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# The Effect of Mechanical Conditioning on Physical Conditions of Miscanthus Plants

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## Abstract

Miscanthus is an emerging dedicated energy crop, which can provide excellent yield on marginal lands. However, this crop is more difficult to harvest than many conventional energy crops such as corn stover and switchgrass due to its tall and rigid stalks. Crop samples for laboratory studies were collected from the field and the effects of roll spacing, roll speed, and crop input of a mechanical conditioning device on the physical conditions of miscanthus were studied in a lab setting. Test results showed that mechanical conditioning is effective to change the physical conditions of miscanthus to make baling possible or easier. Results also showed that the roll spacing had the most significant impact on the physical conditions of miscanthus, shown by a 115% increase in conditioning over a 0.95 cm (75%) reduction in roll spacing. Increased roll spacing and speed were shown to decrease the amount of torque required to condition the miscanthus.

## Keywords

Energy Crop, Baling, Strength, Preprocessing

## 1. Introduction

In a world where the need for energy is ever increasing and the fossil fuels to provide that energy are dwindling, renewable and sustainable forms of energy are needed. Biomass and biofuels offer a very popular, low emission solution to the coming energy deficit. The US Department of Energy has decreed that by the year 2022 the annual amount of biofuels used will be at least 136 billion liters [1]. In order to meet this goal, more effective ways of providing the biomass to biorefineries are needed. Biofuels are a promising energy source; however they are not without certain drawbacks that need to be addressed before their use can effectively be adopted. Biomass can be defined as plant-derived organic matter which includes herbaceous and woody energy crops, agricultural food and feed crops, and agricultural or wood wastes and residues [2]. *Miscanthus x giganteus* (Miscanthus or Elephant Grass) is a sterile C4 grass that is being used as a dedicated energy crop due to its ability to grow on marginal lands while still having high yields [3]. Miscanthus can grow up to 3.5 m tall and net 5 to 55 $\text{Mg}\cdot\text{ha}^{-1}$ of yield annually [3].

While the high yields are beneficial, the structure of the crop can cause issues for many types of traditional harvesting equipment. In particular, there is a need to convert the miscanthus in the field to a baled form that can be easily transported and stored. The stiffness and length of the stems make it difficult for traditional baler pickup heads to lift the crop into the compression chamber and make bales of adequate density. To help alleviate problems in baling miscanthus, various types of conditioning systems can be implemented to break down the crop and make it easier to bale.

Conditioning in this context refers to the breaking and weakening of the crop stem through some mechanical means such as feeding the crop through steel rollers or hitting the crop with steel flails. In theory, by weakening the crop through conditioning it will become easier to handle and bale, meaning that the miscanthus could potentially be harvested faster, baled denser, and stored in less space. By doing this the total cost of miscanthus from field to refinery could be reduced, which is preferred condition necessary for the growth of the biofuel industry. This research took an in-depth look at how changing different parameters of a mechanical conditioning system can affect the physical properties of the conditioned miscanthus plants as well as the torque required to run the conditioning rolls.

Crop conditioning was initially developed for forage harvesting to aid in the drying process of hay. Through conditioning, it is possible to achieve the same drying rate in the stems of a plant as the leaves [4]. Mechanical conditioning systems fall into either impeller/tine-type or roll-type conditioners [4]. Roll type conditioners consist of two rolls that force the crop between them to break the stems. One roll often has a male chevron and the other a female to help keep hold of the crop as it is pulled through the rolls. These rolls can either be made of steel, polyurethane, or a durable rubber. Other types of roll conditioners contain interlocking paddles mounted horizontally on the rolls that are used to pull the crop through and crimp the stems. Flail Type conditioners use metal flails to hit the crop after it is mowed to break the stems. As the crop is fed through the flails it is also rubbed against the conditioning hood which wears away at the stem's surface allowing moisture to escape more easily. Field studies have proved that mechanical conditioning could increase bale densities [5].

Energy crops are harvested after the first killing frost in Northeastern United States to keep nutrients in the soil. Normally this happens in February and march. At the time of mowing, miscanthus should already be at a moisture content that is acceptable to perform the rest of the harvesting operations. It is still important to condition miscanthus for reasons other than further drying. Miscanthus is conditioned to shorten the pieces and create fractures in the crop stems. Thus, conditioning may make it easier to handle in later operations [6]. No other publications related to miscanthus conditioning were found. After being conditioned, the stems can be picked up easier by baling tines and can be compressed easier than unconditioned miscanthus [7]. The objective of this study was to examine the effects of roll spacing, roll speed, and crop input on the physical conditions of mechanically conditioned miscanthus plants.

## 2. Materials and Methods

In this study the miscanthus was gathered from a field located just outside of Easton, Illinois at GPS coordinates 40.201434, −89.831220. The field was established in May 2009 with a miscanthus clone from greenhouses at University of Illinois at Urbana-Champaign (UIUC) turf farm. The crop in the field is an accumulation of two years growth and the stand varies in density throughout the field. Several random samples were taken from the field by cutting the crop 6 in (15 cm) off the ground in 1 $m^2$ sections. The cutting height represents the height that a disc bine mower would cut the crop at and the random samples allow for an accurate approximation of the variations in field density and crop length. The samples were collected in 2015 and then brought back to Penn State and placed in cold storage until the time of testing.

To simulate conditions closest to a February/March harvest the crop was pulled from cold storage directly before being conditioned. Cold storage was kept at 4˚C which was close to actual field conditions and helped to reduce moisture loss from the crop while it was being stored between experiments. For long-term storage the crop was kept in a freezer at <−20˚C to minimize crop moisture loss and quality change. The moisture content of the crop was monitored throughout the experiments as well by drying a representative sample each day and weighing the moisture in the crop.

The research study consisted of feeding miscanthus through the conditioning table shown in **Figure 1** under various settings and conditions. The conditioning table is powered hydraulically by a power pack equipped with a Kawasaki K3VL Pump and an Elektrimax 31NCM-3-15-18 Motor. The conditioning table consists of two enclosed steel crimping rolls driven with a hydraulic motor and a chain drive. A torque sensor and speed sensor are coupled between the output shaft of the motor and the chain drive to keep track of the table’s mechanical performance.

The torque and speed are recorded by the data logger every millisecond. Those two conditioning rolls have different diameters and numbers of paddles requiring separate roll speeds to avoid interference. This is accomplished using varying sprockets run off of the same drive shaft. The table also has adjustable guides on the input side to maintain the crop bundle shape while being fed through the rolls. The specs for the conditioning table can be found below in **Table 1**. One objective of this test was to observe the effect of roll spacing on how well the

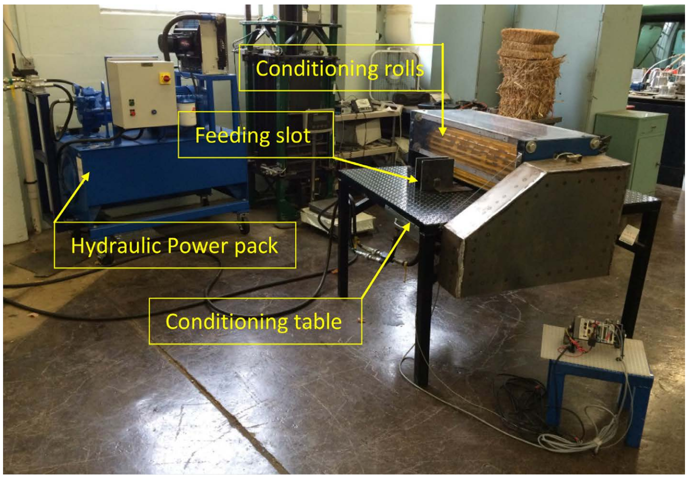

**Figure 1.** Hydraulic power pack, conditioning table, and data logger used in lab tests.

**Table 1.** Conditioning table specifications.

| | |
|---|---|
| Number of Top Roll Fins | 17 fins |
| Depth of Top Roll Fins | 0.025 m |
| Number of Bottom Roll Fins | 8 fins |
| Depth of Bottom Roll Fins | 0.025 m |
| Top Roll Diameter | 0.17 m |
| Bottom Roll Diameter | 0.10 m |
| Roll Shaft Size | 0.03 m |
| Roll Length | 1.04 m |
| Max Hydraulic Motor Displacement | 26.40 cm$^3$/rev |
| Max Hydraulic Motor Speed | 2500 rpm |
| Max Hydraulic Motor Flowrate | 63.33 L/min |
| Max Hydraulic Motor Power | 17.47 hp |

crop was conditioned, and the limitation of throughput at each spacing setting. For this reason, the rolls were mounted in slots to allow for adjustable spacing. Unlike conventional conditioners that use spring tension to hold the rolls together, once set the spacing of these rolls was fixed for the round of tests.

The three variables being tested were roll spacing, roll speed, and the size of the crop bundle being fed through the rolls. The response variables being monitored were torque on the drive shaft and how well the crop was conditioned. The effectiveness of conditioning was quantified in several ways. First, the weight of the crop that was conditioned out of the total crop fed into the rolls was measured and a percent weight conditioned was calculated. Second, the number of internodes conditioned out of the total internodes fed into the rolls was measured to calculate a percentage of internodes conditioned. Finally, the number of pieces greater than 3 in. (7.62 cm) in length coming out of the machine was compared to the number of stalks being fed in to calculate a piece ratio. After conditioning, pieces shorter than 3 in. (7.62 cm) were considered as un-harvestable materials or mass loss, which will be left in field. Piece ratio is defined by:

$$\text{Piece Ratio} = \frac{\text{Pieces Out}}{\text{Stalks In}}$$

The max bundle size that the conditioning rolls would be able to process without jamming was unknown before the experiment. A theoretical maximum for those two rolls used in this study was found to be a 25-stalk bundle when the rolls were set to max speed and max spacing. Thus, the bundle size was increased at five stalk intervals starting at one stalk for each treatment until the crop could no longer be fed through at each spacing and speed. Table 2 summarizes all factor levels used in the treatments for the lab test and Figure 2 shows the treatment combinations. The speed of the rolls was controlled with a flow control valve before the hydraulic motor. The flow was metered to the desired drive shaft speed of 250 rpm and 500 rpm which was also the speed of the top roll. At these speeds the position of the flow control valve was marked for repeatability.

**Table 2.** Lab test factor levels

| | | | | | |
|---|---|---|---|---|---|
| Roll Speed | 250 rpm | 500 rpm | - | - | - |
| Roll Spacing | 0 cm | 0.3175 cm | 0.635 cm | 0.9525 cm | 1.27 cm |
| Bundle Size | 1 stalk | 5 stalk | 10 stalk | 15 stalk | 20 stalk |

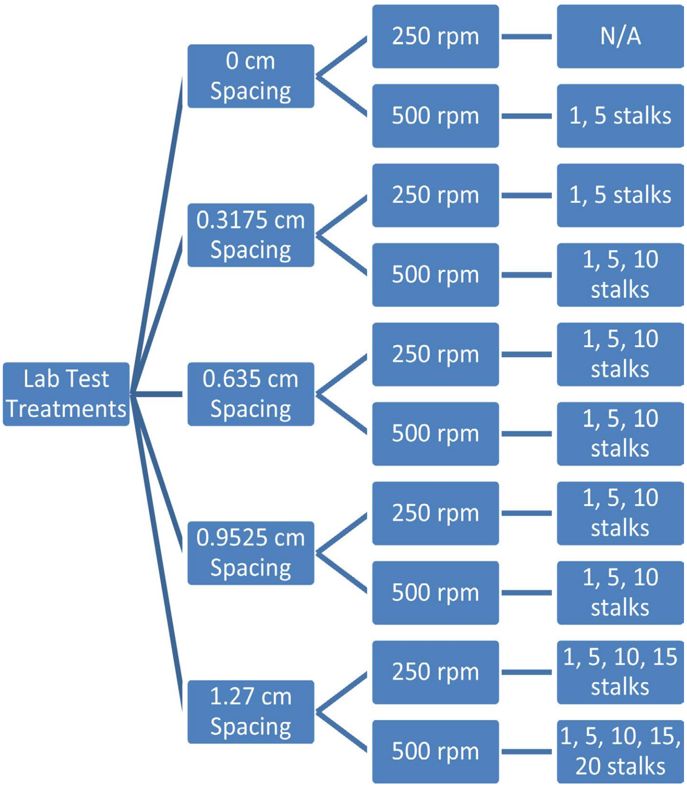

**Figure 2.** Treatment breakdown flowchart.

## 3. Results and Discussions

To minimize the error caused from changing speeds and spacing unnecessarily, all tests for a single spacing were performed in one setting. Once the spacing was set at the desired level the first speed was selected. The crop was then set out in bundles matching the number of stalks required for each treatment. Each bundle had its circumference measured, stalks weighed, and internodes counted before being fed into the machine. The pieces of crop coming out of the machine were then sorted, counted, weighed, and cleaned up so the next bundle could be run. **Figure 3** and **Figure 4** show samples of the crop to be collected from field and after they were conditioned. Each bundle size required three replications and the bundles were run at the same speed and spacing until the crop was jamming in the rolls. At this point the next speed would be selected and the process would be repeated. By performing all treatments for a set spacing at once, the error from constantly adjusting the spacing of the rolls was minimized. The crop used for testing was immediately placed back in the cold storage when testing was finished each day to minimize the loss in moisture from the hot summer weather.

Once conditioned crop samples were collected, the experimental data was analyzed using ANOVA testing in a minitab software package. The analysis compared

**Figure 3.** Miscanthus samples to be collected from field.

**Figure 4.** Conditioned miscanthus.

the significance of the roll spacing, roll speed, and bundle size on the conditioning quality and required torque at a 90% confidence level instead of the typical 95% confidence level due to the variability in biological materials.

The piece ratio is the metric used to compare how well the crop was conditioned because it removes subjective human judgement and provides a number that is easily comparable between the different testing scenarios. It is also known from previous studies that crop which is broken up more will relax less and allow for smaller bales to be made [7]. These physical changes to the plants are beneficial so a larger piece ratio will be considered more conditioned and better quality of conditioned crop. The peak torque was measured for the time when the crop was being fed through the machine. In order to find the change in torque caused by the crop being fed through, an adjusted peak torque was found by subtracting the average torque reading while no crop was being fed through for each test.

While running the tests it was noted that the circumference of the bundles seemed to be the predominant cause of the rolls jamming as opposed to the number of stalks being fed through. To find out if this was the case a sequential SS test was performed in Minitab for circumference, number of stalks, and peak torque. The results were that the circumference of the bundle accounted for more of the variation in peak torque than the number of stalks by an order of magnitude. Instead of using the number of stalks as the predictor for the rest of the tests the circumference was used to represent the size of the bundle.

ANOVA allows for the test of the variables as well as their interaction effects on the response. Initially the interaction of all variables with each other was considered; however, the only one that was kept in the model was the spacing and speed interaction because none of the others could be estimated by Minitab. All of the assumptions necessary to perform the ANOVA test were met and confirmed by analyzing the residual plots. The p values from the analysis are listed below in **Table 3**. P values less than 0.1 results in a rejection of the null hypothesis that the respective variable does not affect the response. The exception to this is for the interaction effect where a p value less than 0.1 results in a rejection of the null hypothesis that the mean for the level of one factor does not depend on the value of the other factor level. If this interaction effect is significant then the interaction of the two variables must be considered when analyzing the main

**Table 3.** Statistical analysis for lab test.

| Variable | ANOVA P Value for Peak Torque | ANOVA P Value for Piece Ratio |
|---|---|---|
| Spacing | <0.001 | <0.001 |
| Speed | <0.001 | 0.574 |
| Circumference | <0.001 | 0.32 |
| Spacing * Speed | 0.379 | 0.082 |
| $R^2$ Value | 96.07 | 81.11 |

effects trends of each factor individually.

The p values for the analysis indicate that roll spacing, roll speed, and circumference of the crop bundle are all statistically significant in predicting the adjusted peak torque. There is also no interaction effect between spacing and speed that is statistically significant so the trends of these factors can be considered by themselves. For how well the crop was conditioned the roll spacing was the only variable to have a significant effect on the piece ratio. There is an interaction effect present between the speed and the spacing for piece ratio. In order to conclude the effect of spacing, the interaction of the two terms needs to be checked as shown in Figure 5. As can be seen the regardless of which speed is used the piece ratio follows the same trend with respect to roll spacing. The reason that the interaction was marked significant was the piece ratio for 0.3175 cm spacing where the piece ratio for the 500 rpm sample did not follow the expected trend. Based on this evidence and the trend present in spacing from 0.635 to 1.27 cm the effect of spacing on piece ratio will be considered on its own.

Figure 6 shows the effect of increasing the roll spacing on how well the crop was conditioned. As the rollers are pulled apart and the spacing becomes bigger the crop becomes less conditioned. When the rollers are close together the fins will interlock more forcing the miscanthus to be bent at sharper angles in order to make it through the rollers. This bending puts more stress on the crop forcing it to break into more pieces than a less stressed crop typical of being fed through greater roll spacing. For a roll spacing of 0.3175 cm the average piece ratio was 8.63. This means that on average every stalk of miscanthus that was fed into the conditioning table was broken up into 8 to 9 pieces. Breaking an approximately 10 ft (3 m) long piece of crop that many times makes it much easier to handle and bale. The crop will no longer be as prone to jamming in the baler pickup and it will be easier to compact smaller pieces in the chamber with less bale

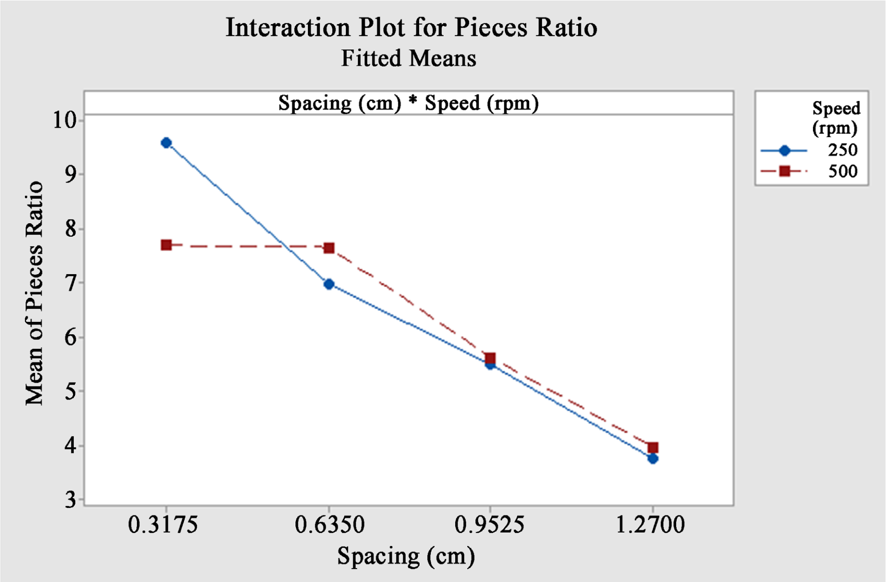

Figure 5. Interaction effect between spacing and speed for piece ratio.

relaxation and stress on the twine once it is ejected.

The effective trends that roll spacing, roll speed, and bundle size have on the adjusted peak torque are clearly seen in **Figures 7-9** respectively. Finding methods to reduce the torque required to condition crop will lead to smaller engine requirements and lower machine costs for consumers. As the roll spacing is made greater (farther apart), there is a decrease in the amount of torque applied on the drive shaft. It appears that there is an asymptote forming as the rolls are opened wider. Once the rolls get to a certain spacing it is expected that there will be no torque on the drive shaft except that required to run the rolls because the crop will freely feed through the gap in the rolls instead of being compressed and

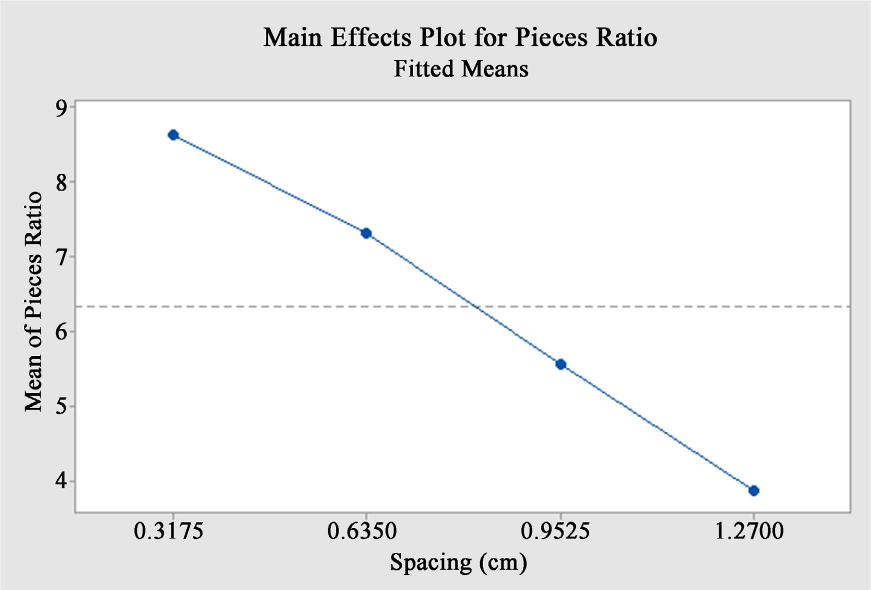

**Figure 6.** Effect of roll spacing on the piece ratio.

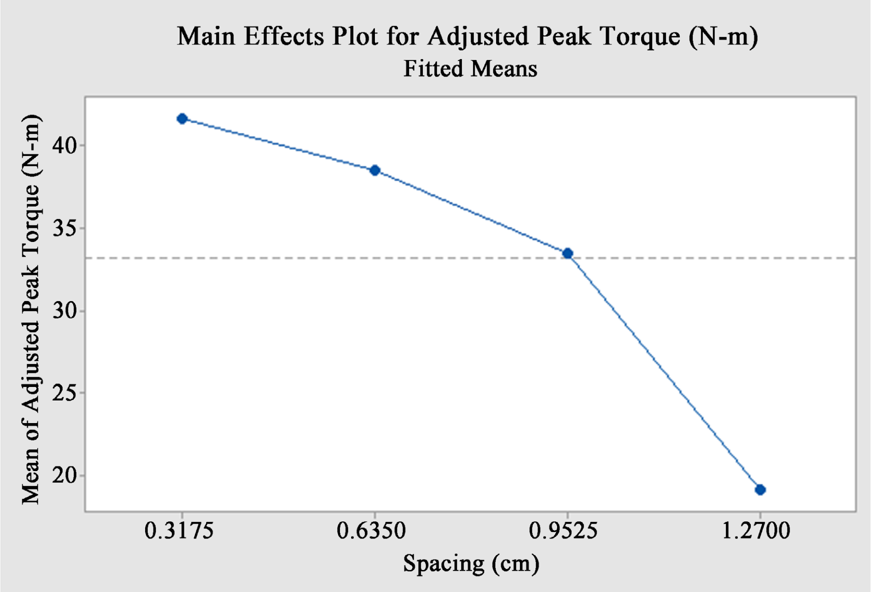

**Figure 7.** Effect of roll spacing on adjusted peak torque.

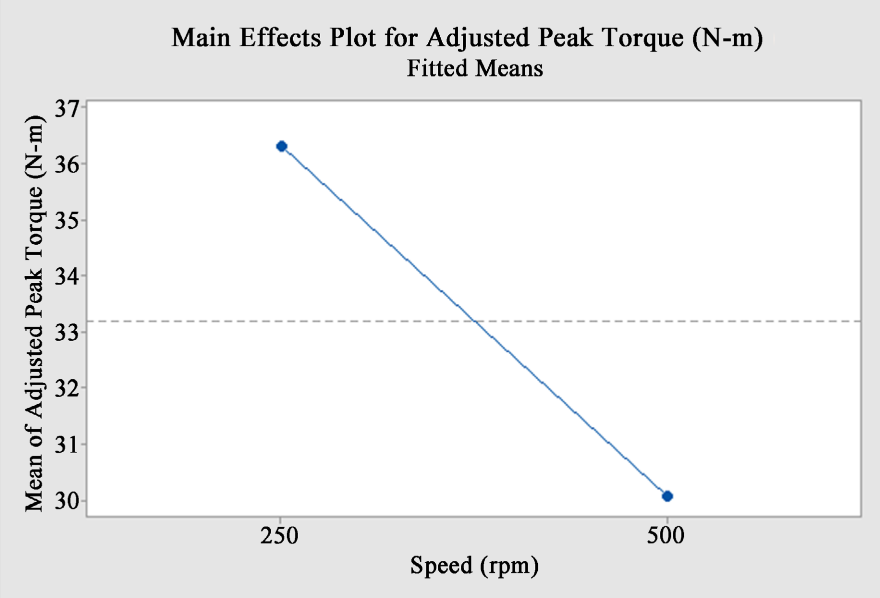

**Figure 8.** Effect of roll speed on adjusted peak torque.

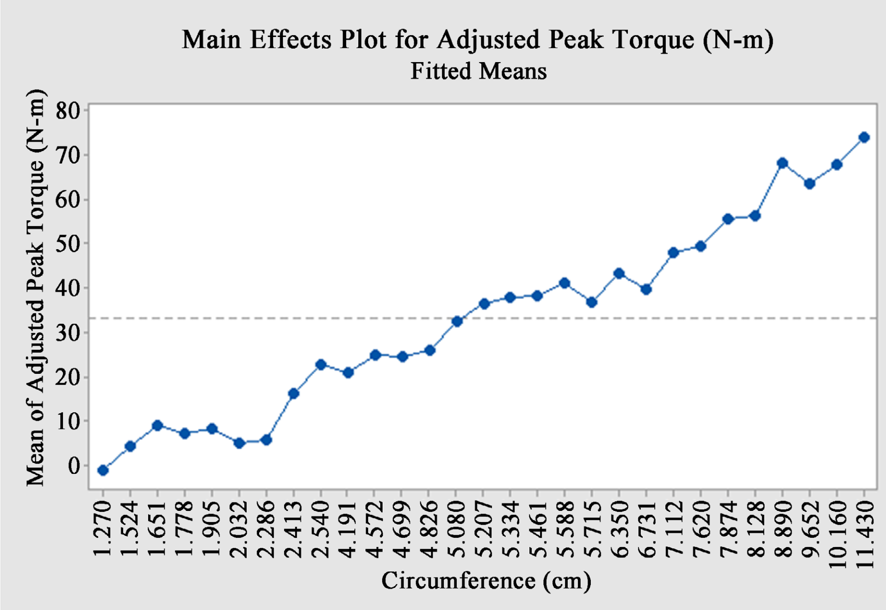

**Figure 9.** Effect of crop bundle circumference on adjusted peak torque.

pulled through. It would be interesting to see if the roll spacing and torque ever converged to a linear relationship; however, no data was collected for smaller roll spacing because the interference in the machine fins made operation while crop was being fed through very unstable and dangerous.

As roll speed was increased from 250 to 500 rpm the peak torque on the drive shaft dropped 6 N·m or 20% to 30.1 N·m. This was expected considering torque and speed have an inverse relationship. While performing the tests it was noted that typically larger crop bundles could be fed through when the rolls were running at the higher speed. It could be that the additional energy stored in the higher angular momentum seen when the rolls are spinning faster is able to pull the crop through the rolls before the hydraulic motor is unable to provide sufficient torque.

The effect of bundle size on the amount of torque required to condition the crop yielded a positive linear relationship. As the bundles increased in size the adjusted peak torque increased by around 7.5 N-m for every centimeter of circumference. Logically it's going to take an increasing amount of torque to condition crop as more is fed into the rolls. If more roll types were available, it would be interesting to see how the torque trends compared to over several kinds of rolls. It would also be useful to determine the capacities that each type of roll can handle without becoming bogged down and inoperable.

## 4. Conclusions

A conditioning table consisting of two steel crimping rolls was used to condition miscanthus and determine the effects of roll spacing, roll speed, and bundle size on the quality of conditioning. The tests found that statistically the spacing of the rolls was the only significant factor in how well the crop was conditioned. As the roll spacing was brought closer together the crop was broken into a greater number of pieces. This suggests that for roll type conditioning modules the spring force holding the rolls together should be increased as much as possible to a point where it isn't causing jamming or diminished travel speed. The more conditioned crop will create bales of higher density and reduce on storage and transportation costs. During the tests it was also found that tighter roll spacing, slower roll speeds, and larger bundle sizes caused the peak torque seen on the drive shaft for the rolls to increase. The torque being measured was the adjusted torque, where the average unloaded torque of the rolls was subtracted from the peak torque of the treatment.

This lab test can be expanded to include different types of conditioning rolls as well as spring loaded spacing. The spring loaded spacing would make the lab setting more consistent with results seen by field machines and would allow for the testing of spring force on the effect of conditioning and capacity. Being able to test different roll configurations would help to determine if the current roll designs are truly the best available for conditioning miscanthus.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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