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In-field direct combustion fuel property changes of switchgrass harvested from summer to fall

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ABSTRACT

Switchgrass, a perennial warm-season grass and potential energy crop, is usually harvested during the time between full maturity in the fall to the following spring. During this wide harvest window, the changes in fuel properties that could occur are important for making appropriate decisions with respect to the optimum harvest time for maximum fuel quality. A field plot study was carried out to investigate the quantitative fuel properties (proximate, ultimate and mineral analyses) of switchgrass over a harvest period from crop maturity in July through November. Harvest moisture decreased from July to November and moisture was uniformly distributed in the switchgrass plant at all times in the harvest period. There were significant differences in ash, volatiles, fixed carbon and nitrogen among months of harvest. Nitrogen, ash and fixed carbon contents decreased while oxygen and volatiles increased through the harvest period. Also, there were significant differences in oxides of silicon, calcium, potassium, phosphorus and sulfur among harvest times. The concentration of oxides of potassium and sulfur decreased at the end of the harvesting period. Fouling and slagging indices decreased as harvest was delayed but remained low throughout harvest. However, the decreases are small and might not dramatically impact fouling and slagging. Overall, the results appear to favor a later harvest for switchgrass used for direct combustion. This study will benefit feedstock producers as well as biomass feedstock facility operators by providing a better understanding of how the properties of switchgrass vary over a typical harvest period and their potential effect on boiler equipment.

1. Introduction

Switchgrass (*Panicum vigratum*, L.), a perennial warm-season grass, is desirable as a potential biofuel in direct combustion systems because of its excellent burn quality, ease of management, and high yield. During the harvest period, the quality and quantity of switchgrass, as well as other herbaceous perennials, change over time. In summer harvest, when the plant is mature, there will be higher yields as opposed to late fall and early winter harvest when dry matter losses can occur due to plant lodging and biodegradation over time. However, switchgrass harvested in the summer is wet and requires that the cut plant be left in windrows to dry before baling. This poses some risk from inclement weather compared to switchgrass harvested in the fall when the plant would have dried to safe baling moisture and thus might not require the cut plant to field dry prior to baling. High moisture feedstock is difficult to manage and reduces the heat available from the fuel during direct combustion by lowering the initial gross calorific value of biomass. Fuel moisture reduces the combustion efficiency since heat is absorbed in evaporation of water in the initial stages of combustion which lowers the flame temperature as well [1].

The prediction of combustion for the purposes of design and control requires knowledge of fuel properties and the manner in which these properties influence the combustion process [2]. A problem that switchgrass and other herbaceous energy crops pose during combustion is the amount of ash in the biomass material. Ash is the inorganic residue remaining after ignition of herbaceous biomass. It influences the performance of combustion equipment and is composed of alkali minerals containing silicon (Si), aluminum (Al), calcium (Ca), magnesium (Mg), sodium (Na) and potassium (K). Jenkins et al. [2] stated that alkali and alkaline earth metals, in combustion with other elements such as silica and sulfur, and facilitated by the presence of chlorine (Cl) are responsible for many undesirable reactions in combustion furnaces and power boilers. Ash components of major concern are Na, K, Cl, S (sulphur), Zn (zinc), and Pb (lead) because about 80% are evaporated during combustion while only about 20–50% of other inorganics such as Ca, Mg, Mn (manganese), P (phosphorus) and Ti (titanium) are released [3]. Miles et al. [4] stated that potassium is often organically bound in biomass which will vaporize and decompose during combustion and will form oxides,

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hydroxides, chlorides and sulfates which react to form low-melting point species such as potassium silicate which condense on boiler walls, tubes and fly-ash particles causing slagging and fouling.

Agricultural crop studies have included implementing a very late season harvest, delayed to after frost to permit retranslocation of nutrients such as K, P and N below ground. Both retranslocation and leaching from senescent foliage contribute to lowering nutrient levels. Parrish et al. [5] stated that biomass harvested in late fall through early spring provides a higher quality fuel with less ash content than that of summer. The harvest of reed canary grass (*Phalaris arundinacea* L.), a herbaceous biomass crop, for combustion was evaluated by Hadders and Olsson [1]. It was determined that the composition of agricultural crops harvested in the summer is generally not very suitable for combustion because of the high contents of ash, nitrogen, potassium and chlorine. Harper [6] added that there are trade-offs in delaying harvest even as late as the following spring. While biomass yield decreases over the winter, mineral and moisture contents decrease as well, which both positively affect the feedstock value from a combustion stand point. Therefore, timing switchgrass harvest two to three weeks after a killing frost through March is desirable.

Due to the composition of minerals in biomass, deposition of the ash occurs when the fuel is mixed intimately with hot air and burned at high temperatures. Part of the ash is deposited on boiler surfaces, producing slagging and fouling in certain areas of the boiler. Skrifvars [7] stated that the accumulation of extensive ash deposits on radiant or convective heat transfer surfaces would lead to higher gas temperatures, damage to pressure parts in the lower area of the furnace and an increase in draft loss increasing static pressure losses and reducing steam output. A running slag is produced along the walls of the boiler as a result of alkali metals reacting with particles of fly ash. The flow characteristics of the generated slag depend on its viscosity. Arvelakis et al. [8] stated that in systems that must maintain a slag flow, the temperatures of the slag must be high enough to produce a low-viscosity slag that will flow (T_{250}); the temperature in which the slag viscosity is 250 poises. Unequivocally predicting the slagging and fouling properties of a given fuel would seem unattainable. However, predicting ash fusibility has been achieved using correlations between fusion temperatures and standardized chemical composition of ashes in a base-to-acid ratio (B/A) which were developed for coal samples. The basic (base) constituents are Fe, the alkaline earth metals Ca and Mg, and the alkali metals Na and K. The acidic (acid) constituents are Si, Al and Ti. Pronobis [9] stated that so-called basic compounds lower the melting temperatures, while acidic ones increase it.

The results of the elemental ash analysis provides data used in calculating fouling and slagging indices via correlations. Gray and Moore [10] recommended using results of the elemental ash analysis to calculate the property of fouling. According to Pronobis [9], the base-to-acid ratio (weight %) in the biomass ash is a procedure for calculating furnace slagging. Furthermore, fouling and slagging potential can be utilized by boiler furnace and superheater designers. With knowledge of ash analysis of switchgrass alone or along with coal, designers can determine the number of wall blowers needed to control slag accumulation in plastic zones and superheaters which can be designed to permit control of ash deposits to avoid fouling/slagging problems. Reducing such problems during combustion of biomass will lead to increased boiler-performance efficiency while reducing operational costs.

In general, biomass components include cellulose, hemicelluloses, lignin, lipids, proteins, simple sugars, starches, water, HC, ash, and other compounds [11]. As was noted previously, these components determine the fuel properties. The concentrations of these components in a particular biomass species depend on the type of plant tissue, stage of growth, and growing conditions (environment, soil type, cultural practices, etc.) [11]. Therefore, it might be important to understand how some of these factors affect biomass fuel properties and evaluate the relevance of their inclusion when reporting fuel properties. This study investigated the in-field combustion fuel properties of switchgrass harvested from maturity in the summer through fall (July to November). The fuel analyses conducted included proximate, ultimate and mineral analyses. Additionally, the moisture content of three sectioned parts of switchgrass stem was monitored from summer to fall harvest to investigate the uniformity of moisture distribution in the plant during the harvest period. In addition, we examined the implications of harvest time decisions in regard to fuel properties as they affect boiler performance using base-to-acid (B/A) ratio, fouling and slagging indices, T_{250}, silica value and percent alkali as Na_2O.

2. Materials and methods

2.1. Sample collection

Switchgrass (variety not stated) which was used in this study was seeded in 1987 and grown in a small plot approximately 20.9 m^2 (225 ft^2) at the Purdue Agronomy Center for Research and Education (ACRE) in West Lafayette, Indiana. Burning of the previous year's residue occurred in late April and nitrogen fertilizer was applied at a rate of 56 kg/ha. The switchgrass plot (Fig. 1) was randomly sectioned in June, 2006 into twelve 1.115 m^2 (12 ft^2) pre-assigned sub-plots representing three replications for the months of July, August, October and November. To allow time for recovery following harvest, switchgrass was not collected between September 5 and October 20. Three samples were collected monthly from their respective sub-plot within an area of 0.3716 m^2 (4 ft^2) using a 0.61 m^2 (2 ft^2) wooden constructed square grid to determine the yield (Mg/ha). Shears were used for cutting, leaving about 15 cm of stubble to provide shoot buds/protection for regrowth. At harvest, each switchgrass plant was separated into three 0.15 m (6 inch) sections (bottom, middle and top), tested for moisture content immediately after harvesting using ASAE S358.2 (25 gram samples were cut to small pieces to fit the sample cup and dried at 103 °C for 24 h) [12]. After harvest, samples were stored for future fuel analyses (proximate, ultimate and mineral) in a storage cooler located in a Purdue University lab at −18 °C (0 °F) to retain initial chemical properties.

2.2. Fuel analysis

After the final harvest in November, 12 samples (4 months, 3 replicates) were collectively sent to Standard Laboratories Inc. (Evansville, Indiana) for proximate, ultimate and mineral analyses using ASTM D3176-89 [13]. Proximate analysis provided percentage values for moisture content, volatile content (when heated to 950 °C), the free carbon remaining at that point, the ash (mineral) in the sample and the energy content of switchgrass on a dry basis. Ultimate analysis provided the composition of the biomass in percent weight of the major components carbon, hydrogen, nitrogen, oxygen and sulfur. Mineral

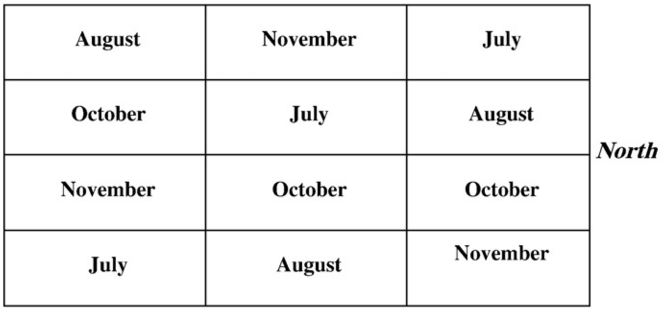

Fig. 1. Diagram of switchgrass plot with randomly chosen sub-plots labeled with the months of harvest.

analysis provided chemical occurrence of fractionations as water soluble/ion-exchangeable, acid soluble and insoluble for K, Na, Ca, Mg, Si, Al, P, S and Fe. In addition, parameters of T_{250} (the sample's temperature at which the slag viscosity is 250 poises), the silica value (the percentage of silica in the sample that aids in the formation of low-melting compounds) and the percentage of alkali as Na_2O, which promotes corrosion in boilers were provided by Standard Laboratory Inc. These are important elements and parameters for the understanding of deposit formation and sintering during combustion of the fuel.

Additionally, the fractionation-elements of mineral analysis were used to compute the base-to-acid (B/A) ratio. The basic constituents of this analysis on a biomass ash sample report the elements present as oxides and are quantitatively measured for B/A as described by Winegartner [14] for coal samples;

$$\text{where } B = Fe_20_3 + CaO + MgO + K_2O + Na_2O$$

$$A = SiO_2 + TiO_2 + Al_2O_3.$$

Fouling and slagging indices were calculated using B/A ratios. The fouling index (FI) below, developed by Huppa and Backman [15] was calculated as the product of the base-to-acid ratio and Na_2O (weight %)

$$FI = (B / A) \times Na_2O.$$

Classification of fouling potential was determined by Bryers [16]:

$FI<0.2$ Low Fouling
$0.2<FI<0.5$ Medium Fouling
$0.5<FI<1.0$ High Fouling
$1.0<FI$ Severe Fouling

The empirical slagging index (SI) below was derived by Attig and Duzy [17], and was calculated as the product of the base-to-acid ratio and the dry basis (% content) of sulfur from ultimate analysis.

$$SI = (B / A) \times S$$

Classifications of slagging potential are [16]

$SI<0.6$ Low Slagging
$0.6<SI<2.0$ Medium Slagging
$2.0<SI<2.6$ High Slagging
$2.6<SI$ Severe Slagging

Fouling and slagging indicators can be used to determine the existence of sulfate forming compounds ($CaO+MgO+Na_2O+K_2O$); however, no absolute deposition indicators can be given because slagging/fouling also depends on boiler lay-out and operation [18].

2.3. Statistical analysis

To determine the influence of plant section (top, middle and bottom) on in-field moisture content, a randomized complete block design was used for the 4 harvest dates, 3 plant sections and 3 replications through a two-way analysis of variance (ANOVA) procedure (0.05 probability) using the SAS statistical software [19]. Upon determination of the fuel analysis data, statistical analyses were conducted to determine if there were differences in fuel properties (proximate, ultimate and mineral analyses) among harvest times using an ANOVA–Proc GLM procedure. Calculation results of slagging and fouling indices used the same Proc GLM procedure. Tukey Studentized Range tests were performed to determine rankings and which fuel property means were significantly different within the harvest period.

3. Results and discussion

3.1. Variability of switchgrass moisture over the harvest period

Table 1 shows that the highest moisture content (65.2% wet basis) occurred in the first month of harvest (July) and the lowest moisture (12.5%) occurred in the final harvest (November) as expected. If summer harvest is planned, switchgrass will be cut and left to dry in the field before baling at a safe low moisture content for storage. The dry matter yield of biomass (Mg/ha) is also shown in Table 1. Yield data shows a maximum yield occurring in August (9.56 Mg/ha) and reductions in October and November to 7.92 and 7.34 Mg/ha respectively. Although the yield is higher, the consequential higher moisture of switchgrass in summer harvest must be reduced by field drying in a short window of 3–4 days before baling. Challenges with harvest could arise if inclement weather does not favor field drying, especially after switchgrass has been cut. Therefore, ensuring that low moisture biomass is baled during field removal is a crucial management step. Nevertheless, summer harvest might be favorable when weighed with equipment and labor availability in the summer when producers are not busy with corn and soybean harvest in the Midwest compared with fall harvest. Corn stover, which is available only after corn harvest in the fall, competes for time, equipment and labor used for corn and soybean harvest. In fall harvest of switchgrass, there are also potential for a large number of lodged plants on the field, which could make harvesting difficult and potentially reduce switchgrass yield and increase soil contamination. All these management considerations need to be thought through with respect to the needs of any enterprise utilizing switchgrass as a fuel feedstock for power generation.

Two-way ANOVA showed significant differences in the moisture of switchgrass sections harvested for the various time periods (p-value < 0.0001), but no significant difference in moisture was found among plant sections (p-value = 0.15). The results indicate that switchgrass dries on the field quite uniformly, losing about 54 percentage points of moisture between July and November.

3.2. Variability of fuel properties over the harvest period

3.2.1. Proximate analysis

Proximate analysis was used to determine the moisture, ash, volatile matter and fixed carbon in each switchgrass sample. Table 2 lists

Table 1
Moisture content of switchgrass plant sampled over the harvest months.

Moisture content (% wet basis)						DM yield
Harvest	Rep	Bottom	Middle	Top	Plant average	Mg/ha
		Mean ± StD	Mean ± StD	Mean ± StD	Mean ± StD	Mean ± StD
July*	3	63.2 ± 6.2a	66.5 ± 0.7a	66.0 ± 0.61a	65.3 ± 1.8	8.77 ± 1.3
August*	3	58.8 ± 0.7ab	62.9 ± 1.6a	59.9 ± 1.7b	60.5 ± 2.1	9. 6 ± 0.62
October*	3	21.2 ± 8.8a	27.9 ± 9.4a	31.3 ± 2.6a	26.8 ± 5.1	7.9 ± 0.49
November*	3	11.1 ± 0.6a	12. 5 ± 0.3b	14.0 ± 0.64b	12.5 ± 1.4	7.3 ± 0.11

*Values followed by a different letter are significantly different at $p<0.05$.

Table 2
Proximate analysis of switchgrass plants sampled over the harvest months.

Proximate analysis (wt.% as-rec'd)						
Month	Rep	Moisture*	Ash*	Volatile*	Fixed carbon*	Energy value* (MJ/kg)
		Mean ± StD	Mean ± StD	Mean ± StD	Mean ± StD	Mean ± StD
July	3	7.22 ± 0.39a	6.17 ± 0.09ba	73.57 ± 0.27d	20.26 ± 0.35a	17.15 ± 0.33a
August	3	7.76 ± 0.21a	6.21 ± 0.87a	75.40 ± 0.75c	18.39 ± 0.31b	17.30 ± 0.43a
October	3	7.53 ± 0.31a	4.93 ± 0.21b	80.60 ± 0.21b	14.47 ± 0.31c	15.85 ± 1.95a
November	3	7.84 ± 0.56a	3.92 ± 0.34c	82.93 ± 0.36a	13.15 ± 0.10d	18.27 ± 0.94a
p-value		0.28	0.0010	<0.0001	<0.0001	0.15
F value		1.51	15.77	286.26	413.46	2.38

* Values followed by a different letter are significantly different at $p<0.05$.

the mean values and standard deviations of the fuel properties from 12 samples (4 months, 3 replicates) in addition to the ANOVA and Tukey test results.

Note that the moisture values reported in proximate analysis were much lower than the harvest moistures reported in Table 1. This was due to sample preparation (drying and grinding) prior to conducting the fuel analysis. From July to November, the ash and fixed carbon contents decreased by 2.3 and 7.1 percentage points, respectively, while the volatile content increased by over 9 percent points. While ash and fixed carbon decreased over time and volatiles increased and the energy content displayed a general increase through harvest. There were significant differences in the percent ash, volatiles and fixed carbon among harvest periods ($p<0.05$). Our data agreed with a previous study by Hadders and Olsson [1] who showed that fixed carbon decreased and the content of volatile matter increased as harvest was delayed to later months. Although there was no significant difference in the energy value ($p=0.146$) with regard to the time of harvest, the last month of harvest (November) provided the highest value (18.27 MJ/kg). A study by Adler et al. [20] reported similar results for switchgrass harvested in fall and spring. Additionally, switchgrass harvested in later months in the fall had a lower ash and higher reactivity compared to earlier months in the summer.

3.2.1. Ultimate analysis

Ultimate analysis (elemental analysis for C, H, N, O and S) was carried out for each of the 12 samples of switchgrass collected from July to November. Table 3 shows the means of the ultimate analysis parameters with their respective standard deviations along with ANOVA and Tukey test results.

Carbon and oxygen increased slightly with harvest time, but only the increase of oxygen in the fall was significantly higher than in the summer (Table 3). The higher oxygen values imply that switchgrass will burn better during combustion when harvested in later months.

Hydrogen and sulfur showed no relationship to harvest time. Only nitrogen showed a steady decrease as harvest was delayed from July to November which can be attributed to nutrient retranslocation over

Table 3
Ultimate analysis of switchgrass sampled over the harvest months.

Ultimate analysis (wt.% as-rec'd)						
Month	Rep	Carbon*	Hydrogen*	Nitrogen*	Oxygen*	Sulfur*
		Mean ± StD	Mean ± StD	Mean ± StD	Mean ± StD	Mean ± StD
July	3	46.82 ± 0.07a	5.66 ± 0.04a	0.70 ± 0.05a	40.42 ± 0.07c	0.23 ± 0.01a
August	3	46.99 ± 0.45a	5.47 ± 0.04b	0.67 ± 0.12a	40.40 ± 0.55c	0.24 ± 0.03a
October	3	47.27 ± 0.03a	5.59 ± 0.03a	0.39 ± 0.01b	41.64 ± 0.18b	0.17 ± 0.02b
November	3	47.41 ± 0.38a	5.67 ± 0.04a	0.35 ± 0.05b	42.42 ± 0.09a	0.21 ± 0.01ba
p-value		0.1373	0.0007	0.0004	<0.0001	0.0097
F value		2.46	17.88	20.83	33.13	7.68

* Values followed by a different letter are significantly different at $p<0.05$.

Table 4
Elemental composition of ash in switchgrass plant sampled over the harvest months.

% of ash*	July	August	October	November	*p*-value	*F* value
SiO_2**	43.61 ± 0.25c	57.39 ± 0.13b	64.93 ± 0.46a	66.93 ± 0.22a	< 0.0001	156.12
TiO_2	0.17 ± 0.02a	0.17 ± 0.02a	0.18 ± 0.02a	0.17 ± 0.01a	0.97	0.08
Al_2O_3	0.11 ± 0.02a	0.49 ± 0.33a	0.24 ± 0.04a	0.26 ± 0.09a	0.14	2.42
CaO	5.63 ± 0.26c	6.37 ± 0.15b	7.60 ± 0.34a	6.11 ± 0.30cb	0.0001	27.69
K_2O	26.60 ± 0.20a	16.80 ± 0.72b	7.80 ± 0.72c	9.00 ± 0.80c	<0.0001	524.72
MgO	4.80 ± 0.20a	4.93 ± 0.11a	4.53 ± 0.11a	4.80 ± 0.91a	0.76	0.37
Na_2O	0.19 ± 0.06a	0.29 ± 0.13a	0.08 ± 0.02a	0.29 ± 0.14a	0.10	2.88
P_2O_5	5.26 ± 0.13d	5.57 ± 0.07c	5.93 ± 0.13b	6.60 ± 0.00a	< 0.0001	94.68
Fe_2O_3	0.50 ± 0.07a	0.84 ± 0.43a	0.87 ± 0.55a	0.67 ± 0.08a	0.59	0.67
SO_3	8.09 ± 0.39a	2.09 ± 0.17b	3.65 ± 3.16b	0.52 ± 0.89b	0.0028	11.59
BaO	0.01 ± 0.00b	0.017 ± 0.006ab	0.017 ± 0.006ab	0.023 ± 0.006a	0.067	3.56
MnO_2	0.19 ± 0.00c	0.23 ± 0.01b	0.26 ± 0.01a	0.26 ± 0.01a	<0.0001	56.6
Undetermined	4.83 ± 1.01a	4.79 ± 1.1a	4.34 ± 1.24a	3.90 ± 1.07a	0.72	0.46

* Mean ± StD of % ash ($n=3$).

** Values of elemental composition followed by a different letter are significantly different at $p<0.05$.

the harvesting period. Therefore, harvesting switchgrass later in the fall as opposed to the summer can reduce plant nitrogen and thus reduce NO_X emissions during combustion. Statistical analysis ($\alpha = 0.05$) showed significant differences in hydrogen, nitrogen, oxygen and sulfur during harvest with p-values of 0.0007, 0.0004, <0.0001 and 0.0097, respectively.

3.2.2. Mineral analysis

The elemental composition of the ash indicates the potential of the feedstock to cause fouling and slagging during combustion. Jenkins et al. [2] stated that elements including Si, K, Na, S, Cl, P, Ca, Mg, and Fe are involved in reactions leading to ash fouling and slagging. Data from mineral analysis (Table 4) provided elemental composition of the inorganic portion (ash) of carbonaceous materials found in the switchgrass samples over the harvest period. There were significant differences for elements (reported as oxides of fuel), SiO_2, CaO, K_2O, P_2O_5, SO_3 and MnO_2. Al_2O_3, Fe_2O_3 and MgO were not significantly different in their relation to harvest time. SiO_2, CaO, P_2O_5 and MnO_2 increased from the summer in July to the fall in November while K_2O and SO_3 decreased over the harvest period. The reduction in K_2O affected the B/A ratio, which decreased over the harvesting period and ultimately the fouling and slagging indices (Table 5). The B/A ratio, fouling and slagging indices were significantly different over all the harvest months. The slagging index declined as harvest was delayed to later months due to the reduction in SO_3. Na_2O increased in the final month of harvest by 0.21 percentage points and this increase led to a fouling index increase in the final harvest month. Using Bryers' [16] fouling and slagging classifications, both indices were characterized as low throughout the harvest period (summer to fall). Results of the mineral analysis indicate a reduction in potential ash deposition in late fall harvests (October and November). In general, reduction in minerals (especially those involved in ash fouling and slagging reactions) would minimize the potential for damage to boiler surfaces while increasing boiler efficiency.

One of the important elements involved in reactions leading to fouling and slagging that was not measured is Chlorine (Cl) [2]. Chlorine is a major factor in ash formation, acting as a carrier which facilitates the mobility of many inorganic compounds [2]. Furthermore, Cl concentration often determines the amount of alkali vaporized during combustion as strongly as does the alkali concentration [2]. Unfortunately, the cost of conducting multiple sample tests for Cl through the harvest period was outside the budget for this study, and so was not conducted. Therefore, the lack of Cl data limits the conclusions that can be drawn from this study.

Additional parameters derived from mineral analysis (T_{250}, silica value and alkali % as Na_2O) were significantly different among harvest times. T_{250}, increased each month from 2170 °C to 2543 °C which signified a decrease in slag viscosity and better flow. The silica value increased slightly each month from about 80–85%. Silica is a low-melting point element which could potentially reduce the melting point of ash. Alkali % as Na_2O significantly decreased from 1.11% to 0.22% which indicates that a better (less corrosion potential) switchgrass fuel is produced in later months of harvest.

4. Conclusions

This research study evaluated the fuel property changes of switchgrass harvested from maturity in the summer (July) to the fall (November) with respect to its use as a solid fuel for direct combustion under Indiana's (Midwest United States) weather conditions. The fuel properties investigated during a four month harvest window were plant moisture content, proximate, ultimate, and mineral analyses which were used as a measure of fuel quality. Moisture contents of switchgrass stems cut into three sections were also monitored over the harvest period.

Switchgrass moisture decreased over the harvest period from summer, which had the highest moisture, to fall which had the lowest moisture. Also, the moisture contents of the switchgrass sections (top, middle and bottom) were not significantly different. Overall, it was seen that fuel properties of switchgrass based on ultimate, proximate and mineral analyses were significantly different from the time of harvest in the summer when switchgrass reaches physiological maturity to the fall when the plant is adequately dried for collection. In particular, some of the ash fouling and slagging minerals decreased in the later months of harvest, however the decreases are small and might not dramatically impact fouling and slagging. The B/A ratio, slagging index and alkali % as Na_2O decreased from the summer to later months in the fall. Additionally, T_{250} and silica value increased with harvest time providing a higher quality fuel for combustion purposes and internal boiler surfaces. Therefore, harvesting switchgrass in the fall would be the preferred option for use as a boiler fuel in direct combustion systems.

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Table 5

Mineral analysis calculations to determine base-to-acid ratio, fouling and slagging indices.

Calculations							
Month	Rep	B/A ratio	Fouling index	Slagging index	T_{250}	Silica value	Alkali % as Na_2O*
		Mean ± StD*	Mean ± StD	Mean ± StD	Mean ± StD	Mean ± StD	Mean ± StD
July	3	0.86 ± 0.02c	0.16 ± 0.05b	0.12 ± 0.00c	2170 + 0.00a	79.97 + 0.295a	1.11 + 0.057c
August	3	0.51 ± 0.01b	0.15 ± 0.07ab	0.06 ± 0.00b	2306.67 + 2.88b	82.55 + 0.722b	0.60 + 0.025b
October	3	0.32 ± 0.02a	0.03 ± 0.01a	0.03 ± 0.00a	2530 + 36.05c	83.30 + 1.039bc	0.20 + 0.010a
November	3	0.31 ± 0.02a	0.09 ± 0.04ab	0.03 ± 0.00a	2543.33 + 35.12c	85.25 + 0.754c	0.22 + 0.015a
p-value		<0.0001	0.03	<0.0001	<0.0001	0.0002	<0.0001
F value		683.47	5.04	998	154.91	25.43	521.54

*Values followed by a different letter are significantly different at $p < 0.05$.

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