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Research paper

Drying models to estimate moisture change in switchgrass and corn stover based on weather conditions and swath density

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ABSTRACT

An environmental chamber was built to evaluate the effect of weather parameters and swath density that affect the drying rate of crops during field drying. A series of 52 drying experiments was conducted on corn stover (CS) of which 27 were used for model development and 25 were used for model validation. Similarly, 80 experiments were performed on switchgrass of which 72 were used for model development and eight were used for model validation. Regression models were developed for switchgrass and CS that predicted the drying rate based on environmental conditions and swath density. During the day, radiation was found to be the most significant variable that affected the drying rate of switchgrass with a correlation coefficient (r) of 0.5 and 0.49 during different maturity stages. During the night, VPD was the most significant variable that affected the drying rate with r of 0.69 for corn stover (CS) and 0.83–0.85 for switchgrass. The effect of wind speed was variable and was found to be dependent on solar radiation. During the day time, an increase in wind speed removed the heat produced by radiation and thus decreased the drying rate. However, at night, the wind speed was positively correlated with drying rate. Swath density was negatively correlated (r = −0.38) with the drying rate of switchgrass which suggested that biomass should be dried in wide swaths if possible. The model should be a useful tool for planning field logistics and transportation operations for biomass supply.

1. Introduction

Switchgrass has a wide harvest window and is harvested from late July to February of the following year (Sharma et al., 2011). When harvested at an early maturity stage, switchgrass has a higher moisture of 70%, and it reduces to less than 10% after the killing frost (Khanchi et al., 2013). Womac et al. (2005) also reported that corn stover, when harvested at early maturity stage, has significantly higher moisture of 34.1% compared to 15.3% for late harvest. These crops when harvested early require a field drying period to reduce the moisture to a safe storage level of less than 18% (Rotz, 1995). The field drying period can vary depending on crop characteristics, environmental conditions and swath structure. As the crop lays in the field, moisture migration takes place between the crop and the environment, until suitable equilibrium moisture is attained. Field drying time of grasses varies from 2 to 7 days. Drying time is reduced to 2–4 days when the grasses are spread in thin layers and weather conditions are favorable (Haghighi, 1990; Moore and Peterson, 1995).

Crop characteristics such as yield, stem diameter, leaf to stem ratio, and swath structure can increase or decrease the moisture migration during field drying (Rotz and Shinners, 2007). Density and thickness of the windrow significantly impact the drying rate of the crop in the field. High yield and narrow width results in high-density windrow, which dries slowly compared to a thin and wide swath containing the same amount of biomass (Moore and Peterson, 1995). A thick windrow also blocks the air movement, which carries moisture away from the lower layers to the ambient atmosphere. Freshly harvested biomass is also high in initial moisture and forms a compact windrow that resists the wind penetration. Wind circulation through the windrow can be enhanced by making the windrow more fluffy by raking (Moore and Peterson, 1995).

Environmental factors such as solar radiation, wind speed, air temperature, relative humidity, and soil moisture influence the drying behavior of crops in the field. These weather parameters are highly correlated in field conditions and it becomes difficult to analyze the effect of an individual parameter on drying potential of crop (Borreani and Tabacco, 1998). From all the environmental factors solar radiation has the most impact on the drying rate (Bartzanas et al., 2010; Khanchi et al., 2013; Smith, 1990). The impact of wind was also related to solar radiation. It was reported that at high radiation intensity, an increase in wind speed decreases the drying rate

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of switchgrass (Khanchi et al., 2013) as some of the heat used to enhance the temperature of swath was carried away by the wind. However, at a low radiation intensity, an increase in wind speed improves the drying of switchgrass depending on the vapor pressure deficit (VPD) of the air (Khanchi et al., 2013). Wright et al. (2000) observed a similar variable effect of wind during drying of rye grass. They suggested drying the grass in fluffy windrows to improve wind circulation under cloudy conditions.

Some models have been developed that simulate the influence of environment on field drying of crops. The model developed by Womac et al. (2005) estimates the stover moisture content based on days after sowing, soil moisture, rainfall, RH, evapotranspiration, minimum air temperature, soil temperature, and wind speed. The model can predict the moisture content at the end of the day. However, the model developed in the present study can predict hourly as well as daily moisture fluctuation in addition to the moisture content at the end of the day. Shinners et al. (2007) also evaluated the influence of shredding, swath density and weather conditions on final moisture content of corn stover in Wisconsin, U.S. They found that at an average daily temperature of 5° C in mid to late October, only shredded corn stover placed flat in windrows reached safe storage moisture of less than 20% in 5–7 days. In the second study, none of the treatments reached below 40% in a 10 day drying period showing the importance of weather conditions in the drying of biomass. In 2003, when the drying conditions were right, the treated stover reached a moisture content of less than 20% in 4 days. However, when drying was interrupted by rain, none of the treatments reached 20% after 10 days of drying. Manstretta and Rossi (2015) also developed a model for estimating moisture fluctuation in CS residues as an inoculum source for several fungal pathogens in maize. They used rainfall and VPD to predict the moisture in CS residue after harvest. The model developed in the present study utilizes environmental variables as well as swath density for moisture prediction of CS. Additionally, in other studies (Bartzanas et al., 2010; Khanchi et al., 2013; Smith, 1990) solar radiation was found to be the most important factor affecting the drying of crops in the field. Thus solar radiation should be included in the models for predicting drying rates of crops in the field conditions.

When compared to corn stover, drying studies on switchgrass are more limited. Shinners et al. (2010) studied field drying rates of switchgrass and reed canary grass. They found that under good drying conditions (14–30° C) switchgrass dried more quickly when placed in wide swath. In all the cases, the crop was below 20% moisture in the afternoon of the day after cutting and in some cases reached baling moisture in a single day of drying. Khanchi et al. (2013) developed an empirical model based on maturity stage and environmental conditions for thin layer drying of switchgrass. However, drying models to predict the drying behavior of switchgrass and corn stover which incorporates swath density are still lacking in the literature. Specific objectives of this present study were to: 1) develop drying models to predict field moisture change of corn stover and switchgrass based on weather conditions, swath density, and maturity stage, 2) evaluate the effect of individual weather parameters and swath density on the drying rate of switchgrass and corn stover, and 3) validate the developed models. The previous design (Khanchi et al., 2013) of the environmental chamber was also improved to reduce the variation or radiation intensity and wind speed in the test section.

2. Material and methods

2.1. Construction of an environmental chamber

The environmental chamber (Fig. 1) was constructed from a wooden framed structure and was 4.6 m long and 1.77 m high. The environmental chamber was divided into a settling section and a test section. The settling section was 1.0 m high, 1.0 m wide and 0.85 m long. The test section was 0.45 m tall, 0.45 m wide and 2.0 m long. There was a transition nozzle in between, which was 0.64 m long. The dimensions of the settling section and test section were selected to achieve the desired uniformity and wind speed in the test section where the drying trays were placed for testing. The test section had a door with a plexiglass inspection window for loading and unloading of trays.

2.2. Radiation intensity control

Solar radiation was simulated by six equally spaced custom built 500W and 240 V quartz radiant heaters. The heaters were fitted in the roof of the test section at the height of 0.46 m. The dimensions of one radiant panel were 0.1 m by 0.36 m (MORGQFX10113 Mor Electric Heating Assoc. Inc., MI) and it held a quartz heating element (MORGQQT10305 Mor Electric Heating Assoc. Inc., MI) with an overall length of 0.31 m and the heating length of 0.2 m. The radiation intensity was controlled by a single solid state power controller (Model no. VHC 32, Fostoria Ind., TN). The radiation intensity was measured by a pyranometer (Model no. LP 02, Hukseflux Thermal Sensors, Netherlands) with a detection range of 285–3000 nm. The radiation intensity variation was measured at every 2.5 cm along the length of the test section. A standard deviation of 19 W m^{-2} was observed at a radiation intensity of 410 W m^{-2} along the length of the test section.

2.3. Vapor pressure deficit control

Temperature and humidity were controlled by a PGC 400–700 CFM vertical conditioner (Model no. 9240, Parameter Generation and Control, NC). The conditioner unit maintained the air temperature and relative humidity levels within 0.1° C and 0.5% RH, respectively from the set values in the test section. The inlet and outlet of the conditioner unit were connected to the sides of the settling section before the honeycomb and the screen (Fig. 1). The temperature and relative humidity were also recorded at one-minute interval by two temperature and humidity data loggers (Model no. UX 100-011, Onset Computer Corp., MA) placed just before the test section. Vapor pressure deficit (VPD) of air in Pa was calculated by using temperature (T) and humidity (Rh) data in the equation below.

$$VPD\,(Pa) = \left(1 - \frac{Rh}{100}\right)\left(6.11 * exp\left(\frac{17.47 * T}{239 + T}\right)\right) * 100 \qquad (1)$$

2.4. Wind speed control

The PGC unit attached to the environmental chamber provided an air flow of 0.25 $m^3\,s^{-1}$ inside the settling section. A 0.31 m diameter and 560 W axial fan (Model no. D 3702, Sukup Manufacturing Co., IA) controlled by a variable frequency drive (Model no. ATV12H055M2, Schneider Electric, France) were added to the circulation loop of the environmental chamber to change wind speed in the test section. A maximum speed of 5 m s^{-1} was attained at the center of the test section with a variation of 0.3 m s^{-1} along the height of the test section. The axial fan creates lateral mean velocity variation as well as swirls in the air flow which have to be minimized before it reaches the test section. A honeycomb, screens, and transition nozzle were used to improve the flow of air inside the wind tunnel. The details about the functionality and selection criteria of the honeycomb, screens and turning vanes is discussed in detail in the previous study (Khanchi et al., 2013). A honeycomb structure made of PVC tubing having a cell diameter of 0.0254 m and a length of 0.15 m was used in the present study. A single screen