal and the rear pair being rubber. Table 1 showed all settings applied to both windrowers.

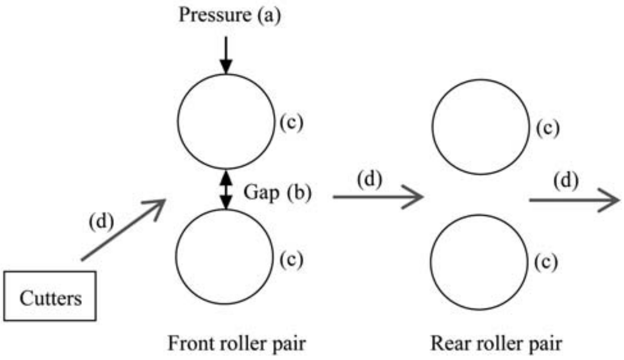


Figure 1 Simplified disc header of Massey Ferguson 9185 windrower scheme. Three different pressures (a) such as 0, 3500, and 7,000 kPa were applied in all conditioner rollers (c); and two different gaps (b), such as 0 and 0.02 m were applied in both roller pairs (rear/front). Sorghum biomass (d) was compressed when passing between both roller pairs.

Table 1 Settings applied in both self-propelled windrowers

Self –propelled Windrowers	Treatment Number	Pressure /kPa	Gap /m	
			front	rear
Disc header[a]	1	0	0	0
	2	3500	0	0
	3	7000	0	0
	4	0	0.02	0
	5	3500	0.02	0
	6	7000	0.02	0
	7	0	0.02	0.02
Sickle header[b]	8	standard	Standard	

Note: [a]Massey Ferguson 9185; [b]Massey Ferguson 9145.

2.3 Field description

The total number of experimental plots was 32 which were composed of eight different treatments and four replications. The treatments were: the seven different gap/pressure settings of Massey Ferguson 9185 (disc), and the standard setting of Massey Ferguson 9145 (sickle) which were represented in Table 1.

All plots and borders were 5 m wide and 30 m long in which four rows were spaced apart by 0.9 m. Each block was separated by borders.

2.4 Biomass samples

The total dry aboveground matter produced by the evaluated sorghum was approximately 6.3 Mg ha^{-1} and was established by collecting 0.25 m^2 samples from the all plots before harvesting. Sorghum was harvested on 16 October 2008. Biomass samples were collected after harvest and wet-basis moisture content - M_{wb} (%) was evaluated until it remained constant. Samples were collected daily in early afternoon, except for rainy days and subsequent wet days. However, biomass samples were collected eight times from 16 to 30 October 2008, where the collection days were: 0, 4, 5, 6, 7, 12, 13, and 14 days after harvesting (DAH). All plots were disturbed using a Frontier TD10E hay Tedder (Deere & Company, Moline, IL) on 28 October 2008 (12 DAH) in order to achieve faster biomass drying.

Three homogenous handfuls of biomass subsamples were taken randomly from each plot, and placed in bags where the wet biomass weight was recorded. The biomass subsamples were taken randomly in each plot accounting all biomass windrow thickness. Additionally, all aboveground plant structures such as leaves and stems were collected keeping the amount of leaf and stalk matter constant. Biomass samples were dried at 55℃ until constant weight was achieved. M_{wb} (%) was calculated using the following formula (Equation (1)):

$$M_{wb} = \left(\frac{m_w - m_d}{m_W} \right) \times 100 \qquad (1)$$

where, M_{wb} = wet-basis moisture content, %; m_w= mass of wet biomass matter, kg; m_d = mass of dry biomass matter, kg.

2.5 Statistical analysis

Statistical analyses were performed in a randomized complete block design (RCB) with eight different treatments as shown in Table 1. The predetermined significance level was $P \leq 0.10$ and Fisher's least-significant-difference test (LSD) was performed for means comparisons. Treatment means were reported followed by their standard deviation (SD) values (mean ±SD). Preplanned single degree of freedom contrasts (Table 2) were performed to compare the distinct effects of gaps and pressures settings applied on disc header windrower. The data were analyzed with GLM procedure using software SAS 9.2 (SAS Inst. Inc., Cary, NC).

Table 2 Preplanned single degree of freedom contrast used for mean comparisons

Contrast	Treatments[a]
0 vs. 0.02 m gap	1,2,3 vs. 4,5,6
0 vs. 3,500 kPa pressure	1,4 vs. 2,5
0 vs. 7,000 kPa pressure	1,4 vs. 3,6
3,500 vs. 7,000 kPa pressure	2,5 vs. 3,6

Note: [a] treatments indicated by number were described in Table 1.

3 Results and discussion

3.1 Effect of different MF 9185’s roller pressures on sorghum moisture content

Results showed that higher pressures applied on rollers tended to dry sorghum biomass faster than lower pressures (Figure 2). For all sampled days, rollers set to 7,000 kPa were significantly more effective in drying biomass than rollers set to 0 kPa. This difference in pressure treatments was highest on 14 DAH (29.8% vs. 15.2%, P = 0.01).

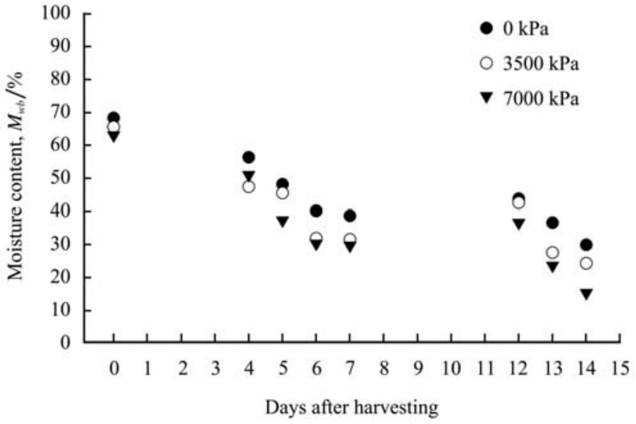


Figure 2 Sorghum moisture content (M_{wb} / %) for different disc header pressures for all sampled days

Different results were found when comparing 3,500 and 7,000 kPa pressures. No significant differences were found between those applied pressures on 6, 7, 12 and 13 DAH. Controversially, 5 and 14 DAH showed significant differences between different applied pressures. And, the last sampled day (14 DAH) had the highest difference between 3,500 and 7,000 kPa (24.2 vs 15.2%, P = 0.04).

3.2 Effect of different MF 9185’s roller gaps on sorghum moisture content

Sorghum biomass tended to dry faster when rollers were contacting each other (Figure 3). Comparing two different gap sets: “0 m gap front/rear” vs. “0.02 m gap front / 0 m gap rear”, all sampled days showed numerically low moisture content values for “0 m gap front and rear” treatments. But, they were significant different on 7, 12 and 14 DAH. Additionally, the last sampled day (14 DAH) showed averages of 19.8 and 26.4%, respectively for “0 m gap front/rear” and “0.02 m gap front / 0 m gap rear” treatments (P = 0.07).

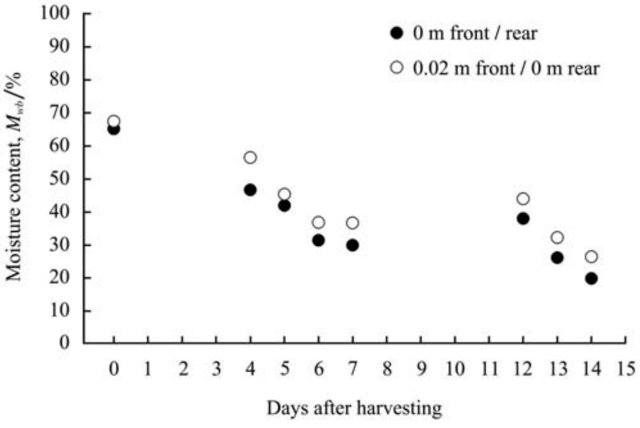


Figure 3 Sorghum moisture content (M_{wb} / %) for different disc header gaps for all sampled days

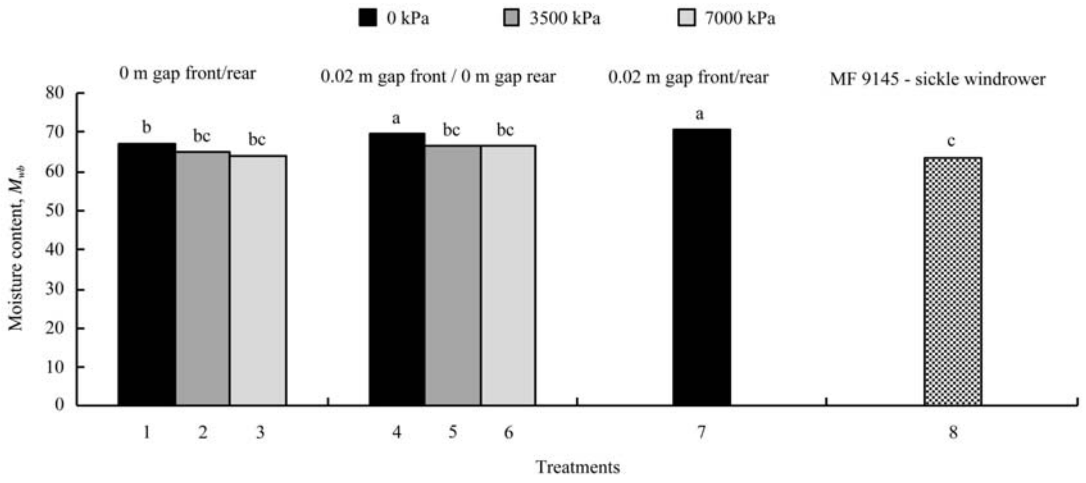
3.3 Interaction of different MF 9185’s roller gaps and pressures on sorghum moisture content

3.3.1 At harvest day (0 DAH)

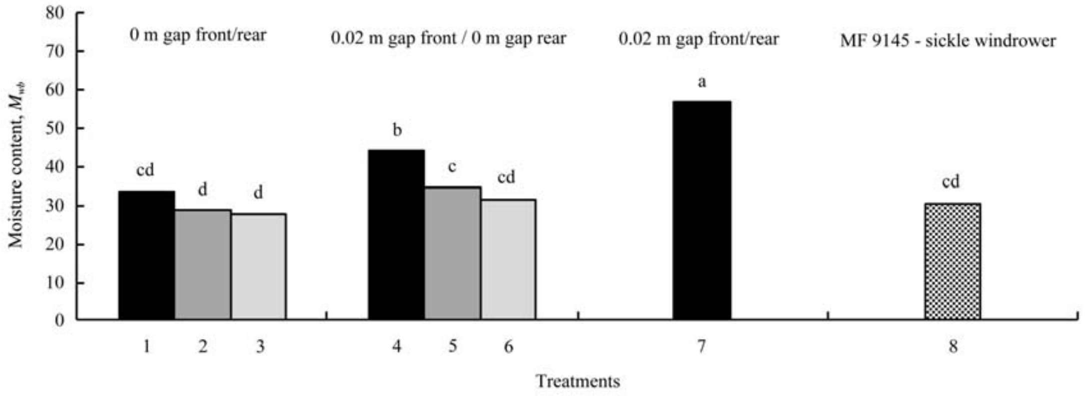
Different moisture contents among treatments were observed 5 h after harvest on 0 DAH. Treatment 8 showed minimum moisture content (63.5%% ± 2.4) followed by treatment 3 (63.8%%±2.9), 2 (64.8%%±2.4), 5 (66.1% ±2.9) and 6 (66.2% ± 3.8), which showed no significant differences among each other. Treatment 1 (67% ±2.5) was considered not significantly different from treatments 2, 3, 5, and 6. Treatment 4 (69.8% ± 1.6) and 7 (70.7% ± 2.7) showed highest moisture content (Figure 4a). The average temperature during 0 DAH was 20.5℃ (AWIS, 2011). Additionally, MF 9185 showed similar biomass moisture content to MF 9145 when set at 3,500 or 7,000 kPa; but MF 9185 had higher moisture content when set to 0 kPa.

3.3.2 Seven days after harvest (7 DAH)

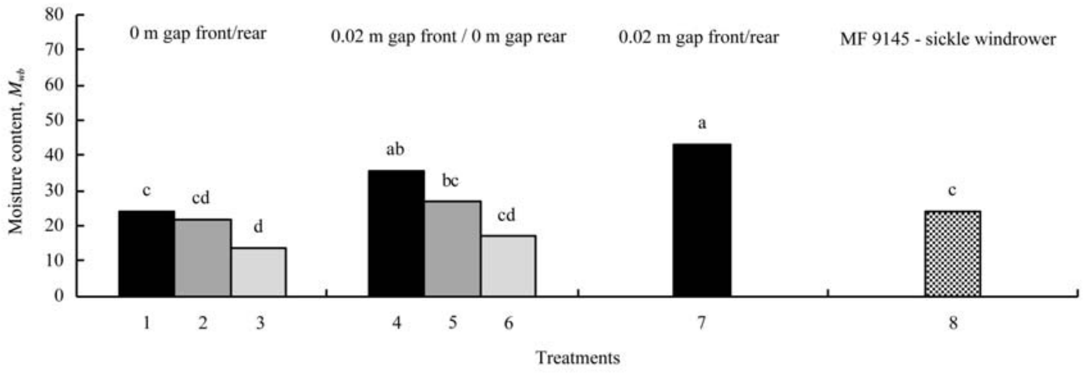
Seven days after harvest, treatment 3 (27.7% ±5.3) and 2 (28.5% ±6.3) showed reduced values of moisture content followed by treatments 8 (30.9% ±6.6), 6 (31.6 % ±6.9) and 1 (33.4% ± 4.6), which showed no significant differences among each other. Treatment 5 (34.4% ±7.5) was considered not significantly different from 1, 6 and 8. Thus, treatments 4 (43.8% ± 7.2) and 7 (56.5% ± 3.5) showed the highest moisture content, but they were not statistically different from each other (Figure 4b). All previous sampling days including 4, 5 and 6 DAH showed the same trend as on 7 DAH. During those 7 days, the average daily temperature, relative humidity, and cumulative total daily solar radiation was respectively 17.0℃, 68.5, and 134 MJ m^{-2}. In addition, a total precipitation of 8 mm of precipitation was recorded on October 18th (2 DAH). Table 3 shows the daily weather data from 0 to 15 DAH.



a. At harvest day (0 DAH) LSD = 3.0



b. Seven days after harvesting LSD = 5.7



c. Fourteen days after harvesting LSD = 1.0

Figure 4 Sorghum moisture content (M_{wb}) for all treatments and in different days (a) 16 October 2008, (b) 23 October 2008, and (c) 30 October 2008. Treatments indicated by numbers (1-8) were described in Table 1

However, MF 9185 showed similar biomass moisture content to MF 9145 when rollers set to any pressure with 0 m gap, and when rollers submitted on 7,000 kPa with 0.02 m gap in front roller. Additionally, moisture content was higher in MF 9185 plots than MF 9145 ones when rollers set with 0 and 3,500 kPa or had at least a 0.02 m gap. On 12 DAH, the biomass moisture content had an average increment of 7% in all experimental plots due to 57 mm of precipitation on 8 DAH as shown in Table 3. Consequently, the sorghum biomass in all experimental plots was fluffed with the tedder to improve biomass drying.

Table 3 Daily average temperature, total precipitation, average relative humidity, and total solar radiation during the drying period (AWIS, 2011)

Days after harvest (DAH)	Temperature /℃	Precipitation /mm	Relative Humidity/%	Solar Radiation /MJ m^{-2}
0	20.5	0	65.5	18.9
1	22.7	0	65.0	18.6
2	17.2	8	84.0	5.4
3	14.4	0	66.0	18.8
4	12.7	0	68.0	18.8
5	13.3	0	66.0	18.7
6	16.6	0	66.0	18.2
7	18.3	0	67.5	16.5
8	15.5	57	73.5	6.8
9	13.8	0	90.5	2.7
10	13.8	0	68.0	16.5
11	16.1	0	65.5	17.8
12	8.3	0	58.0	17.9
13	6.1	0	64.5	17.5
14	8.3	0	61.0	17.2
15	12.2	0	59.5	16.9

3.3.3 Fourteen days after harvest (14 DAH)

Fourteen days after harvest, biomass from treatment 3 (13.6% ± 3.7) and 6 (16.9% ± 5.5) showed minimum moisture content followed by treatment 2 (21.8% ± 4.4), 1 (24.0% ± 5.8), 8 (24.1% ± 3.9) and 5 (26.7% ± 4.2), which were not significantly different among each other. Treatment 4 (35.6% ± 4.8) was considered not significantly different from 5. Thus, treatment 7 (43.2% ± 2.2) showed the highest moisture content (Figure 4c). The sampled previous day (13 DAH) showed the same trend as 14 DAH. Thus, the average daily temperature, relative humidity, and cumulative total daily solar radiation from 8 to 14 DAH was respectively 11.7℃, 68.7, and 96.4 MJ m^{-2} during those 7 days (AWIS, 2011).

However, biomass harvested from plots where the MF 9185 was used for harvesting showed 13.6% and 16.8% of moisture content for treatment 3 and 6, respectively. It has been recommended that moisture content of biomass samples fall between 15.0 and 20.0% of moisture content (Wilcke et al., 1999). Therefore, MF 9185 was able to dry sorghum biomass when rollers were set on 7,000 kPa with “0 m gap front/rear” and “0.02 m gap front / 0 m gap rear”. Additionally, MF 9145 exceeded the recommended values by still containing 24.1% moisture after 14 days.

According to visual observations, MF9185 rollers applied a more severe physical treatment to the biomass than the MF 9145 conditioners. The MF 9185 roller pairs, when properly set, disrupted the plant stems exposing more plant tissues to the atmosphere, and consequently resulting in fast biomass moisture loss (Figure 5).

Figure 5 Physical treatments of MF 9185 (A) and MF 9145 (B) on sorghum sudangrass.
Figure section (A) illustrates the physical treatment under MF 9185 settings of “0.02 m gap front / 0 m gap rear”.

4 Conclusion

1) MF 9185 windrower dried sorghum biomass faster when higher pressures were applied on conditioner rollers. Therefore, pressures of 7,000 kPa caused reduced moisture content values as compared to 0 and 3,500 kPa

after 15 days of harvest.

2) No gap between the rollers on the MF 9185 conditioner dried sorghum biomass faster than 0.02 m gap.

3) MF 9185 windrower was considered more efficient in drying sorghum biomass than MF 9145 when conditioner rollers were set with "0 gap front/rear, 7,000 kPa". The settings "0 m gap front and rear, 7,000 kPa" and "0.02 gap front / 0 m gap rear, 7,000 kPa" reduced moisture content to values lower than 20.0%, which was considered the maximum moisture content value for storing biomass.

Therefore, high biomass crops such as sorghum were successfully dried for baling in southeastern U.S. condition, when using MF 9185 set with both "0 m gap front and rear, 7,000 kPa" and "0.02 m gap front / 0 m gap rear, 7000 kPa".

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