DRYING AND STORAGE OF SWITCHGRASS

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CHAPTER I

INTRODUCTION

The rapid increase in global energy demand has directed the attention of researchers in exploring alternative energy sources. The total energy used in the year 2009 was near 150 EJ, and about 50, 19.8 and 3.2 % of the total demand was met by oil, natural gas and coal respectively (IEA, 2011). The use of fossil fuels adversely affects the environment by adding greenhouse gases such as CO_2 into the atmosphere. This is one of the major causes for global warming. With rising fossil fuel prices and environmental concerns, there is increased interest for exploring alternative energy sources that are cheap, renewable, and particularly derived from plant materials. Relying on organic plant sources for electric power generation or in the form of liquid fuel for transportation is a renewable approach. Biofuels decrease greenhouse gas emissions, support agricultural economies, and reduce dependence on foreign oil (Schmer et al., 2008). In addition, the biomass feedstock used for biofuel production, has virtually no sulfur content which offset the SO_X emissions associated with burning of fossil fuels (Turnbull, 1994). Currently, bioethanol is produced from corn, sugarcane, sweet sorghum and other sources that are rich in fermentable carbohydrates. Use of food crops for ethanol production has resulted in an increase in price of food products and other downstream animal products (Anderson & Akin, 2008).

Herbaceous and woody crops along with crop residues are considered potential sources for ethanol production (Sanderson et al., 2007). With the improvement of technologies to convert plant cell wall carbohydrates into ethanol, these plant biomass sources have a huge potential to replace depleting fossil fuels (Varvel et al., 2008). The global increase in bioethanol production was from 17.25 billion liters in the year 2000 to more than 46 billion liters in the year 2007 (Balat & Balat, 2009). Historical and projected ethanol production from 2001 to 2019 is shown in Figure 1 below. The Energy Independence and Security Act of 2007 mandates that 36 billion gallons of ethanol will be produced by the year 2022 and out of which 16 billion gallons will be from cellulosic feedstock (EPA, 2009).

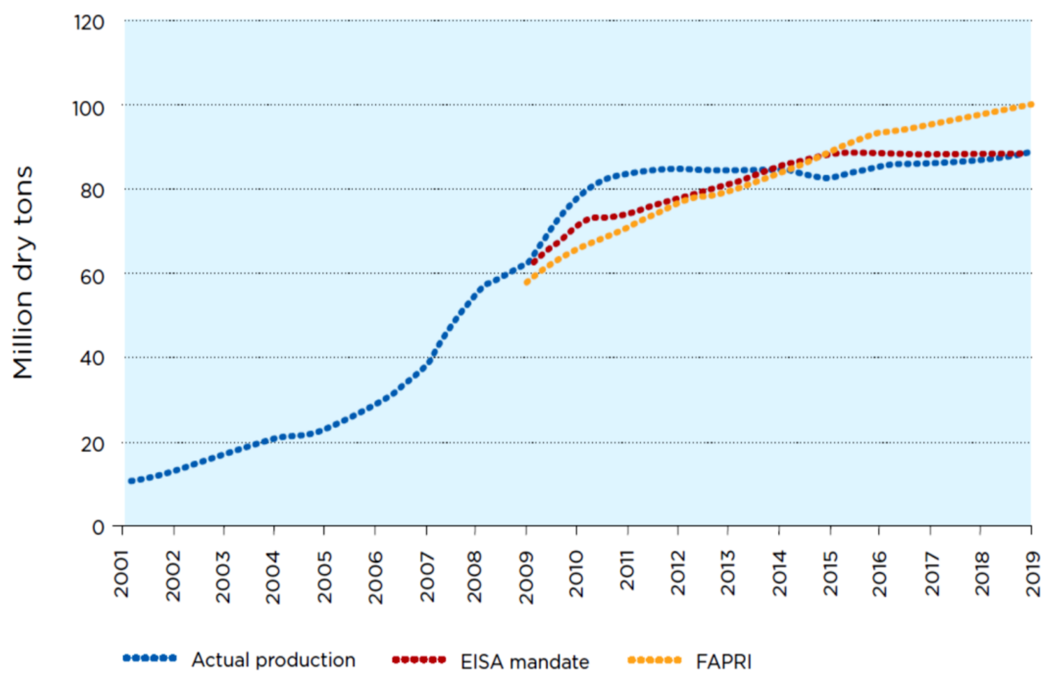

Figure 1. Historical and projected ethanol production increase from 2010 to 2019 (US Department of Energy, 2011)

However, the major barrier for the commercialization of cellulosic ethanol is the conversion process and the biomass supply chain. Researchers are studying different aspects of cellulosic ethanol production so as to make the overall system efficient and economically feasible (Balat & Balat, 2009). In addition, planting lignocellulosic biomass feedstock will require land availability, competition for water resources, use of fertilizers and pest control techniques, and competition with food and feed production etc. (IEA, 2007). Proper management and careful monitoring is required in order to make the process sustainable and environment friendly.

Biomass feedstock, such as switchgrass is recognized as potential bioenergy crops for bioethanol production. Switchgrass (*Panicum virgatum* L.) is a warm season (C_4) energy crop, native to central, midwestern, and southeastern United States (Lemus et al., 2002). Switchgrass has many advantages such as high productivity across many environments, relatively low water and nutrient requirements, suitability to marginal and erosive lands and positive environmental benefits (Sanderson et al., 2007). Switchgrass can also remove harmful residues such as atrazine and radionuclides from the soil, and helps to clear ground water from nutrient contamination (Trócsányi et al., 2009). '*Alamo'* is one of the best cultivars of switchgrass because it is well adapted to the southern United States and '*Cave-in-Rock'* is well adapted for the Mid-Atlantic northeast, and Midwest regions (McLaughlin & Adams Kszos, 2005; Sanderson et al., 2007). Annual biomass yield of 5.2 to 11.1 Mg ha^{-1} is obtained in established switchgrass fields resulting in an average estimated net energy yield of 60 GJ ha^{-1} y^{-1} (Schmer et al., 2008). Switchgrass also produced 540% more renewable energy than nonrenewable energy consumed and the estimated greenhouse gas emissions (GHG) from ethanol produced from switchgrass were 94% lower than GHG from gasoline (Schmer et al., 2008).

According to USDA/DOE Billion Ton Study, 189 billion liters of ethanol a year is required to replace 30% of the nation's transportation fuel requirement (US Department of Energy, 2005). This would require 454-544 million metric tons (400-500 million dry tons) of biomass from different crop sources (Gale et al., 2008). The updated billion ton study, estimates an availability of 370 million dry tons from forest resources and 1 billion dry tons from croplands under high yield and large scale planting scenarios (US Department of Energy, 2011). To ensure continuous availability of raw material at this scale would require storage of biomass at biorefineries or nearby sites for 6 to 12 months to avoid disruption in ethanol production during non-harvesting seasons (Wiselogel et al., 1996). Switchgrass has a wide harvest window starting from July to February of the following year (Thorsell et al., 2004). During the harvest season from July to February, switchgrass can be harvested, dried, and directly transported to the biorefinery. For the remaining months, from March to June, biorefineries will be dependent on stored biomass or alternate sources. Additionally, to reduce dry matter loss during storage, moisture content of less than 18% (wet basis) is desirable (Moore & Peterson, 1995). Switchgrass harvested at early stage of maturity have much higher moisture content and require field curing period to reduce moisture content to safe storage level. The field drying period can vary depending on crop characteristics, environmental conditions and swath structure (Barnes et al., 2007). Economic analysis, and biomass supply chain and logistics planning require estimation of storage losses as well as drying time needed for safe storage of biomass. Studies related to storage losses as well as drying time estimation of switchgrass are limited. In order to provide the lacking information, the present study has following objectives:

- Development of an empirical model to predict drying rate of switchgrass based on environmental variables and evaluate the effect of individual weather parameter on the drying rate of switchgrass
- Assessment of qualitative and quantitative losses in round and square switchgrass bales stored under different conditions

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CHAPTER II

REVIEW OF LITERATURE

2.0 Field drying

In order to provide a continuous supply of biomass to biorefineries, harvest time and frequency must be optimized. In Oklahoma, harvest frequency and nitrogen rate application were found to be the most important factors affecting the yearly yield of switchgrass (Thomason et al., 2004). A dry matter yield of 16.3, 14.7, and 12.9 Mg ha^{-1} was obtained for three, two, and one harvests per year, respectively (Thomason et al., 2004). Due to variation in harvest timing and frequency, the moisture content at the time of harvest may vary depending on the maturity stage of the crop. At young vegetative growth stage, moisture content of switchgrass averaged 70% (wet basis) and declines to 40 to 50% (wet basis) after flowering and seed set stage. Moisture content can further decline to less than 10% (wet basis) after a killing frost (Christensen & Koppenjan, 2010). For safe biomass storage, a moisture content of less than 18% is desirable (Moore & Peterson, 1995). If switchgrass is harvested in the late fall and before frost, drying in windrows is required to reduce the moisture content to safe storage level.

As the crop lies in the field, moisture migration takes place between the crop and the environment, until suitable equilibrium moisture is attained. Field drying involves both drying and rewetting processes. Moisture loss or drying occurs during the daytime hours. However, high humidity or dew at night can result in moisture gain by the crop. During field drying, plant respiration and leaching by rainfall are the major causes for loss of dry matter. Barr et al. (1995) reported a dry matter loss of 209 g kg^{-1} for a mixture of alfalfa and timothy hay during extended field drying periods. The simulation model developed during the study estimated that plant respiration and leaching accounted for 72% and 5% of the total dry matter loss respectively, during field drying (Barr et al., 1995). Initially after harvesting, the plant cells are alive and continue to respire until the moisture content of crop reduces to 30% on dry basis (Gupta et al., 1990). With production of every gram of CO_2, 0.68 grams of carbohydrates are lost from plant dry matter (Gupta et al., 1990). Rainfall results in rewetting of the partially dried crop, as well as extending the losses caused due to respiration. Leaching losses are further related to the amount of rainfall the crop receives and the moisture content of the crop at the start of a rainfall event (Gupta et al., 1990).

Several factors other than rainfall influence the drying rate of crops during field drying. Environmental factors such as solar radiation, wind speed, air temperature, relative humidity, and soil moisture affect the time required to bring the crop moisture content to safe storage level. Crop characteristics such as yield, stem diameter, leaf to stem ratio, and swath structure can increase or decrease the moisture migration during field drying (Barnes et al., 2007). Faster drying rates are obtained during sunny days, high temperatures, and dry soil when there is a thin swath. Less favorable conditions and periodic rainfall delays the drying process. Generally field drying time of grasses varies from 2 to 7 days. Drying time is reduced to 3 to 4 days when the grasses are spread in thin layers and weather conditions are favorable (Haghighi, 1990; Moore & Peterson, 1995). To better understand the field drying process and methods for improving the drying rate of biomass, some knowledge of basic moisture movement is discussed in the following sections.

2.1. Theory of drying

Two transport processes occurs at the same time during drying of agricultural material: (1) transfer of heat from external medium to the surface of agricultural material and combined with heat transfer within the material; and (2) mass transfer in terms of moisture from inside the agricultural material to the surface and then external transport of moisture to the surrounding environment. During drying energy is transferred to the agricultural material by:

- Convection, when the energy for evaporation is provided by heated air flowing over or through the material
- Radiation, from solar insolation

Heat transfer with in agricultural material generally occurs by conduction due to gradient in temperature and to a lesser extent by convection due to moisture migration (Valentas et al., 1997). Moisture movement in agricultural materials can occur by different transport mechanisms such as capillary flow due to difference in capillary suction pressure, liquid diffusion due to concentration gradients, and vapor diffusion due to partial vapor pressure gradients (Valentas et al., 1997). Agricultural materials generally dry in falling rate period in which liquid diffusion is the major mechanism. The moisture diffusion is affected by concentration difference, temperature and the structure of the product (Erbay and Icier, 2009). Mass transfer from the material to the atmosphere takes place by convection due to difference in partial vapor pressure at the boundary layer of the material and the surrounding air. During convective drying, the boundary conditions for heat flux, q_c and the evaporation rate, n_w is given by (Valentas et al., 1997):

$$\text{Heat transfer: } q_c = h_g\left(T_{sf} - T_g\right) \qquad (1)$$

$$\text{Mass transfer: } n_w = k_g\left(P_{vsf} - P_{vg}\right) \quad (2)$$

Where, h_g and k_g are the heat and mass transfer coefficients, T is the temperature, P_v is the partial vapor pressure of water, and sf and g represent surface and gas respectively. Drying processes are generally explained by two types of model: (1) distributed models and (2) lumped parameter models.

2.1.1. Distributed models: These models consider both heat and mass transfer simultaneously. Distributed models predict the temperature and moisture gradient more accurately as they take into account both internal and external heat and mass transfer (Erbay and Icier, 2009). These models are derived from Fick's second law of diffusion or their modified forms (Luikov, 1975):

$$\frac{\partial \mathrm{M}}{\partial \mathrm{t}} = \nabla^2 K_{11} M + \nabla^2 K_{12} T + \nabla^2 K_{13} P$$

$$\frac{\partial \mathrm{T}}{\partial \mathrm{t}} = \nabla^2 K_{21} M + \nabla^2 K_{22} T + \nabla^2 K_{23} P$$

$$\frac{\partial \mathrm{P}}{\partial \mathrm{t}} = \nabla^2 K_{31} M + \nabla^2 K_{32} T + \nabla^2 K_{33} P \quad (3)$$

Where, M is the moisture content, T is the temperature, P is the pressure, t is the time, K_{11}, K_{22}, K_{33} are the phenomenological coefficients, and K_{12}, K_{13}, K_{21}, K_{23}, K_{31}, K_{32} are the coupling coefficients (Luikov, 1975).

For most of the processes, the effect of pressure can be neglected in comparison to the effect of temperature and moisture (Brooker et al., 1974), therefor the eq (3) can be simplified to eq (4) below:

$$\frac{\partial \mathrm{M}}{\partial \mathrm{t}} = \nabla^2 K_{11} M + \nabla^2 K_{12} T$$

$$\frac{\partial T}{\partial t} = \nabla^2 K_{21} M + \nabla^2 K_{22} T \qquad (4)$$

2.1.2. Lumped parameter models: These models do not consider the temperature variation with the product and assume a uniform temperature distribution equal to the drying temperature of air. This assumption further simplifies the eq (4) to eq (5) below:

$$\frac{\partial M}{\partial t} = K_{11} \nabla^2 M$$

$$\frac{\partial T}{\partial t} = K_{22} \nabla^2 T \qquad (5)$$

Phenomenological coefficient K_{11} is known as effective moisture diffusivity (D_{eff}) and K_{22} is known as thermal diffusivity (α). For constant values of D_{eff} and α, eq (5) can be arranged as (Erbay and Icier, 2009):

$$\frac{\partial M}{\partial t} = D_{eff} \left[\frac{\partial^2 M}{\partial x^2} + \frac{a_1}{x} \frac{\partial M}{\partial x} \right]$$

$$\frac{\partial T}{\partial t} = \alpha \left[\frac{\partial^2 T}{\partial x^2} + \frac{a_1}{x} \frac{\partial T}{\partial x} \right] \qquad (6)$$

Where, a_1=0 for planar geometries, a_1 = 1 for cylindrical shapes and, a_1 = 2 for spherical shapes.

The assumption used in lump parameter models regarding uniform temperature distribution with in a material result in errors. These errors can be minimized by reducing the thickness of the material and doing thin layer drying studies.

2.2. Principles of moisture movement:

The major goal of the field drying process is to remove moisture from the crop and reduce it to a level which is safe for storage. Water present in cytoplasm makes up 50% to 95% of total plant water content (Moore & Peterson, 1995). Other than the cytoplasm, water is also present in xylem, cell walls and, intercellular spaces (Hill, 1976). Moisture movement between the crop and environment take place by three major interrelated processes: evaporation, condensation and diffusion (Hill, 1976; Moore & Peterson, 1995). The water present in the plant tissues moves to the plant surface and from there, the moisture evaporates based on the environmental conditions present at that time.

2.2.1 Moisture movement within the plant

Field drying begins with the mowing of a living plant. In plants, water continuously moves from roots to leaves and then converts to water vapor by absorption of solar energy. This process is called transpiration. Water moves through xylem and parenchyma in the core of the stem to the leaf (Moore & Peterson, 1995). Loss of water from the leaf causes a moisture gradient within the plant. To neutralize the gradient, more water is drawn from the soil and the process continues in a living plant. During this process, most of the water leaves the plant surface through small holes called stomata, present on the leaf surface. These small holes in the epidermis cover only 1 to 3% of the plant surface, but about 80 to 90% of moisture leaving the plant surface passes through them (Moore & Peterson, 1995). Moisture present in the intercellular spaces reaches to the surface and evaporates freely when the stomata are open. Initially, when the crop is mowed and laid in the field to dry, water loss continues as in living plants. Since the stem and leaves are no longer in contact with roots, the moisture which is lost through stem and leaves is not replaced (Moore & Peterson, 1995). This initiates the drying process. Stomata openings may increase initially after mowing, but they decrease after a couple of hours as the plant senses a moisture stress (Bartzanas et al., 2010). As stomata close, the moisture loss or drying rate decreases. The rate of diffusion into the atmosphere is restricted by the moisture gradient, air resistance and the resistance offered by stomata (Hill 1976). Before the stomata are closed, about a third of initial water is lost during this period (Moore and Peterson 1995). The moisture is removed quickly during the initial drying phase of crops, until the intercellular moisture is removed. Most of the remaining water is now within the cells, which is removed slowly due to resistance offered by cell walls and membranes and thus decreases the drying rate (Hill, 1976). As drying continues, moisture moves both axially along the stem and radially towards the surface of the stem. As the moisture reduces to 400g kg^{-1}, air pockets and dried tissue develops in the xylem and parenchyma (Barnes et al., 2007). The formation of air pockets break the moisture gradient within the plant which results in no further moisture movement through this pathway.

As the axial movement of moisture slows, radial movement becomes the major pathway for further moisture loss. The drying rate further slows down due to higher resistance to water loss along the radial direction. The radial diffusivity of moisture in alfalfa stems was found to be 10 times less than in axial direction (Moore & Peterson, 1995). The waxy epidermal layer is the primary restraint with diffusivity 1000 times less than the radial diffusivity (Moore & Peterson, 1995). Removal of epidermis layer can greatly increase the moisture loss from grasses at low moisture contents (Haghighi, 1990). Drying rate can also be improved by reducing the length of stem by the crimping process known as conditioning. Patil et al. (1992) found that the drying rate constant decreases logarithmically with increase in stem length and is given by the relation below:

$$k = 0.133\, L^{-0.48}$$

Where, L is the stem length (mm) and k is the drying rate constant (min^{-1})

In order to compliment the drying process, several machines have been developed that crush stems to hasten the drying process. The conditioning and crimping process exposes the moisture present inside the plant tissues to the drying environment and therefore overcomes the resistance offered by cuticle layer (Hill, 1976).

2.2.2 Moisture movement to the environment

Once the moisture reaches the plant surface, it evaporates and leaves the plant. As the moisture is converted to vapor, the moisture moves away by the principles of moisture diffusion. In a dense swath, the air within the swath structure is nearly saturated, holding as much water vapor as it can at that temperature (Moore & Peterson, 1995). As the temperature of air increases, the amount of water vapor it can hold also increases. The vapor pressure of ambient air increases with increase in relative humidity and reaches a maximum value when the relative humidity is close to 100%. The difference in vapor pressure between the plant surface and the ambient atmosphere is therefore dependent on the temperature of air within the swath and the relative humidity of surrounding atmosphere (Moore & Peterson, 1995). Moisture moves from the relatively high vapor pressure at the plant surface to low vapor pressure of the ambient air. Drying rate of crop increases as the vapor pressure deficit between the plant surface and ambient atmosphere increases. When the relative humidity of ambient atmosphere is high such as during night or rainfall, the vapor pressure gradient may reverse and the moisture goes back to the plant and deposited as dew.

The drying rate of grass in the field depends on crop characteristics, swath structure and the surrounding environment. In general, all these factors have some effect on limiting the drying rate of cut grass. For instance, when environmental conditions are not favorable for drying such as low temperature, high relative humidity, and low solar radiation, the vapor pressure deficit is low. At low vapor pressure deficits a little amount of moisture moves from the plant surface to the ambient environment. Spreading the swath or conditioning the crop will have little effect on drying rate, as environmental act as a dominating constraint to moisture movement (Moore & Peterson, 1995).

Similarly, when the crop is laid in a thick swath, the crop dries at a slower rate, even though the drying conditions are favorable. Conditioning might have a little effect on drying rate as the moisture cannot escape rapidly due to the thick swath and less air movement. In this case, the swath structure acts as a dominating constraint to the drying process. On the other hand, when the grass is dried in a thin open swath under favorable drying conditions, the plant becomes the predominant constraint to moisture movement. Drying rate can be increased in this scenario by providing mechanical treatments such as crushing, crimping or other treatments to the plant.

2.3 Factors affecting the drying rate of cut grass

As discussed in earlier section, plant, swath structure, and environmental variables affect the drying rate and extent of grass drying. Under certain conditions, grass dries to very low moisture content safe for storage, whereas, in other conditions grass may lie in the field for days with a moisture content of 300 to 400g kg^{-1}(Moore & Peterson, 1995). The extent to which a crop dries depends on equilibrium moisture content which is further related to environmental conditions and crop characteristics. Effect of crop characteristics, swath structure and environmental conditions on drying rate of biomass is discussed in detail in the following section.

2.3.1 Effect of crop characteristics on drying rate

Crop factors that impact the drying rate are the initial moisture content, variety or species, and physical characteristics (Moore & Peterson, 1995). Initial moisture content varies with crop maturity, environmental conditions and time of day, with maturity stage having the highest affect. Wright et al. (2001) found a quadratic trend between moisture content and number of days after planting. They concluded that it is important to include initial moisture content of grass, while developing any grass drying rate model. During early stages of maturity, plants have a moisture content varying from 80 to 85% on wet basis. As the crop matures and comes to a reproductive stage, the moisture reduces to as low as 60% wet basis (Moore and Peterson, 1995). Womac et al.(2005) reported that moisture content of corn stover harvested early (34.1% wet basis) was significantly higher than late harvest (15.3% wet basis). Crops with higher initial moisture content take a longer time to dry than crops with low initial moisture content. Patil et al. (1992)

reported a saving of 43% in drying time, when alfalfa was harvested at 10% bloom (68% wet basis) stage instead of pre-bloom (85% wet basis) stage. During lab drying of timothy hay, Savoie & Mailhot (1986) found that initial moisture content and drying rate are negatively correlated (r=0.5723). Timothy hay at a higher initial moisture content dries at a slower rate than timothy hay at lower initial moisture content (Savoie & Mailhot, 1986). During later reproductive stages, the stems of the grasses have more exposure to environment than early vegetative stages and thus dry faster compared to the vegetative stage (Haghighi, 1990). It was also reported that the drying rate of crop was also affected by density of material per unit area. During thin layer drying under lab conditions, biomass at vegetative stage of maturity dries at a faster rate than in reproductive stage of maturity (Moore & Peterson, 1995). Immature plants have higher initial moisture content, thinner stems and less cuticle layer thickness, which results in a faster drying rate. But, in case of field drying, a younger, leafy crop may dry at a lower rate than a mature crop as they fall in a denser swath which slows the drying rate (Smith, 1990b).

Moisture content is generally higher during early morning hours and lowest in afternoon. Womac et al (2005) reported that corn stover moisture was significantly higher in the morning (38.3 % wet basis) compared to afternoon (26.7% wet basis). When the drying conditions are favorable, the amount of water lost by plants is more than the water replenished by the roots which results in 30% less moisture in late afternoon compared to early morning (Moore and Peterson, 1995). In addition, moisture content was also found to be lower in late evenings. To evaluate the effect of initial moisture content on storage losses, Shinners et al. (1996) conducted baling at three different times in a day. They found that alfalfa baled in June at 1530, 1845, and 2000 h had a moisture content of 16.18, 17.95, and 21.2% on wet basis, respectively. The bales which were stored at low, intermediate and high initial moisture content lost 4.4, 3.6 and 15.7% of dry matter, respectively.

Physical characteristics such as thickness of epicuticular wax also vary among different crops, varieties and cultivars, which results in variation of drying rate (Smith, 1990b). Additionally, species having a higher surface area to dry weight ratio, dries faster due to more exposure to the drying elements (Moore & Peterson, 1995). Due to higher exposed surface area of leaves compared to stems, leaves dry at a much faster rate (Smith, 1990b). Leaves also function as a natural pathway for transpiration of water through stomata openings. Under similar conditions, leafy forage dries faster than forage having less leaves (Clothier & Taylor, 1980). Haghighi (1990) found that, cocksfoot and ryegrass leaves dry approximately four times faster than their stems. Drying rate is also affected by the stem diameter, as thicker stems dry at a slower rate. In the later stages, when the moisture drops below 40% wet basis, water only flows along the radial direction which is restricted by the thickness of the stem (Moore & Peterson, 1995).

2.3.2 Effect of swath structure on drying rate

Density and thickness of the windrow significantly impact the drying rate of crop in the field (Smith, 1990b). Thickness of the windrow is the distance between the top and the bottom layer of biomass, and is controlled by width of the swath and the yield of biomass. A windrow of biomass lying in the field can be considered as several layers of biomass lying on top of each other. The windrow moisture content at any time during drying is the mean of moisture content in different layers. Spreading the swath in a wider area results in better drying rates. Wright et al. (1997) observed that on the initial day of field drying, weight of grass per unit area was a major factor influencing the field drying rate. When the weight of unconditioned ryegrass was reduced from 6 to 3 kg m^{-2}, the drying rate increased by 47% (Wright et al., 1997). Higher yield and narrow width results in higher density windrow, which dry at a slower rate compared to a thin and wide swath containing the same amount of biomass (Moore & Peterson, 1995). Shearer et al (1992) reported a significant increase in the drying rate of alfalfa, when the crop was placed in wide swath, instead of narrow windrows. Drying coefficients increased by 35% and 152% for 3rd and 4th cutting respectively, when the alfalfa was dried in wide swath, instead of narrow windrows.

The upper layer of biomass absorbs and reflects the maximum amount of solar energy and therefore comparatively much less solar energy reaches the lower layers. Firth and Leshem (1976) reported that when herbage was dried in windrows, the top layer took 13 hours to dry, compared to 80 hours for middle layers. In contrast, the bottom and top layers of a thin swath, 3 to 5 cm in height dry at a same rate (Clothier & Taylor, 1980). A thick windrow also creates a barrier to convective air currents which carry moisture away from the lower layers to the ambient atmosphere. Turning or inversion of the swath helps to improve the drying rate, as it exposes the wet lower layers to the more favorable drying environment (Smith, 1990b). Freshly harvested biomass is high in initial moisture content and forms a dense windrow that resists wind penetration. Wind circulation through the windrow can be improved by making the windrow more fluffy using a raking operation. Sometimes, after the raking operation the biomass again settles into a thick windrow which restricts further drying. This can be avoided by performing the raking operation when the biomass is relatively dry (Moore and Peterson 1995).

The effect of conditioning is also enhanced when the crop is dried in wide swath instead of narrow windrows (Smith, 1990b). Wright et al. (1997) reported that during the field drying of ryegrass, the benefit of conditioning over no conditioning was dependent on the grass density and initial dry matter content. When the initial dry matter was high (>150 g kg^{-1}) and grass density was low (<6 kg m^{-2}), conditioning treatments resulted in higher drying rates over no conditioning of ryegrass. When the density of grass was high (12 kg m^{-2}), the drying rate of unconditioned ryegrass (0.73 day^{-1}) was higher than mower conditioned (0.70 day^{-1}) and flail treated (0.51 day^{-1}) ryegrass. Extensively conditioned ryegrass at higher grass densities (6, 12, 24 kg $m-^{2}$) dried more slowly than the respective unconditioned ryegrass, showing negative effects of conditioning

(Wright et al., 1997). These findings suggest that drying grass in wide swaths is the most important factor that affects the drying rate of crops.

Dry matter loss during rainfall is also dependent on the concentration of crop per unit area and degree of conditioning. Wright et al. (1997) reported that during rainfall, unconditioned ryegrass dried at a density of 12 kg m^{-2} gained 82% less water than unconditioned ryegrass dried at 3 kg m^{-2}. Womac et al. (2005) also reported that corn stover which was harvested by a combine harvester absorbed more moisture after rainfall than mowed stover. Conditioning caused by combine harvester increased the exposure of internal components of corn stover, resulting in higher moisture uptake.

2.3.3 Effect of environmental factors on drying rate of cut grass

The surrounding weather and soil surface make the environment for field curing of biomass. Weather parameters have a more prominent effect on the drying rate of crop than soil surface (Moore & Peterson, 1995). Weather parameters such as solar radiation, air temperature, relative humidity and wind velocity impact the drying rate of biomass. These weather parameters are highly correlated and make it difficult to analyze the effect of individual parameter on drying rate of biomass (Borreani & Tabacco, 1998).

2.3.3.1 Effect of solar radiation on drying rate

From all the environmental factors solar radiation has the highest impact on drying rate (Bartzanas et al., 2010; Haghighi, 1990; Smith, 1990). Field drying rates of biomass are low or negligible when the sunlight is not available. When all other variables are kept constant, a 10 time increase in drying rate was observed between the minimum and maximum values of solar radiation (Moore & Peterson, 1995). Under lab drying conditions, Savoie & Mailhot (1986) found that radiation intensity was positively correlated (r=0.5420) with drying rate of timothy hay. Most of the solar radiation received by the crop during early morning hours is utilized as latent heat by the swath (Smith, 1990b). In the late afternoon, the solar radiation provides sensible heat to the swath which is utilized in increasing the temperature of the crop. This sensible heat is simultaneously lost to the atmosphere and is accelerated by an increase in wind speed (Smith, 1990b). Moreover, low solar radiation intensity can result in lower temperatures and higher relative humidity which slows drying.

Absorptivity of solar radiation by crop also changes as the crop dries in the field. During the start of the drying process when the moisture content is high, the absorptivity of biomass is around 80% (Ajibola et al., 1980). The absorptivity decreases to less than 50% for the later drying period which reduces the drying rate (Moore & Peterson, 1995). The thickness of the swath also affects the amount of radiation intensity absorbed by the crop. In a thick swath, radiation intensity below 2 cm of the top layer is approximately half of that is available at the surface. At the bottom layers, it further reduces to less than 10% to the available amount at the surface (Clark, 1966). Therefore, drying in wide swaths is recommended to achieve faster drying rates.

2.3.3.2 Effect of vapor pressure deficit on drying rate

The other important weather parameter affecting the drying rate of biomass is vapor pressure deficit (VPD) (Haghighi, 1990; Moore & Peterson, 1995). VPD is a measure of the drying power of air and is obtained by the difference of actual vapor pressure and the total vapor pressure at a given air temperature (Wright et al., 2000). Savoie & Mailhot (1986) found that VPD was positively correlated (r=0.3605) with drying rate of timothy hay. The gradient in vapor pressure is controlled by temperature of biomass and relative humidity of the surrounding air. When the radiant energy is falling on the biomass, some of the energy is reflected back to the environment and a part of the energy is absorbed by biomass. The absorbed energy can increase the temperature of biomass by up to 20 °C above that of ambient air (Moore & Peterson, 1995). Therefore, solar radiation also has an affect together with air temperature and relative humidity on the drying rate of biomass. Relative humidity (RH) has a small effect on drying during sunny days. However, under cloudy conditions, RH can have a greater impact on the drying rate. In general, lower humidity favors the drying of biomass. On sunny days, when RH is less than 60%, VPD is high enough to reduce the moisture content of biomass to a safe storage level (Moore & Peterson, 1995). However, under low solar radiation, RH can be a greater constraint to the drying of crop. With high RH and low temperature, vapor pressure deficit decreases and results in slower drying of crop (Borreani & Tabacco, 1998; Moore & Peterson, 1995).

2.3.3.3 Effect of wind speed on drying rate

The effect of wind speed on drying rate of swaths is related with initial moisture content of crop and solar radiation intensity. Savoie & Mailhot (1986) found a weak correlation (r=0.0266) of wind speed with drying rate of timothy hay. When the swath has high initial moisture content, increase in wind speed improves the drying rate. However, when the initial moisture content is low, increase in wind speed reduces the drying rate (Smith et al., 1988). During early harvesting (high moisture), a correlation coefficient of 0.22 was observed between wind speed and drying rate of field dried corn stover, suggesting wind speed has a slight positive effect on drying. However, during late harvest (low moisture) of corn stover, a correlation coefficient of -0.24 was observed suggesting an inverse relationship of wind speed with drying rate (Womac et al., 2005). Also, models based on Penman-Monteith model assume that the evaporation rate from a wet surface increases with increase in wind speed. However, it was observed that, in case of crops, drying rate decreases with increase in wind speed under high solar radiation intensity conditions (Bartzanas et al., 2010, Smith, 1990b). This happens because a part of heat energy used to increase the temperature of the swath is carried away by the wind. However, when the radiation intensity is low the effect of wind is to improve the drying rate depending on the temperature of drying air. A variable effect of wind speed was also observed by (Wright et al., 2000) during lab drying of ryegrass. When the initial dry matter concentration was low (<160 g kg^{-1}) and solar radiation intensity was low, the wind speed of 3 ms^{-1} increased the drying rate of ryegrass. This suggests that during early maturity stages when the dry matter concentration is low and the days are not sunny, the crop should be laid in fluffy or low material density swath to promote drying by wind (Wright et al., 2000). However, when the initial dry matter concentration was high (>210 g kg^{-1}) and solar radiation intensity was high (432 W m^{-2}), the effect of wind speed was to decrease the drying rate. This finding suggests that during late maturity stages when the crops are relatively dry and weather is sunny, the increase in wind speed results in slow drying rates. It was also reported that, if the grass has surface moisture due to rainfall or dew, than increase in wind speed is beneficial for drying process (Smith, 1990b).

2.3.3.4 Effect of soil moisture on drying rate

Soil is an environmental factor which can impact the drying rate of biomass. Soil moisture is more important than soil temperature. If the biomass is lying on a wet soil then the vapor pressure near the soil surface can be higher than the vapor pressure in swath. This gradient can cause moisture movement from soil to the biomass, resulting in prolonged drying period (Borreani & Tabacco, 1998). Womac et al. (2005) found that the stover which was in contact with the ground had the highest moisture content throughout the drying period compared to other layers. Raking can also be used to make narrow fluffy windrows which helps to expose the wet soil to solar radiation. Uniform stubble of at least 50 to 75 cm also helps to restrict moisture movement between the windrows and soil surface (Haghighi, 1990; Moore & Peterson, 1995; Smith, 1990).

2.4 Drying simulation modeling

The main objective of field drying studies is to develop mathematical models which can predict the time needed to dry a crop, depending on the weather conditions at time of drying. In addition, the effect of an individual weather parameter on the drying rate of cut crops is of particular interest. A number of models have been developed, that can simulate the environment and conditioning effects on field drying of crops. Both field drying and lab drying studies have been conducted to evaluate the effect of crop architecture, weather conditions, and plant characteristics. A model was developed by Hill et al. (1977) to use vapor pressure deficit to predict drying time of alfalfa hay. Rotz and Chen (1985) collected data from 1977 to 1984 from field drying experiments, to determine the effect of environmental factors on in-field drying rate of alfalfa. Savoie & Mailhot (1986) evaluated the effect of eight factors: dry bulb temperature, vapor pressure deficit, wind speed, radiation, conditioning, soil moisture, forage density and initial moisture content on drying rate of timothy hay. Lamond et al. (1989) also studied the effect of thin layer drying rate and swath architecture on the drying rate of swath under controlled conditions. An automated chamber was developed by Thibault et al. (1991a) to simulate field drying conditions of air temperature, relative humidity, wind speed and solar radiation for timothy hay. A mathematical model was also developed by Wright et al. (2001) to predict drying rate of cut ryegrass. They evaluated the effect of material density, effect of conditioning and effect of inverting and mixing on the drying rate of ryegrass. The models developed by several authors during field and lab drying studies of crops are provided in Table 2.1.

The mathematical models for field drying of crops can be divided into two major groups. The first group uses an analytical approach to model the physical processes, affecting the drying of crops. This analytical approach results in a large number of equations. The second approach uses empirical modeling techniques, which are based on field trials and results in a smaller number of equations. Both models give good results if they are fitted in the range of variables,

Table. 2.1. Review on empirical models developed from field and lab drying studies of crops

Ref.	**Crop**	**Location**	**Drying rate model**	**Drying rate Constant**	R^2	**Description of variables**
(Savoie et al., 1982)	Alfalfa	Field	$\frac{dM}{dt} = -k\,(M - EMC)^c$	k = -0.016+0.000104*S_h + 0.00555*T - 0.00000734*D + 0.019722*RF + 0.029649*CF	0.35	S_h= Solar Radiation (J/s/m2), T= Dry bulb temperature (°C), D=Dry matter density (Kg/ha), RF= raking factor, CF= Conditioning factor K= Drying rate constant (h^{-1})
(Womac et al., 2005)	Corn Stover	Field	Combine-harvested Stover : MC =-85.12-0.05* DAW+2.97*SM+9.02*R+0.77*RH+9.06*E Mower-harvested stover: MC =-27.31-0.23* DAW+1.16*SM+2.96*R+0.28*RH+3.57*E		0.61 0.5	MC=Moisture content (%wb) DAW= Days after sowing, SM= Soil moisture (%wb), R= Rainfall (mm), RH= relative humidity (%), E= Evapotranspiration (mm/day)
(Lamond et al., 1989)	Grass	Lab	$\frac{M - M_e}{M_o - M_e} = e^{-kt^{0.63}}$	**Conditioned:** k=-0.0182-0.0248 T+0.0056 ($T^{1.5}$)-0.1367 ln(Lr) + 0.212 ln(Mo)	0.94	T=Temperature (°C), Lr=Leaf to stem ratio, Mo=Initial Moisture Content
				Unconditioned: k=0.1222-0.0257 T+0.0052 ($T^{1.5}$) - 0.0973 ln(Lr) + 0.0938 ln(Mo)	0.95	
(Savoie & Mailhot, 1986)	Timothy grass	Lab	$\frac{M - M_e}{M_o - M_e} = e^{-kt}$	Only drying rates were compared	0.99	Me= Equilibrium Moisture content Mo=Initial Moisture content M= Moisture content at time t T= Time in hr K= drying rate constant (hr^{-1})
			$\frac{M - M_e}{M_o - M_e} = e^{-kt^{0.879}}$		0.99	
(Wright et al., 2000)	Rye grass	Lab	$M(t) = e^{\alpha - \gamma^{E(t)}}$	Only drying rates were compared		M(t)= Moisture Content (%dry basis) at time t, α= log transformed initial moisture content(%dry basis), E(t)= accumulated evaporation parameters up to time t, ϒ= drying rate constant in terms of particular evaporation parameter

Table. 2.1. Review on empirical models developed from field and lab drying studies of crops (continued)

Ref.	Crop	Location	Drying rate model	Drying rate Constant	R^2	Description of variables
(Lamond et al., 1989)	Grass swath	Lab	$\ln\left(\frac{M-M_e}{M_o-M_e}\right) = -B(-\ln(1-MR))^m\ t$	Only drying rates were compared		B and m are constants
(Patil et al., 1992)	Alfalfa	Lab	$\frac{M-M_e}{M_o-M_e} = e^{-kt}$	k = 0.133 $L^{(-0.48)}$	0.97	L= Stem length (mm), k= drying constant (min^{-1})
(Hill et al., 1977)	Alfalfa	Lab	$\frac{M-M_e}{M_o-M_e} = e^{-kt^{0.8}}$	k= 0.007 (VPD)+0.1164		VPD= Vapor pressure Deficit (milibars), k= drying constant (hr^{-1})
(Sokhansanj & Patil, 1996)	Alfalfa	Lab	$\frac{M-M_e}{M_o-M_e} = e^{-kt^n}$	**For Stems:** k=4.1*10-2$E^{(-0.409*Mt+3.04*10-2*T-3.06*10-5*T2-1.07*10-3*T)}$	0.97	M= Moisture content at time t (%dry basis), T= temperature (°C) Me= Equilibrium Moisture content (%dry basis), Mo=Initial Moisture content (%dry basis), M= Moisture content at time t (%dry basis), t= Time in hr k= drying rate constant (hr^{-1})
				n=0.34 $e^{(0.12*Mt+1.07*10-2*T-2.39*10-5*T2)}$	0.85	
				For Leaves: k=1.4*$10^{-2}e^{(-5.16*10-2*Mt+5.85*10-2*T-6.27*10-5*T2-6.68*10-3*Mt*T)}$	0.96	
				n=0.31$e^{(0.842*Mt+1.26*10-2*T-2.11*10-5*T2-2.02*10-4*Mt2-1.35*10-3*Mt*T)}$	0.89	

Table. 2.1. Review on empirical models developed from field and lab drying studies of crops (continued)

Ref.	**Crop**	**Location**	**Drying rate model**	**Drying rate Constant**	R^2	**Description of variables**
(Patil et al., 1993)	Alfalfa	Lab	$\frac{M-M_e}{M_o-M_e}=e^{-k_1 t}$	**For Single term model drying constant:** **Leaves:** M_o=14.1, M_e=1.8, K_1=0.23 **Stems:** Mo=26.2, Me=2.2, K1=0.16 **For Stems+ Leaves:** Mo=21.8, Me=3.3, K1=0.15 **Crushed Stems:** Mo=21.2, Me=2.0, K1=0.24		Mo= initial Moisture Contet(% dry basis), Me= Equilibrium Moisture Content (% dry basis), k_1,k_2=Drying Constants (min^{-1}), a and b= constants
			$\frac{M-M_e}{M_o-M_e}= e^{-k_2 t}+(1-a)e^{(-k_2 bt)}$	**For two term model drying constant:** **Leaves:** a=0.84, b=0.016, k2=0.36 **Stems:** a=0.85, b=0.074, k2=0.220 **For Stems+ Leaves:** a=0.87, b=0.037, k2=0.207 **Crushed Stems:** Mo=0.89, Me=0.033, K1=0.311		
(Thibault et al., 1991)	Forage	Lab	$\frac{M-M_e}{M_o-M_e}=e^{-k_1 t}$	Only drying rates were compared		Mo= initial Moisture Contet(% dry basis), Me= Equilibrium Moisture Content (% dry basis), k_1=Drying Constants (min^{-1}),
(Hill, 1976)	Alfalfa	Lab Field	$\frac{M-M_e}{M_o-M_e}=e^{-kt^{0.8}}$ $M_n=M_o e^{[-a\sum_{i=1}^{n} PE_i]}$	k= 0.008 (VPD)+0.098 Evap = 0.1125 (VPD) + 0.1784 (Barlow et al.) + 0.004923 (Sun) -2.032		k= Drying constant (hr-1) M_n= Moisture content at the end of n th day, a= Weighting factor characteristics of a material, PE_i = Potential evaporation on the ith day after cutting, Evap= Total daily pan evaporation in mm, VPD= Vapor pressure deficit in mbar, Wind=Wind speed in km/h, Sun= Solar radiation in Ly/day

used to develop each model (Erbay & Icier, 2010). Analytical models are derived using energy and mass balance equations. In most cases, energy balance model use the Penman-Monteith equation to calculate the evapotranspiration from crop surface by including the effects of radiation, wind and vapor pressure deficit (Bartzanas et al., 2010). In other cases, differential equations are developed by using numerical methods, which provide accurate solutions for drying of crops (Mujumdar, 2004).

For the empirical drying model given by equation 1, which is based on field drying data and environmental variables, the crop is presumed to dry following a single term exponential relationship. Smith (1990) described that most common model used for describing falling rate period of crops is

$$\frac{M - M_e}{M_{o-} M_e} = e^{-k(t)} \qquad (7)$$

Where, M is the moisture content (% wet basis) at time t, M_o is initial moisture content (% wet basis) of crop, M_e is the equilibrium moisture content (% wet basis) and k is the drying rate constant.

Several authors use a combination of linear and exponential functions with some parameters that are fitted to the thin layer drying data (Smith, 1990b). The equilibrium moisture content is assumed to be negligible when drying in field conditions. Generally, the equilibrium moisture content of crop is related to its physical characteristics, ambient temperature and humidity (Mujumdar, 2004). As the initial moisture content of forage is high during early maturity stages, equilibrium moisture content is also high (Savoie & Mailhot, 1986). As the crop becomes more mature, the initial moisture content and equilibrium moisture content of the crop decreases. The error in neglecting the equilibrium moisture content is minimal when the initial moisture content in the crop is less than 50% (Mujumdar, 2004).

The empirical drying rate model developed by Rotz and Chen (1985) for alfalfa drying in the field is also given by equation 1 above.The model was found a better fit when the equilibrium moisture content was set to zero. They found that, when alfalfa was dried under sun, and with moisture range above 20%, equilibrium moisture content had little or no influence on drying. The equilibrium moisture content was therefore set to zero, which gave a simplified equation below:

$$M = M_o e^{-k(t)} \qquad (8)$$

The environmental variables selected in the model which influence the drying rate constant (k) of alfalfa are solar insolation, swath temperature, dry bulb temperature, vapor pressure deficit, chemical application rate, forage moisture content, relative humidity, swath density, day indicator, soil moisture content, wind speed, forage crop cutting number and crop maturity. The day indicator (Spath & Dayton) is 1 during the first drying day and 0 otherwise. The drying rate constant k in eq (2) is given by:

$$k = \frac{S\big(1 + 9.03\ (AR)\big) + 43.8\ (VPD)}{61.4\ (SM) + SD\ \big(1.82 - 0.83\ (DAY)\big)\big(1.68 + 24.8\ (AR)\big) + 2767}$$

Where, S is the solar insolation on a horizontal surface, W/m^2; AR is the application rate of chemical solution, g sol/g dry matter; SM is the soil moisture content on % dry basis; SD is the swath density, g/m^2

Predicting the in-field drying rates of a crop is important to maintain the quality and quantity of harvested biomass. The study of parameters during field experiments may require several years of experimentation to cover a wide range of variables. Rotz and Chen (1985) collected data from 1977 to 1984, to develop a model (given above) that can determine the effect of environmental factors on in-field drying rate of alfalfa. The weather parameters are correlated with each other and moreover, the environmental conditions change continuously with time. All of these environmental and fieldvariations make it difficult to understand the effect of individual weather parameters on the drying rate of the crop, when evaluating under field conditions.

Alternatively, useful data can be collected in much less time by using drying chambers to cover a wide range of parameters. It is difficult to simulate the exact conditions of the field in the lab drying chambers, but lab conditions offer more control over the variables that affect the drying rate. To better understand the effect of these variables, thin layer drying of crop under controlled conditions is helpful (Lamond & Graham, 1993). The data obtained from thin layer drying experiments can provide a better understanding of physical processes by which moisture is removed from crops (Menzies & O'Callaghan, 1971). A layer of material is considered to be thin when a single layer of material is dried. During thin layer drying the grass dries under the same, constant values of air temperature, humidity and wind speed (Haghighi, 1990). Field drying of crops in windrows can be assumed as drying of series of thin layers of crop, lying on top of each other. The overall drying rate of windrows can be estimated from the drying rate of each successive layer (Lamond & Graham, 1993). Lamond et al. (1989) related thin layer drying rates of a mixture of grasses to swath drying under controlled air conditions.

Thin layer drying models can be theoretical, semi-theoretical and empirical in nature. Theoretical models consider only the internal resistance offered by the product to moisture transfer. On the other hand, the empirical models take into account the external resistance to moisture transfer between the product and air (Erbay & Icier, 2010). Theoretical models can be used at all process conditions, but they also include many assumptions which result in substantial errors during calculations (Erbay & Icier, 2010). Theoretical models are generally derived from Fick’s second law of diffusion. Semi-theoretical models are also derived from Fick’s second law and modifications of its simplified forms, and Newton’s law of cooling (Erbay & Icier, 2010). Semi-theoretical models are easier to use, and require less assumption; as they include experimental data during calculations. Empirical models are rather similar to semi-empirical models, but are strongly dependent on experimental data, providing limited information about the drying behavior of products (Erbay & Icier, 2010). Semi theoretical models which are used in the present switchgrass drying study can be categorized according to their derivation as:

1) Newton's law of cooling: Derived from Newton's law of cooling, the models can be sub grouped as:
    a. Lewis model
    b. Page model and modified forms
2) Fick's second law of diffusion: The models in this group are derived from Fick's second law of diffusion. These can be sub grouped as:
    a. Single term exponential model and modified forms
    b. Two term exponential models and modified forms
    c. Three term exponential model

2.4.1. Models derived from Newton's law of cooling:

a. Lewis (Newton) Model: This model suggests that, during the drying of porous hygroscopic material, the change of moisture content in the falling rate period is proportional to the difference between the moisture content and the expected moisture content, as it comes in equilibrium with the drying air at that instant (Erbay & Icier, 2010). This method assumed that the material is thin, or the air velocity is high enough, and the drying condition such as temperature and relative humidity are kept constant. The model is given as:

$$\frac{dM}{dt} = -K(M - M_e) \qquad (9)$$

Where, K is the drying constant (s^{-1}), M is the moisture content (% wet basis) at time t and M_e is the equilibrium moisture content (% wet basis). In thin layer drying, the drying constant (K) is the combination of drying transport properties such as moisture diffusivity, thermal conductivity, interface heat, and mass coefficients (Erbay & Icier, 2010). If K is independent from M, then

Equation (3) can be expressed as Equation (Chayaprasert et al.) given above. Equation (Chayaprasert et al.) is also known as the Lewis (Newton) model (Erbay & Icier, 2010).

b. Page Model: Page modified the Lewis Newton model by adding a dimensionless empirical constant (n) and applied that to the mathematical modeling of drying of shelled corn (Page, 1949). The modified model is given below:

$$\frac{M-M_e}{M_{o-}\ M_e} = e^{(-kt^n)} \qquad (10)$$

c. Modified Page models: The Page model was further modified during several research studies. During the study on drying of soybeans (Overhults et. al, 1973), the Modified Page-1 Model was used which is described below:

$$\frac{M-M_e}{M_{o-}\ M_e} = e^{(-kt)^n} \qquad (11)$$

This model was further modified by White and Bridges (1980) during drying of soybeans and termed as Modified Page-II Model given below:

$$\frac{M-M_e}{M_{o-}\ M_e} = e^{-(kt)^n} \qquad (12)$$

2.4.2 Models derived from Fick's second law of diffusion:

A model based on Fick's second law of diffusion was modified by Henderson and Pabis (1961) for drying of corn. For sufficiently long drying times, the model can be used with slight error and is given below:

$$\frac{M-M_e}{M_{o-}\ M_e} = A_1 e^{(-\frac{\pi^2 D_{eff}}{A_2}t)} \qquad (13)$$

Where A_1 and A_2 are geometrical constants, D_{eff} is effective moisture diffusivity (m^2/s) and t is time (sec.). If D_{eff} is constant during drying, then equation (7) can be rearranged by using drying constant k as:

$$\frac{M - M_e}{M_{o-} M_e} = a\, e^{-k(t)} \qquad (14)$$

Where 'a' is defined as the indication of shape and generally named as dimensionless model constant obtained from experimental data. There are several other models based on Fick's second law of diffusion such as Logarithmic model, Midilli model, ModfiedMidilli model, Demir Model, Two term Model etc. and described by Erbay and Icier(2010) in review on thin layer drying of foods.

2.4.3 Determination of appropriate model:

Thin layer drying equations require moisture ratio versus time analysis. Experiment conducted on grasses shows that the drying rate decreases with time (Haghighi, 1990). Moisture ratio data is plotted against time and regression analysis is performed on the selected model to determine the constant values that provides the best appropriateness of the model. The validation of model fitting can be analyzed by performing various statistical analysis such as correlation analysis, reduced chi-square test and root mean square error analysis (RMSE) (Erbay & Icier, 2010). In general, the correlation coefficient (r) is the major selection criteria for selecting the best model to describe the drying curve equation (Erbay & Icier, 2010). The model which gives the highest r value is selected to describe the drying curve. Moreover, In addition to r, the reduced chi-square and RMSE are used to determine the best fit. The highest r value, and lowest chi-square and RMSE values help in selecting the best model for drying behavior of the crop.

2.5 Storage Losses

According to USDA/DOE Billion Ton Study, 189 billion liters of ethanol a year is required to replace 30% of the nation's transportation fuel requirement (U.S. Department of

Energy, 2005). This would require 454-544 million metric tons (400-500 million dry tons) of biomass from different crop sources (Gale et al., 2008). To ensure continuous availability of raw material at this scale would require storage of biomass at biorefineries or nearby sites for 6 to 12 months to avoid fluctuation in production (Wiselogel et al., 1996). Switchgrass has a wide harvest window starting from July to February of the following year (Thorsell et al., 2004). During the harvest season from July to February, switchgrass can be harvested, dried, and directly transported to the biorefinery. For the remaining months, from March to June, biorefineries will be dependent on stored biomass or alternate sources. The main concerns in a biomass storage system are the cost of storage and the dry matter losses during the storage period. For biofuel production, indoor storage of bales will not be economical (Wiselogel et al., 1996). Bale inventories stored outside are easier to manage and have reduced risk of fire damage compared to inside storage (Coblentz, 2009). Outside unprotected storage results in higher dry matter losses, changes in composition, and loss of both structural and nonstructural components.

The spoilage of bales during storage is mainly due to the biochemical reactions of respiration by microbes (Greenlees et al., 2000). Such spoilage mainly results from high moisture content of the bales. The major portion of biomass that is lost during storage is the water soluble part called extractives which account for 15% of the dry weight of switchgrass (Chen et al., 2010). Carbohydrates such as sucrose, glucose, and fructose were found to be a major component of switchgrass and account for 18 to 27% of the dry weight of these extractives (Chen et al., 2010). Therefore, loss of extractives due to rainfall and other environmental conditions is a direct loss of substrate for the biochemical conversion process. There are several other factors which affect the quality of bales during storage such as weathering, storage surface, length of storage, erosion, bale density, and bale orientation (Wiselogel et al., 1996). Weathering and biochemical reactions which occur during storage may produce chemical compounds that affect the conversion process and efficiency of feed stock conversion to ethanol.

For safe bale storage, a moisture content of less than 18% (wet basis) is recommended for round and square bales (Cundiff and Marsh, 1996; Egg et al., 1993; Kevin et al., 2006). Field losses are comparatively low when the crop is baled at moisture content above 18% (wet basis); however, high moisture will cause higher dry matter loss and compositional changes during the storage period. Buckmaster et al. (1989) reported that moisture content at the time of baling was the most significant factor affecting dry matter loss. The bales continue to loose moisture until they reach a moisture content of 8 to 15% (wet basis). The final moisture content depends on the climatic conditions such as relative humidity, and storage structure (Barnes et al., 2007). Moreover, the final moisture content of bales will remain constant, unless water is absorbed from rain, ground or humid air. Various factors that results in dry matter loss during storage are divided into biological causes, microbial activity, spontaneous heating, and physical causes and are discussed below in the following section.

2.5.1. Biological causes

Respiration and enzymatic activity are the major biological causes by which the biomass deteriorates during storage. Respiration during bale storage includes respiration from plant cell components and microorganisms. Plant respiration and enzymatic activity is very low at moisture level between 20% to 27.3% wet basis (Barnes et al., 2007). However, bales stored at higher moisture content had significantly higher plant respiration and enzymatic activity. Plant respiration and enzymatic activity are also positively correlated with temperature. Plant respiration and heat released are highest at about 30 to 35°C, which is easily attainable in moist hay (Moore & Peterson, 1995). Moreover, plant cells die as temperature increases to 40 to 45°C which stop the plant respiration process (Barnes et al., 2007).

2.5.2 Microbial activity

Microbial respiration is responsible for most of the spontaneous heating and dry matter loss in moist hay (Barnes et al., 2007). However, it was difficult to separate the effect of plant and microbial respiration. Moisture and temperature are the main factors that affect the population of microbes in the biomass during storage (Russell and Buxton, 1985). Coblentz (2009) also described that microbial growth is exacerbated by rainfall and warm temperatures during storage. Dry matter losses could be less severe during storage in winter months of northern climate. However, it was also reported that lower temperatures during storage causes slow drying of bales, which could result in higher dry matter losses (Coblentz, 2009). Microbial activity is high at the start of storage period, but it decreases as the bales dry out during storage. A relative humidity of more than 70% and temperature above 20 °C is needed for significant fungal growth (Barnes et al., 2007; Moore and Peterson, 1995; Rees, 1982). Bacterial population is generally low during the first two or three weeks of storage, but the fungal population of several genera increases during the same time. Counts of 13 different fungal genera were observed in the early storage period and were increased to maximum, after 9 days of storage (Moore and Peterson, 1995). Barnes et. al. (2007) reported a change from field genera fungi such as *Fusarium* and *Cladosporrum* to storage genera such as *Aspergillus* and *Penicillium*.

Bacterial growth and resulting increase in temperature is also a function of density and moisture content (Huhnke, 1990b). Round bales formed with a fixed chamber baler have less dense core compared to the bales formed with a variable chamber baler. The belt in the variable chamber baler maintains the tension during the bale formation process, resulting in uniform and dense bales. In general, losses in bales formed with a variable chamber baler are less severe compared to bales formed with a fixed chamber baler. A dry matter loss of 4% was reported from uncovered bales stored on pallets and formed with a variable chamber baler. Under similar storage conditions, a dry matter loss of 10% was reported from bales formed with a fixed chamber baler (Huhnke, 1990a). Denser bales from variable chamber baler maintain their shape better during storage period and resist moisture accumulation due to higher density. A dry matter loss of 8.3% was also reported in dense alfalfa-brome grass bales compared to 10.3% in low density bales stored for 4 to 9 months (Russell et al., 1990). In contrast, an opposite trend was also observed by Huhnke (1990b) during storage study of wheat hay harvested at different stages of maturity. Variable chamber bales harvested at boot stage of maturity had higher dry matter loss than fixed chamber bales. Higher initial moisture at boot stage (23.1% wet basis) resulted in higher microbial growth during storage in both type of bales. Due to high density of variable chamber bales, air circulation was restricted which increased the temperature inside the bales and resulted in more losses than low density fixed chamber bales (Huhnke, 1990b).

Heating of biomass occurs due to plant and microbial respiration in stored hay. This results in high dry matter losses and unfavorable composition changes that decrease the overall quality of biomass. Factors that results in increased spontaneous heating include

- Higher moisture content above 15% to 20%, as higher moisture results in higher microbial growth
- Bale size and type, because larger size bales have restricted moisture and heat dissipation to surroundings
- Bale density, as high density bales lose heat less rapidly than low density bales
- Environmental factors, such as relative humidity, ambient temperature, and air movement, as they affect microbial growth and dissipation of heat to environment
- Storage structure, as well ventilated bales heat less
- Use of preservatives to control microbial growth.

As discussed earlier, moisture content at the time of baling is the most important factor affecting spontaneous heating of bales. Bales that have higher initial moisture content reached higher temperatures and remained hotter for a longer period of time than drier hays (Barnes et al., 2007). Changes in hay appearance and quality are also observed if the bales are stored at moisture content higher than 15% wet basis. Green color at baling of moist hay changes to various shades of brown. The degree of color change provides an idea about the extent of heating that occurs inside the bale during storage. Dark color is due to Maillard reaction which involves condensation of sugars and amino acids, and thus results in undesirable changes in biomass (Moore and Peterson, 1995). Bale density and bale size affects the internal temperature during storage. Higher density bales have higher heating losses because a larger quantity of biomass is present in the bale. Size of the bale and stacking pattern during storage also affect the losses during storage. Shinners et al. (1996) reported higher temperatures and higher dry matter loss of 6.9% in mid-size bales compared to 1.3% in small rectangular bales of alfalfa. They also found higher average and maximum temperatures in mid-size bales stored in stacks compared to mid-size bales stored individually. Bale temperatures above 70 °C are generated by oxidative chemical reactions rather than heat from microbial and plant respiration (Festenstein, 1971). The potential for combustion exists if the temperature exceeds 170 °C (Moore and Peterson, 1995). If the temperature reaches 165 °C, the soluble carbohydrates are almost completely eliminated, together with some of the cellulose and hemicellulose fraction (Festenstein, 1971; Moore and Peterson, 1995). Normally, spontaneous combustion occurs near the outside of the hay stack as concentration of oxygen is higher near the surface than the inside of the bales.

2.5.3. Physical causes

Weather parameters such as rainfall, snow fall, high relative humidity, temperature, wind, ultraviolet degradation by sunlight severely affect the dry matter content in the bales. Storage losses are directly related to the amount of rainfall the bales receive during a storage period. Quality of the bales stored outside decreases due to leaching of water soluble plant components. Coblentz (2009) reported a dry matter loss of 14.8% compared to 8% from unprotected bales stored on ground with a rainfall of 1005 mm and 512 mm, respectively. Water from rainfall or water absorbed from ground removes the soluble carbohydrates that are important for biofuel production. Species or type of the crop also affects the amount of dry matter lost during storage. Fine leafed grasses are reported to shed water more efficiently than legumes during a rainfall event (Coblentz, 2009). Other forage types such as bermuda grass and tall fescue form a tight thatch on the bale surface that also helps to shed rain water more effectively than courser and thick stemed forages such as sorghum-sudan grass (Barnes et al., 2007). A slight effect of orientation was also observed during round bermuda grass bale storage. Bales surface oriented towards north had significantly higher moisture content of 42.8% (wet basis) in outer layers compared to 23% (wet basis) in south oriented side (Huhnke, 1990a). In addition, round bales stored in east/west direction had lower dry matter loss than bales stored in north/south direction, but the difference was not significant (Huhnke, 1990a). Similarly, an increase (Table 2.2) in dry matter loss was also observed for round bales stored in north/south direction compared to east/west direction, when the study was repeated on alfalfa bales stored for 7 months (Huhnke, 1993). Effect of bale orientation was not significant on dry matter loss but orientation did significantly affect the moisture content and chemical composition of the round bales (Huhnke, 1993).

Storage structure also has a significant effect on storage losses. Large round bales of alfalfa lost 38 g kg^{-1} of dry matter when stored inside and lost around 91 g kg^{-1} when stored outside without any protection. These losses increased to 46 g kg^{-1} and 109 g kg^{-1} respectively for inside and outside storage during the next year (Shinners et al., 2009). Dry matter loss can be minimized during outside storage if they are covered with some protection such as polyethylene tarps. During all the studies, a significant difference in dry matter loss was observed between covered and uncovered bales (Table 2.2). Huhnke (1988) reported a dry matter loss of 6.5% in covered alfalfa bales compared to 13.1% in exposed alfalfa bales stored for 8 months in central Oklahoma. Dry matter losses were further reduced to 1.9% and were similar to barn storage losses, when tarped alfalfa bales were stored on pallets (Huhnke, 1988). Coblentz (2009) also observed an improvement in dry matter recovery when the bales were stored on pallets instead of ground. Bales stored for 11 months on pallets lost 9.2% of dry matter compared to 14.8% in bales stored on ground (Coblentz, 2009). These findings suggest that storage surface also significantly affects the dry matter loss during storage (Table 2.2).

Furthermore, the amount of dry matter lost during storage is also dependent on the type of wrap used to tie the bales. Round switchgrass and reed canarygrass bales wrapped with plastic film, net wrap, plastic twine, and sisal twine lost on average 3.4, 7.7, 8.3, and 14.9% of dry matter respectively, when stored for 9 and 11 months (Shinners et al., 2006). Sisal twine used to wrap bales rotted during storage causing bales to lose their integrity and resulted in increased ground contact. The samples collected from bottom of the twine wrapped bales were contaminated with soil and were found to be of poor quality. Harrigan & Rotz (1994) also reported a dry matter loss of 9.6, 16.3, and 16.5% from round alfalfa bales wrapped with plastic, net wrap and twine respectively, stored for six to nine months in Michigan. Shinners et al. (2009) observed that to protect the bale bottom, it was important to store net wrap bales on a well-drained surface, as they shed more moisture than twine wrapped bales. Net wrap bales also maintained nutrient ratios better in the outer layers than the twine wrapped bales. Dry matter loss is also affected by the maturity stage of the crop. (Huhnke, 1990b) found that wheat hay baled at boot stage of maturity had higher dry matter losses than the mid head stage. Higher initial moisture content of 23.1% (wet basis) during boot stage compared to 9.6% (wet basis) in mid-head stage was considered to be one of the reason for higher dry matter losses during storage.

Table 2.2 A review on dry matter loss observed during storage studies of bales by different methods

Source	**Crop**	**Storage Period (months)**	**Bale Type**	**Storage Treatment**	**Dry Matter Loss (% of total)**
(Collins et al., 1987)	Alfalfa	3	Large Round	Inside Exposed on ground Exposed on poles Covered on ground Covered on poles	4.6 10.9 7.5 5.2 7.5
(Huhnke, 1988)	Alfalfa	8	Large Round	Exposed on ground Exposed on pallets Covered on ground Covered on pallets Inside	13.1 8.6 6.5 1.9 1.9
(Huhnke, 1990a)	Bermudagrass	8	Large Round	**Surface/Density/Orientation** Exposed ground/high/NS Exposed ground/low/NS Exposed ground/low/EW Exposed pallet/high/NS Exposed pallet/low/NS Exposed pallet/low/EW Inside	 7.0 14.1 9.7 3.8 10.0 2.6 3.4
(Huhnke, 1990b)	Wheat hay	10	Large Round	**Surface/Orientation** Row-Exposed ground/NS Row-Exposed ground/EW Row-Exposed pallet/NS Row-Exposed pallet/EW Exposed on ground Inside	4.3 6.2 5.2 4.1 10.5 0.9
(Russell et al., 1990)	Alfalfa-bromegrass	4 or 9	Large Round	**Density** Low High **Binding** Net wrap Sisal twine **Surface** Ground Rock	 10.3 8.3 7.0 11.7 10.6 8.1
(Huhnke, 1993)	Alfalfa	7	Large Round	**Surface/Orientation** Exposed ground/NS Exposed ground/ EW Exposed pallet/NS Exposed pallet/ EW Covered pallet/NS Inside	 5.8 5.1 3.1 2.6 1.3 2.2

Table 2.2 A review on dry matter loss observed during storage studies of bales by different methods (Continued)

Source	**Crop**	**Storage Period (months)**	**Bale Type**	**Storage Treatment**	**Dry Matter Loss (% of total)**
(Harrigan & Rotz, 1994)	Alfalfa	6 to 9	Large Round	Covered on pallets Net-wrap on pallets Twine on pallets Inside	9.6 16.3 16.5 6
(Taylor et al., 1994)	Alfalfa	9	Large Round	**Location/wrap type/surface** Reno/net-wrap/inside Reno/net-wrap/outside ground Reno/sisal twine/inside Reno/sisal twine/outside ground Saline/net-wrap/inside Saline/net-wrap/outside ground Saline/sisal twine/inside Saline/sisal twine/outside ground Stafford/net-wrap/inside Stafford/net-wrap/outside ground Stafford/sisal twine/inside Stafford/sisal twine/outside ground	 4.2 4.6 5.3 3.1 0.1 2.1 1.2 2.4 0.8 1.7 1.1 0.8
(Shinners et al., 1996)	Alfalfa	4.5	Small and Mid-size Square	**Bale size/storage method/moisture** Mid-size/stacked/low Mid-size/stacked/inter Mid-size/stacked/high Mid-size/individual/low Mid-size/individual/inter Mid-size/individual/high Small/stacked/low Small/stacked/inter Small/stacked/high Small/individual/low Small/individual/inter Small/individual/high	 5.0 4.4 8.2 4.4 3.6 15.7 0.6 1.4 0.1 3.7 1.5 0.4
(Shinners et al., 2006)	Reed Canarygrass, Switchgrass	11	Round exposed on sod	Sisal twine Plastic twine Net wrap Inside	14.9 7.5 7.7 2.6
(Turner et al., 2007)	Mixture of Cool season grasses (Tall fescue 55%, orchard grass 30%, white clover 12%, Kentucky blue grass and timothy 3%)	7 or 15	Large Round	**Surface/time period (months)** Exposed on ground/7 Exposed on pallets/7 Covered on ground/7 Covered on pallets/7 Inside/7 Exposed on ground/15 Exposed on pallets/15 Covered on ground/15 Covered on pallets/15 Inside/15	 24.2 21.2 12.1 7.9 2.7 29.8 31.6 19.3 12.0 10.2

Table 2.2 A review on dry matter loss observed during storage studies of bales by different methods (Continued)

Source	Crop	Storage Period (months)	Bale Type	Storage Treatment	Dry Matter Loss (% of total)
(Shinners et al., 2009)	Alfalfa	5 (First cutting) 11 (Second cutting)	Large Round	**Cutting/ wrap type/surface**	
				First/ sisal twine/ground	14.6
				First/plastic twine/ground	9.9
				First/to-edge net wrap/ground	7.6
				First/cover-edge net wrap/ground	7.2
				First/bale cover/ground	5.9
				First/Inside/ground	2
				First/ sisal twine/pallets	8.2
				First/plastic twine/pallets	7.5
				First/to-edge net wrap/pallets	6.0
				First/cover-edge net wrap/pallets	4.9
				Second/ sisal twine/ground	24.3
				Second/plastic twine/ground	11.2
				Second/to-edge net wrap/ground	6.7
				Second/cover-edge net wrap/ground	7.1
				Second/bale cover/ground	3.1
				Second/Inside/ground	1.8
				Second/ sisal twine/pallets	11.6
				Second/plastic twine/pallets	8.5
				Second/to-edge net wrap/pallets	6.4
				Second/cover-edge net wrap/pallets	5.8
(Coblentz, 2009)	Orchardgrass, Alfalfa	9 (First cutting) 11(Second cutting)	Large Round	**Cutting/wrap type/surface**	
				First/net-wrap/Inside	1.9
				First/net-wrap/pallets	5.0
				First/net-wrap/ground	7.7
				First/sisal twine/pallets	5.1
				First/sisal twine/ground	8.0
				Second/net-wrap/Inside	3.6
				Second/net-wrap/pallets	8.9
				Second/net-wrap/ground	10.4
				Second/sisal twine/pallets	9.2
				Second/sisal twine/ground	14.8

2.6. Compositional changes during storage

There are a variety of analytical procedures developed to measure lignin and structural carbohydrates in woody materials. They have been used for a long time to evaluate plant materials as an animal feedstock, compare potential biofuel feed stocks and to measure the efficiency of conversion process from biomass to biofuels (Sluiter et al., 2010). Most of the past literature (Huhnke, 1988; Huhnke, 1990a; Huhnke, 1993; Mandebvu et al., 1998; Shinners et al., 2009) on composition and forage fiber analysis of plant material is analyzed by detergent fiber analysis methods developed by Goering & Van Soest (1970). Results from detergent fiber analysis method include three fractions: neutral detergent fiber (NDF), acid detergent fiber (ADF) and acid detergent lignin (ADL). Cell wall fractions such as cellulose, hemicellulose and lignin are left in NDF portion after extraction with a detergent at neutral pH. However, pectic substances which are also a part of cell wall are solubilized and lost during the extraction process. Since grasses have very low concentration of pectin substances compared to legumes, NDF fraction generally provides a good estimate of cell wall fraction in grasses (Jung & Lamb, 2004). The ADF fraction primarily consists of cellulose and lignin portion and was developed as a preliminary step for calculation of lignin content as ADL. Hemicellulose content is often calculated as a difference of NDF and ADF fraction whereas, cellulose is calculated by the difference of ADF and ADL fraction (Jung & Lamb, 2004; Wolfrum & Lorenz, 2009).

Second common technique for compositional analysis is based on Uppsala method and also referred to as dietary fiber analysis method (Jung & Lamb, 2004). In this method cell wall polysaccharides are broken down into their monomeric forms by a two stage hydrolysis treatment with sulfuric acid. The sugars obtained are detected and quantified using HPLC or GC analysis. A series of laboratory analytical procedure (Samson et al.) has also been developed by National Renewable Energy Laboratory (NREL) which are based on Uppsala or dietary fiber analysis methods (NREL, 2010; Wolfrum & Lorenz, 2009). The NREL methods, were specifically designed for biofuel purposes and measure the composition of biomass on whole as well as extractive free bases (NREL, 2010). These dietary fiber analyses are considered accurate, but are also very labor intensive, time consuming and expensive (Jung & Lamb, 2004). A complete compositional analysis by dietary fiber analysis costs between $800 to $2000 per sample and results are not available for many days and sometime weeks (Hames et al., 2003).

The third common technique uses NIRS (Near Infrared Reflectance Spectroscopy) combined with statistical multivariate analysis tool to predict the chemical composition of biomass. NIRS is an attractive, non-destructive approach which can be used to precisely and timely detect the composition of sample. Sampling cost by using NIRS methods of analysis can decrease the cost to about $10 per sample (Hames et al., 2003). In addition, this technique can also be used for on-the-spot payment of biomass to the farmer or producer based on the quality of feed stock.

Most of the storage studies have been based on evaluating biomass as feed stock for improving animal performance rather than as a biofuel feedstock. Most of the results are presented by detergent fiber analysis method and presented in the form of NDF, ADF and ADL fractions. For biofuel purposes, researchers are more interested in evaluating results as change in cellulose, hemicellulose and lignin fraction. To find correlation between cellulose, hemicellulose and lignin content obtained from detergent fiber and dietary fiber analysis, some research has been done in past. Theander & Westerlund (1993) compared the results obtained from dietary fiber analysis and detergent fiber analysis for alfalfa, bromegrass, reed canary grass, and miscanthus. The results obtained showed good correlation of 0.81 to 1.00 between cellulose (ADF-ADL) obtained from detergent fiber analysis and cellulose (glucan) obtained from dietary fiber analysis (Uppsala method). Hemicellulose content predicted by detergent fiber method (NDF-ADF) also correlated well with other non-glucose sugars for alfalfa samples obtained by Uppsala method. However, for bromegrass, reed canary grass, and miscanthus detergent method overestimated the hemicellulose content compared to Uppsala method. Similar study was conducted by Jung & Lamb (2004) on alfalfa stems and found a good correlation (R^2= 0.98) between cellulose (ADF-ADL) obtained from detergent fiber analysis and glucose obtained from dietary fiber analysis. However, detergent hemicellulose (NDF-ADF) was not well correlated (R^2= 0.58) with hemicellulose (sum of xylose, mannose, and fructose) obtained from dietary method. They found that detergent fiber method slightly overestimated the hemicellulose and cellulose content when compared to concentrations obtained from Uppsala method. Wolfrum &

Lorenz (2009) also correlated cellulose and hemicellulose content based on detergent fiber analysis and dietary fiber analysis of corn stover. More than 2000 corn stover samples were tested in the study and all the data for dietary fiber analysis and detergent fiber analysis was obtained by using NIRS spectroscopy. NREL corn stover model was used which was developed using Uppsala dietary fiber method to predict structural glucan and xylan content for dietary fiber analysis method. Similarly, a calibration developed at University of Wisconsin- Madison was used to predict NDF, ADF, cellulose (ADF-ADL) and hemicellulose (NDF-ADF) content. A good correlation (R^2= 0.87) was found between cellulose content obtained from both methods. Cellulose obtained by detergent method was found to be slightly higher by 2-4% than cellulose (glucan) obtained by Uppsala method. In case of hemicellulose content, detergent method overestimates the hemicellulose content by approximately 14% when compared to Uppsala method, with a correlation of 0.69. These findings suggests that cellulose content (ADF-ADL) obtained by detergent methods are similar to cellulose content obtained from Uppsala method. However, detergent method slightly over estimates the hemicellulose content when compared to Uppsala method. In case of storage study of bales, both methods can provide useful information, as results are focused on finding the percent change in cellulose and hemicellulose content between initial and final samples.

NDF fraction which consists of cell wall polysaccharides such as cellulose, hemicellulose and lignin does not change much during storage compared to soluble portion of biomass called extractives. Since the results are presented on dry matter basis, a slight increase in NDF content is also observed during storage. This increase is due to loss of extractives instead of increase in cellulose, hemicellulose or lignin content. NDF content increased slightly from 68.4 to 73.8% (dry basis) in round bermudagrass bales stored on ground without any cover for 8 months (Huhnke, 1990a). A slight increase in NDF content from 68.5 to 73.5% (dry basis) was also observed when the bales were stored inside a barn (Huhnke, 1990a). Similarly, Taylor et. al.

(1994) observed an increase in NDF content of 7.1% in twine wrapped bales compared to 4.6% in net wrapped bales. A decrease of 0.6% in NDF content was also observed in the same study for net wrapped bales stored outside and uncovered for 9 months.

Cellulose content also decreases during storage but the change is less dramatic than the extractive portion. No change in cellulose content was reported in outer 0.15 m depth of round orchardgrass and alfalfa hay, stored unprotected for 9 months (Coblentz, 2009). Wiselogel et al. (1996) conducted a storage study on switchgrass bales and evaluated the results by following the methods developed by NREL. During harvest 1, a slight but significant decrease in cellulose content was observed from 37.8% in initial samples to 35.7% and 35.6% in final samples of switchgrass bales stored inside and outside unprotected for 6.5 months, respectively. However, during 2nd harvest, no significant change in cellulose content was observed between initial and final samples of inside and outside stored bales. Relatively dry weather conditions during harvest 2 season resulted in no significant change during storage (Wiselogel et al., 1996). A more significant decrease of 30% and 28% was reported in cellulose content for round switchgrass and tall fescue bales stored for 9 and 11 months respectively (Agblevor et al., 1994). A cellulose content of 30.9% was reported in unweathered portion of switchgrass bales compared to 21.9% in weathered portion. For tall fescue bales also a cellulose content of 24.4% was observed instead of 15.8% in weathered portion.

A slight increase in hemicellulose content (NDF-ADF) from 18.5% to 20.6% for surface layer of orchardgrass and alfalfa was reported by Coblentz (2009). However, no statistical difference in hemicellulose content for outer surface layer were observed for control vs outside ($p=0.338$), net wrap vs sisal twine ($p=0.210$), and elevated vs ground ($p=0.135$) (Coblentz, 2009). However, a significant decrease of 1.4% was observed in hemicellulose content (measured as a sum of the acids, arabinan, xylan, mannan and galactan) for harvest 1 samples by Wiselogel et al. (1996). For harvest 2, no significant decrease in hemicellulose content was observed in switchgrass bales stored outside and inside, due to better drying conditions. A decrease in hemicellulose content (sum of arabinan, xylan, mannan and galactan) was also observed by Agblevor et al. (1994) for switchgrass and tall fescue bales stored for 9 and 11 months, respectively. Hemicellulose content of 22.8% was observed in unweathered portion of switchgrass bales, compared to 17.3% in weathered portion. In tall fescue bales also, significantly higher hemicellulose content of 12.1% was observed in weathered portions compared to 18% in unweathered portions.

Ash content is relatively stable during storage. No change in ash content was observed for orchard grass and alfalfa hay stored unprotected for 9 months (Coblentz, 2009). A slight increase in ash content was observed from 5.8% to 6.0% during harvest 1 and 4.8% to 5.8% in harvest 2 samples of switchgrass bales. This increase could be due to systematic error during analysis (Wiselogel et al., 1996). An increase in ash content was also reported by Agblevor et al. (1994) for switchgrass bales stored for 9 months. Switchgrass bales stored unprotected on ground had much higher ash content of 7.3% in weathered portion compared to 4.2% in unweathered portion. Loss of soluble components due to leaching or loss due to respiration results in an apparent increase in ash content.

Lignin content which was measure on extractive free basis, increased during harvest 1 period compared to time zero samples and decreased during harvest 2 samples (Wiselogel et al., 1996). During harvest 1, lignin content increased from 21.4% in initial samples to 23.0% in final samples from switchgrass bales stored outside and unprotected (Wiselogel et al., 1996). Samples taken from weathered outer layer had much more increase (1.6%) in lignin content compared to unweathered interior of the bales (0.9%). In harvest 2 switchgrass samples, a slight decrease from 20.6% to 20.2% was observed which could be due to experimental variation. An increase of lignin content in weathered portion of biomass was also observed by Agblevor et al. (1994) for switchgrass and tall fescue bales stored for 9 and 11 months respectively. In case of switchgrass bales, a lignin content of 17.5% was observed in unweathered portion compared to 27.3% in weathered portions. In case of tall fescue also, weathered portion had a significantly higher lignin content of 30.8% compared to 15.8% in unweathered portion. This increase in lignin content in uncovered bales may be due to the loss of sugars and extractives caused by precipitation and microbial growth. Humic substances can also form during storage if the bales are unprotected from precipitation and sunlight (Agblevor et al., 1994). Humic compounds are partially water insoluble and they are formed by the browning reactions between amino compounds and decomposed carbohydrate products due to weathering (Agblevor et al., 1994). These humic substances are insoluble in hydrolysis liquor and thus analyzed as lignin by the wet chemical methods resulting in an increase in lignin content. Consequently, increase in lignin content can also be associated with increase in humic substances.

The highest change in chemical composition was observed for switchgrass extractives during the storage study (Wiselogel et al., 1996). During harvest 1, extractives decreased from 17% in initial samples to 9.3% in inside stored samples and 6.5% in outside stored samples. Agblevor et al. (1994) also observed a threefold decrease in extractive content from tall fescue and switchgrass bales stored unprotected for 11 and 9 months, respectively. Carbohydrates such as sucrose, glucose, and fructose were found to be a major component of switchgrass and account for 18 to 27% of the dry weight of these extractives (Chen et al., 2010). Total monomeric and oligomeric sugars in switchgrass contribute to 25-32% of the dry weight of extractives (Chen et al., 2010). Except for the carbon content, these extractable sugars are not so important in the gasification process, but these sugars could easily be fermented to ethanol by the biochemical conversion processes (Wiselogel et al., 1996). Therefore, loss of extractives due to rainfall and other environmental conditions is a direct loss of substrate for the biochemical conversion process.

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CHAPTER III

AN EMPIRICAL MODEL TO PREDICT INFIELD THIN LAYER DRYING RATE OF CUT SWITCHGRASS

Abstract

A series of 62 thin layer drying experiments were conducted to evaluate the effect of solar radiation, vapor pressure deficit and wind speed on drying rate of switchgrass. An environmental chamber was fabricated that can simulate field drying conditions. The range of environmental variables tested during the study was based on the prevalent environmental conditions encountered during the field drying of harvested switchgrass. An empirical drying model based on maturity stage of switchgrass was also developed during the study. Separate drying rate equations were developed for seed development stages of maturity, and seed shattering and seed shattered stages of maturity. During both maturity stages, radiation intensity was positively and strongly correlated with drying rate. Vapor pressure deficit was also positively correlated (r=0.50) with drying rate during the seed development stage of maturity, but the effect was not significant for later stages of maturity. In environmental chamber, the effect of air speed was found to be dependent on radiation intensity. Under high radiation intensity, increase in wind speed decreased the drying rate of switchgrass. However, under low radiation intensity, increase in wind speed increased the drying potential of switchgrass. Initial moisture content was weakly correlated with drying rate.

3.0 Introduction

In order to provide a continuous supply of biomass to biorefineries, harvest time and frequency must be optimized. Depending on the climatic conditions, drying in windrows is required to reduce the moisture content to safe storage level. Moisture content of switchgrass also changes with maturity. At early vegetative growth stage, moisture content of switchgrass is about 70% (wet basis) and declines to 40 to 50% (wet basis) after flowering and seed set stage. Moisture content can further decline to less than 10% (wet basis) after a killing frost under dry field conditions (Christensen & Koppenjan, 2010). To reduce dry matter loss during storage, moisture content of less than 18% (wet basis) is desirable (Moore & Peterson, 1995).

Several factors other than rainfall influence the drying rate of the crop during field drying. Solar radiation, wind speed, air temperature, relative humidity, soil moisture, and other environmental factors affect the time required to bring the crop moisture content to a desired storage level. Crop yield, stem diameter, leaf to stem ratio, swath structure and other crop parameters can increase or decrease the moisture migration (Barnes et al., 2007). Faster drying rates are achieved with sunny days, higher temperatures, dryer soil and thinner swaths. Less favorable conditions and periodic rainfall can delay the drying process. Of all the environmental factors, solar radiation has the highest impact on drying rate of grasses (Bartzanas et al., 2010; Haghighi, 1990; Smith, 1990a). The next most significant weather parameter affecting the drying rate of biomass is vapor pressure deficit (VPD) (Haghighi, 1990; Moore & Peterson, 1995). VPD is a measure of the drying power of air and is obtained by the difference of actual vapor pressure and the total vapor pressure at a given air temperature (Wright et al., 2000). Savoie & Mailhot (1986) found that vapor pressure deficit was positively correlated (r=0.3605) with drying rate in timothy hay. Wind speed has a variable effect on drying rate of swaths and is related with initial moisture content of crop and solar radiation intensity. Generally field drying time of grasses varies from 2 to 7 days. Drying time is reduced to 3 to 4 days when the grasses are spread in thin layers and weather conditions are favorable (Haghighi, 1990; Moore & Peterson, 1995).

The main objective of field drying studies is to develop mathematical models to predict the time needed to dry a crop by utilizing the weather conditions. In addition, the effect of individual weather parameters on drying rate of cut crops is also of particular interest. A number of models have been developed, that can simulate the environment and conditioning effects on field drying of crops. Both field drying and lab drying studies have been conducted to evaluate the effect of crop architecture, weather conditions, and plant characteristics. A model was developed by Hill et al. (1977) to use vapor pressure deficit to predict drying time of alfalfa hay. Savoie & Mailhot (1986) evaluated the effect of eight factors: dry bulb temperature, vapor pressure deficit, wind speed, radiation, conditioning, soil moisture, forage density and initial moisture content on drying rate of timothy hay. A mathematical model was also developed by Wright et al. (2001) to predict drying rate of cut ryegrass. They evaluated the effect of material density, effect of conditioning and effect of inverting and mixing on the drying rate of ryegrass. However, an empirical model that can calculate the drying rate of switchgrass based on the environmental conditions is still unavailable in literature.

Predicting in-field drying rates is important to maintain the quality and quantity of harvested biomass. The study of parameters for field experiments may require several years of experimentation to cover a wide range of variables. Rotz and Chen (1985) collected data from 1977 to 1984, to develop a model that can determine the effect of environmental factors on in-field drying rate of alfalfa. Weather parameters were correlated with each other and moreover, the environmental conditions changed continuously with time. All these variations make it difficult to understand the effect of individual weather parameters when evaluating processes under field conditions. Alternatively, useful data for empirical drying models can be collected in much less time by using drying chambers to cover a wide range of parameters. It is difficult to simulate field conditions in drying chambers, but laboratory conditions offer more control over the variables that affect drying rate. To better understand the effect of environmental variables, thin layer drying of plant material under controlled conditions is helpful (Lamond & Graham, 1993). The data obtained from thin layer drying experiments can provide a better understanding of physical processes by which moisture is removed from plant materials (Menzies & O'Callaghan, 1971). Field drying of crops in windrows can be approximated as the drying of a series of thin layers of the crop, lying on top of each other. The overall drying rate of windrows can be estimated from the drying rate of each successive layer (Lamond & Graham, 1993).

Studies related to drying rate estimation for switchgrass are limited. Shinners et al. (2010) evaluated drying rates of two perennial grasses: switchgrass and reed canary grass. They reported that under similar crop yields, switchgrass dries faster than reed canary grass. Drying rates of both crops were higher than typically experienced with forage crop such as alfalfa. There is lack of literature that can predict the drying rate of switchgrass, based on the environmental conditions. A drying rate prediction model is also highly desirable for several logistics models which require calculation of drying time based on weather conditions. In order to develop a model to estimate the effect of environmental variables on the drying rate of switchgrass, the present study had three specific objectives:

- Design and construction of an environmental chamber that can simulate field conditions for drying switchgrass
- Evaluation of the effect of individual weather parameters on the drying rate of switchgrass
- Development of an empirical model to predict drying rate of switchgrass based on environmental variables

3.1. Material and methods

3.1.1. Construction of environmental chamber

The environmental chamber or wind tunnel constructed was a wooden framed structure 2.44 m long, 0.46 m high, and 0.46 m wide. The chamber was divided into three sections: a settling section (0.91 m in length), the test section (1.22 m in length) and diffuser section (0.31 m in length). The dimensions of the environmental chamber were selected to achieve the desired range of wind speed in the test section. The chamber had a door with a plexiglass inspection window located on the side of the test section for loading and unloading drying trays.

3.1.1.1 Control of vapor pressure deficit

Temperature and humidity were maintained by an air conditioning unit manufactured by PGC unit Model No. 1080 (Parameter Generation & Control Inc., Black Mountain, NC). The air conditioning unit maintained chamber air temperature and relative humidity levels within 0.1 °C and +/- 0.5% RH from the set values. The intake and outlet of the air conditioning unit were located in the chamber settling section in front of the honeycomb and screens (Figure 3.1).

3.1.1.2 Control of wind speed

A honeycomb is an effective device for removing swirl and lateral mean velocity variation created by the fan. A honeycomb with a cell length of at least six to eight times the cell diameter are preferable for improving the flow characteristics in a low speed wind tunnel (Bradshaw & Pankhurst, 1964). In the present study, a honeycomb made of PVC tubing having a cell diameter of 0.0254 m and a length of 0.15 m was used. Screens are also helpful to control separation of flow and reduce turbulence in wind tunnels. Screens are characterized by porosity (β), which is a function of wire diameter (d) and weave density (ρ) (Barlow et al., 1999). If w is the width of 1 square mesh cell, then the weave density (ρ= 1/w) and the porosity is related by (Barlow et al., 1999):

$$\beta = (1 - d\rho)^2$$

The typical porosity values for wind tunnel screens are between 0.5 to 0.8 (Barlow et al., 1999). For the present study, two screens of porosity 0.6 were used. A screen was also installed in the diffuser section to prevent objects from being blown into the circulating fan. A 0.36 m diameter duct with an inline axial fan connected the outlet of the chamber to the inlet (Figure 3.1, front view). Turning vanes to minimize losses and maintain straight flow were installed in the curved duct before the settling chamber (Figure 3.1, front view). A total of seven turning vanes subtending an angle slightly less than 90° were used in a circular arc pattern. The air conditioning unit provided an air flow of 0.23 m^3s^{-1} to the environmental chamber. The axial fan (1/3 HP and 3450 rpm) was attached to a variable speed controller was added in the recirculation loop of the environmental chamber to control the wind velocity over the trays of switchgrass. A maximum speed of 5 ms^{-1} was attained at the center of the test section with a variation of 0.5 ms^{-1} along the height of the test section.

3.1.1.3 Control of radiation intensity

Two 1.6 KW quartz radiant heaters (Chromalox QR-16 B Chromalox Inc., PA) were used as a radiation source to simulate solar radiation. The radiant heaters were fitted in the roof of environmental chamber at a height of 0.46 m above the trays. The radiation intensity of the heaters was controlled by a single solid state digital power controller (Model no. SCTR 120-240, Solaira Inc. Ontario, CA). The radiation intensity from the heat source was measured using a spectrometer (FieldSpec Pro, ASD Inc. CO) calibrated to measure radiation intensity in the range of 350 to 2500 nm. Radiation intensity was measured every 2.5 cm along the length and side of the test section. A region of high intensity was observed in the middle of the test section due to an overlap of radiation coming from the light sources as shown in Appendix I. Trays were not placed in this location during the drying experiments (Top view, Figure 3.1). When the overlapping high intensity region was not considered, a maximum variation of 50 watts·m^{-2} was observed between 350 to 2500 nm at the mean radiation intensity of 590 watts·m^{-2}.

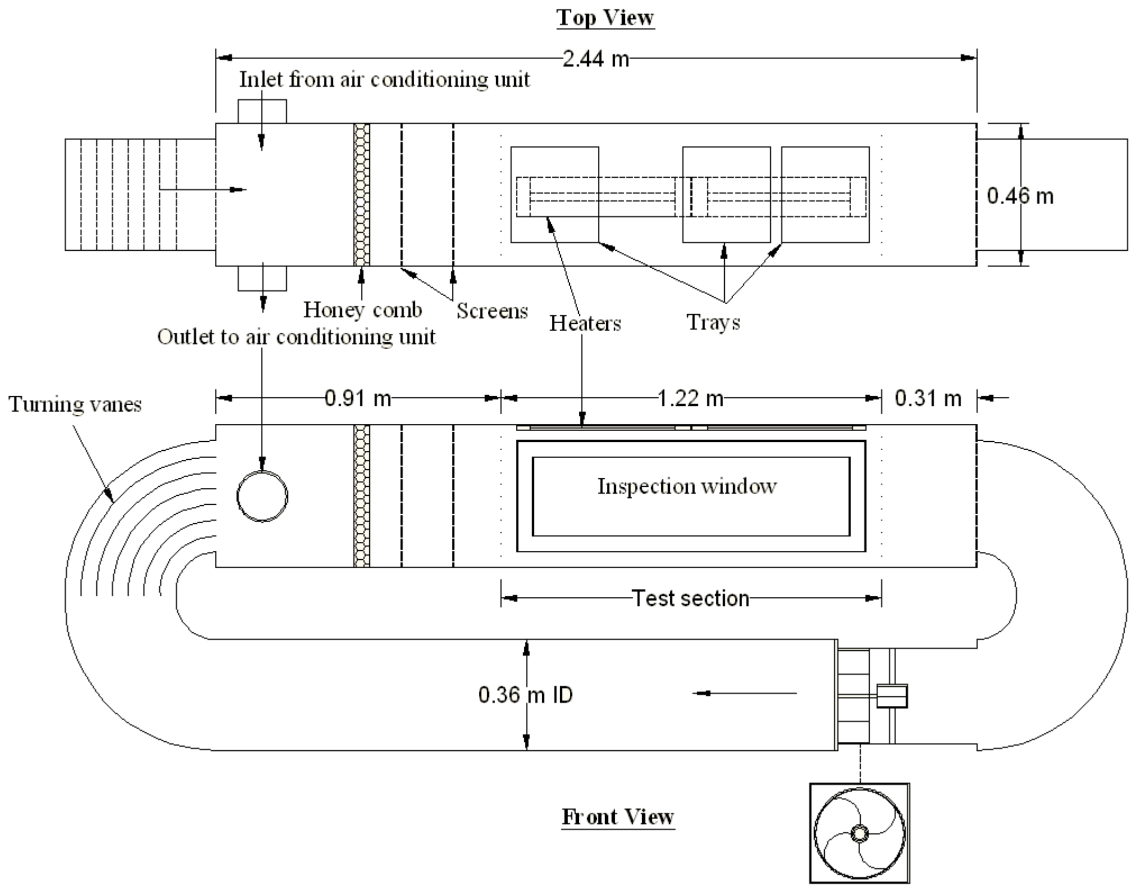

Figure 3.1. Top and front view of the environmental chamber designed for drying studies

3.1.2. Selection of weather data

Switchgrass is generally cut to dry in windrows from July to November. After a killing frost in late November or early December, moisture content of switchgrass reduces to a safe storage level. No further drying in windrows is required. Therefore, the chamber conditions evaluated in the study are limited to the weather conditions experienced in months from July to November. Weather data was obtained from the Oklahoma Mesonet which consists of 120 weather stations located throughout Oklahoma (Mesonet, 2011). Data for total solar radiation, average daily vapor pressure deficit, and average wind speed at 2 m height were collected from the Oklahoma Mesonet for the years 1996 through 2011 website (www.mesonet.org). Total solar radiation received in a day was converted to average solar radiation by dividing with the day light hours (Allen et al., 1998). Because wind speed varies with height above the ground, the speed measured at 2 m elevation by the Oklahoma Mesonet weather station will be higher than the wind speed experienced by swaths lying on the ground. Wind speed data measured at 2 m height was converted to wind speed at 0.31 m above the ground by use of the following equation (Chayaprasert et al., 2010):

$$U_h = U_{ref}\left(\frac{h}{h_{ref}}\right)^{a}$$

Where,

U_h is the local wind velocity measured at height h (m)

U_{ref} is the wind velocity at a reference height (h_{ref}) say 2 m

a, the exponent value, 0.14 represents an atmospheric wind boundary layer in an open terrain (Chayaprasert et al., 2010) .

The calculated wind speed at 0.31 m above the ground was used to dry the switchgrass in the environmental chamber and was converted again to wind speed at 2 m height for model formulation.

Most of the solar radiation that reaches the earth's surface is in the visible and infrared regions with wavelengths from 0.35 to 2.6 micrometers. The sun and the artificial light source used in the drying chamber are at different temperatures and therefore their radiation intensity spectra are different in corresponding waveband regions (Figure 3.2, 3.3). To simulate the solar radiation energy received by biomass in field and lab conditions, absorptivity of switchgrass in different wavelength regions were recorded using a spectrometer (FieldSpec Pro ASD Inc. CO). The absorptivity of switchgrass was then multiplied with published solar radiation intensities for

Stillwater, OK. In this way, the amount of solar radiation intensity which is actually used to evaporate moisture from switchgrass was evaluated. Similarly, the amount of radiation intensity absorbed by switchgrass in different wavelength regions from the artificial light source was measured using the same spectrometer. From the intensity of the artificial light source selected during an experiment, its equivalent solar radiation intensity was calculated from the absorptivity data of switchgrass and used in the model formulation. In this way, by keeping the absorbed energy the same for both heating sources, variation between drying rates for in-field and in-lab conditions were minimized.

Since absorptivity is also dependent on the moisture content of biomass (Ajibola et al., 1980) which changes with maturity stage, the absorptivity spectrum of each sample was collected at the start of each experiment. For obtaining solar radiation intensities at different wavelengths for Stillwater, OK, a spectral model developed at National Renewable Energy Laboratory (NREL) by Bird & Riordan (1986) named SPCTRAL2 was used. The model produces both direct and diffuse spectral data between 0.3 and 4.0 μm with a resolution of approximately 10 nm. Solar radiation intensity varies throughout the day and seasonally. The solar intensity spectrum from the model was therefore multiplied with the absorption spectrum of switchgrass to evaluate any variation of absorptivity within a month. When data were analyzed, little variation in absorptivity was observed among the days within a month. For this reason, spectral data for the midpoint of every month at solar noon was used to obtain the solar spectrum for that month. Switchgrass daily absorptivity change within a month, calculated at solar noon is provided in the Appendix II.

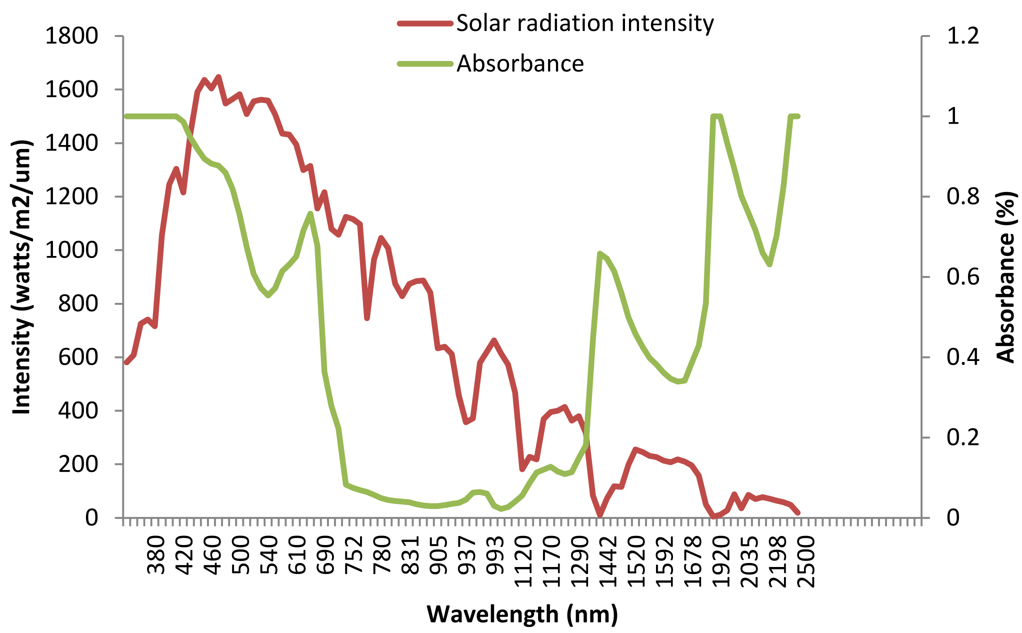

Figure 3.2. Solar radiation intensity and switchgrass absorption spectrum at different wavelength

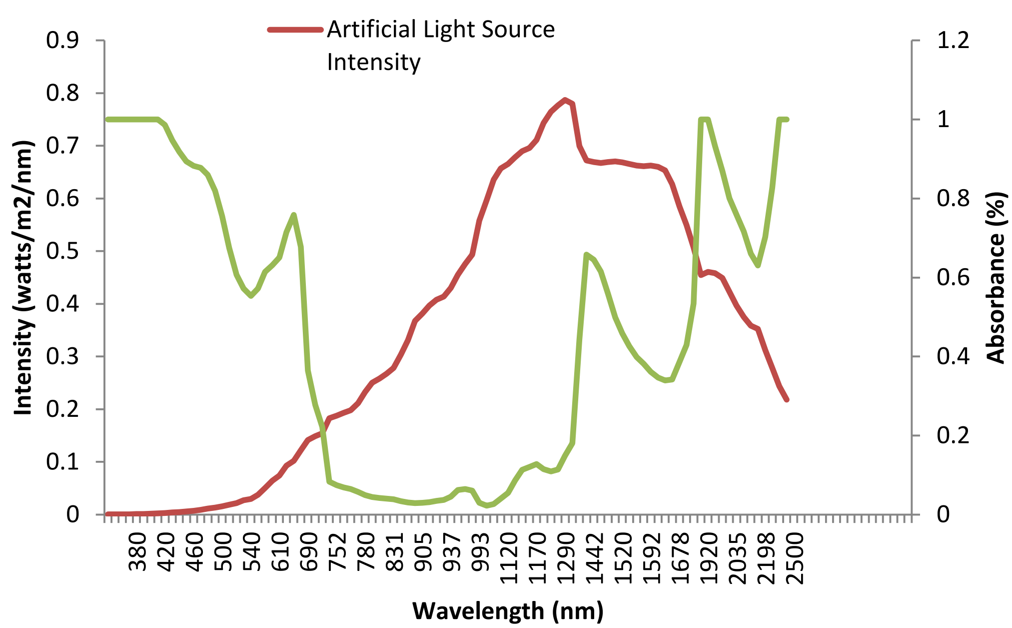

Figure 3.3. Artificial light source intensity and switchgrass absorption spectrum at different wavelength

3.1.3. Evaluation of environmental chamber

To evaluate the effect of environmental variables on the drying rate of switchgrass, it was important to maintain uniform and steady environmental conditions throughout the experiment. Environmental chamber was tested for uniformity of controlled conditions by placing 6 petri plates at different locations in the test section. An evaporation rate of 1.97 mm/hr was observed with a standard deviation of 0.12 mm/hr under a radiation intensity of 590 watt/m^2, wind speed of 4 m/s and vapor pressure deficit of 1.83 KPa. The variation of drying rate with drying time data for three switchgrass trays placed in the test section is shown in Figure 3.4.

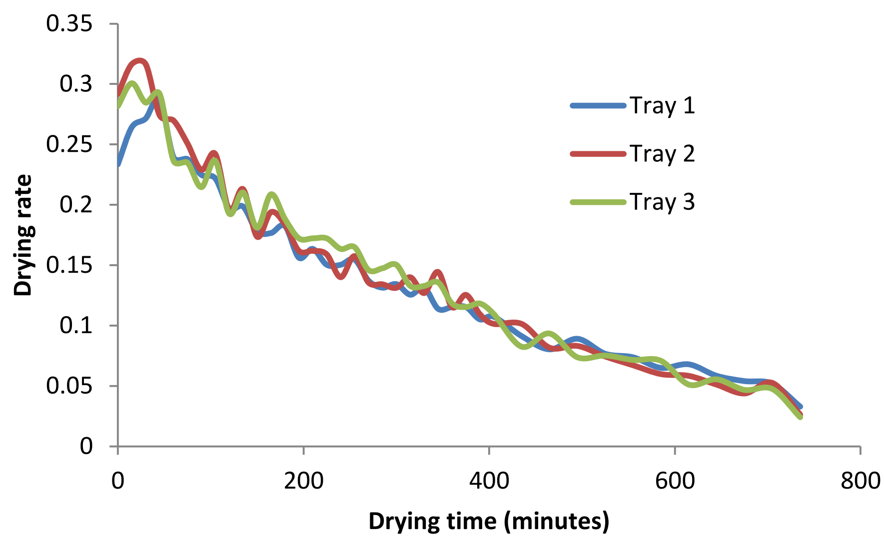

Figure 3.4. Drying rate vs. drying time plot for switchgrass dried at VPD of 1.93 KPa, Radiation of 351 watts/m^2 and wind speed of 3.25 m/s in seed development stage of maturity

3.1.4. Drying experiments

A representative sample of switchgrass (*Panicum virgatum* L) was harvested manually from the Efaw farm at Oklahoma State University in Stillwater, OK. The switchgrass field at Efaw is a well-established stand and was planted in 1998. The samples were taken beginning 1 August 2011 through 29 November 2011. The date of each drying experiment is also provided in

Appendix III. The material consisted of approximately 150 to 200 stems which were hand-cut approximately 6 cm above the ground from randomly selected locations in the field. Material was immediately sealed in plastic bags and transported to the lab for experimentation. A total of 54 drying experiments were conducted with a set of 27 experiments in seed development stage, and 27 experiments in seed shattering and seed shattered stage. A 3 by 3 by 3 factorial design was used with three levels of solar radiation, vapor pressure deficit (VPD) and wind speed as the variables (Table 3.1). A set of 8 experiments which were not a part of model development were also conducted during the study to validate the model. During each experiment, three trays of switchgrass were placed in the test section. Whole switchgrass plants including stems and leaves were cut to fit the aluminum trays which were 0.25 m in length, 0.20 m in width and 0.0003 m in thickness. Samples of 100 g of fresh switchgrass arranged in thin layers to a depth of 0.03 m, and simulating a density of 2 kg m^{-2} were placed in each tray. The switchgrass stems with leaves were oriented in a direction perpendicular to the air flow. The drying rate experiments were conducted within 30 to 60 minutes after harvesting of switchgrass. Once the desired conditions of radiation, VPD and wind speed were set, the trays were removed briefly and manually weighed every 15 minutes until the MC of switchgrass was reduced to 15 % w.b. The conditions of temperature and humidity were also measured at one minute intervals using a data logger (HOBO model U12-011, Onset Inc. MA). The wind speed was measured before the start of each experiment by an air flow meter (Fluke model 922, Fluke Corporation, WA). The three levels of each weather parameter selected for a maturity stage is shown below in Table 3.1. Upper and lower levels were based on the extreme weather conditions recorded in the maturity stage. The middle level was calculated from the average of upper and lower level.

Table 3.1. Experimental plan for switchgrass drying experiments with environmental conditions tested at each maturity stage.

Maturity Stage	Vapor pressure Deficit (KPa)	Solar Radiation (Watts/m^2)	Wind Speed (m/s at 2 m above ground)
Seed Development (Aug, Sept)	1.93, 1.44, 0.64	568, 351, 161	5.83, 3.25, 1.3
Seed Shattering (Oct), Seed Shattered (Nov)	1.5, 1.04, 0.47	495, 325, 130	5.83, 3.25, 1.3

Regression analysis of moisture ratio with drying time data was performed to determine the drying rate constant based on the environmental conditions used in the experiment. During the initial trials, an exponential model (eq. 1) was a better fit to the moisture ratio data and had higher R^2 values than the Page model (eq. 2). For the final experiments, an exponential model was used given by eq. (1).

$$\frac{M-M_e}{M_o - M_e} = e^{-k(t)} \qquad (1)$$

$$\frac{M-M_e}{M_o - M_e} = e^{(-kt^n)} \qquad (2)$$

Where k is the drying constant (min^{-1}), M is the moisture content at time t, M_o is the initial moisture content, n is the dimensionless empirical constant, and M_e is the equilibrium moisture content (EMC) on a dry basis. The drying constant (k) is obtained by plotting the graph between moisture ratio and drying time data. Since, the drying time was in minutes; therefore the units of drying rate constant are given by min^{-1} in the following sections.

In general, the equilibrium moisture (M_e) to which a crop dries in lab conditions is dependent on the temperature and humidity of the air. In this study, radiation was also considered thus the equilibrium moisture content will also depend on the intensity of radiation used during the drying experiment. There are no data available in the literature that relates radiation intensity, humidity and temperature with EMC of switchgrass. Moreover, the error in neglecting the EMC is minimal when the initial moisture content in a crop is less than 50% on wet basis (Mujumdar, 2004). Rotz and Chen (1985) also found that a better fit model was found when the EMC was set to zero. They also reported that, when alfalfa was dried under sun with moisture range above 20% wet basis, EMC had little or no influence on drying. In the present study, initial moisture content varied from 40% to 58% on wet basis. For this reason, M_e was dropped from equation 1 and the model was reduced to

$$M = M_o e^{-k(t)} \qquad (3)$$

The drying rate constant obtained from each drying experiment was used to develop an empirical model based on the range of environmental variables selected during a specific maturity stage. Regression analysis was completed using Proc Reg in SAS 9.3 (SAS Institute, NC, 2010).

3.2. Results and Discussion

During the experiments, switchgrass drying under all the environmental conditions was in a falling rate period described by Equation 3, an exponential function. In falling rate period the drying rate decreases with time. Initially, the drying rates were higher as moisture easily escaped from the intercellular spaces in plant. As the intercellular moisture evaporated, the remaining moisture present inside the cells was difficult to remove due to resistance offered by the plant cell membranes and cell wall. Initial moisture content at the time of harvesting also affected the drying rate of the crop. In this study, initial moisture content varied widely and was dependent on maturity stage as well as the time of the day at which the switchgrass was harvested. During the seed development stage, initial moisture content varied from 47.92% to 59.18% with an average of 54.28 % on wet basis. Moisture content was higher during early maturity stage and decreased during the end (Figure 3.4). During the seed shattering and seed shattered stage, the decrease in moisture content was more pronounced than earlier maturity stage (Figure 3.5). Moisture content varied from 35.48% to 58.33% on wet basis with an average of 50.98% in later maturity stages.

In addition, it was observed that initial moisture content was higher when the switchgrass was harvest during the early morning compared to afternoon. Due to observed variation of initial moisture content of switchgrass with maturity stage, it was decided to consider the initial moisture content in the drying rate model development.

During the experiments, solar absorptivity of switchgrass varied from 39% to 47% between 350 to 2500 nm, when the initial moisture content changed from 42.86% to 59.18% on wet basis respectively. During the same experiments, absorptivity of switchgrass from the artificial light source was equivalent to 27% to 46% when the initial moisture changed from 42.86% to 59.18% on wet basis, respectively.

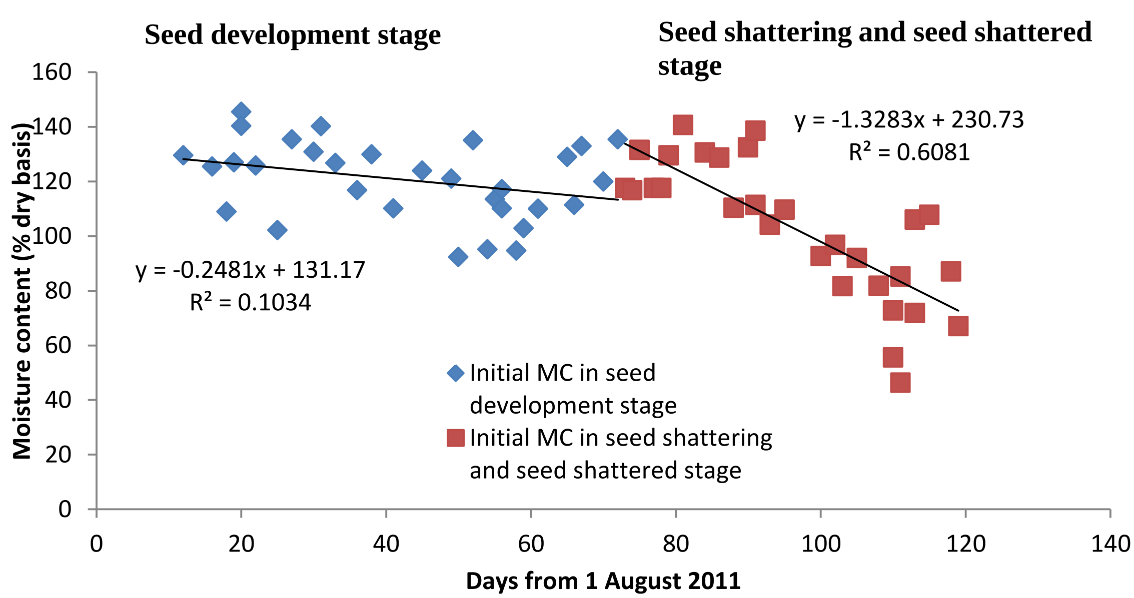

Figure 3.5. Initial moisture content of switchgrass during different maturity stages

3.2.1. Effect of weather parameters on drying rate

Pearson correlation coefficients with probability level between environmental variables and switchgrass thin layer drying rate are listed in Table 3.2. During seed development stage of maturity, radiation intensity (r=0.54), air temperature (r=0.48), and vapor pressure deficit (r=0.51) were strongly and positively correlated ($p<0.0001$) with the drying rate constant of switchgrass. A strong correlation of the alfalfa field drying rate with solar insolation, air temperature, and VPD was also observed by Rotz & Chen (1985). During their seven-year field drying experiments, correlation coefficient for solar insolation, air temperature, and VPD varied from 0.51 to 0.70, 0.30 to 0.45, and 0.25 to 0.48, respectively.

Table 3.2. Pearson correlation coefficient between switchgrass drying rates and environmental variables tested for different maturity stages in environmental chamber

Environmental variable	**Correlation coefficients (r)**	
	Seed development stage (Aug., Sept.)	Seed shattering and seed shattered stage (Oct., Nov.)
Radiation intensity	0.54**	0.70**
Vapor pressure deficit	0.51**	0.14
Air Temperature	0.48**	0.44**
Wind speed	-0.31**	-0.43**
Initial moisture content	0.23*	-0.15

*** Significant at 5% level, ** Significant at 1% level**

Models based on the Penman-Monteith model assume that the evaporation rate from a wet surface will increase with increase in wind speed. However, it was observed that, in case of crops, drying rate decreases with increase in wind speed under high solar radiation intensities (Bartzanas et al., 2010, Smith, 1990b). This happens because a part of heat energy used to increase the temperature of the swath is removed by the wind. However, under low solar radiation intensity, the effect of wind is to improve the drying rate of crops. The effect of radiation intensity and wind speed can be explained better by observing the temperature of switchgrass during the drying study. In the present study, temperature of switchgrass was estimated by using modified Penman- Monteith equation used for computation of foliage-air temperature derived by Jackson et al. (1981) below:

$$(T_c - T_a) = [r_a (R_n - G)/C_v] \left[\gamma \left(1 + \frac{r_c}{r_a}\right) / \left\{\Delta + \gamma \left(1 + \frac{r_c}{r_a}\right)\right\}\right] - \left[\frac{VPD}{\left\{\Delta + \gamma \left(1 + \frac{r_c}{r_a}\right)\right\}}\right] \quad (4)$$

Where, T_c is the crop foliage temperature (°C), T_a the air temperature (°C), r_a the aerodynamic resistance (s m^{-1}), R_n the net radiation heat flux density (W m^{-2}), G the soil heat flux density (W m^{-2}), C_v the volumetric heat capacity of air (J $°C^{-1}$ m^{-3}), r_c the canopy resistance (s m^{-1}) to vapor transport, γ the psychrometric constant (Pa $°C^{-1}$), Δ the slope of the saturated vapor pressure-temperature relation (Pa $°C^{-1}$), and VPD the vapor pressure deficit of the air (Pa). The soil heat flux density (G) was ignored in the present study as the drying took place in the environmental chamber without soil surface. Temperature of switchgrass was calculated for each experimental condition of radiation intensity, vapor pressure deficit and wind speed using the above equation (Appendix IV). The difference between calculated switchgrass temperature and air temperature for different conditions of radiation intensity, vapor pressure deficit, and wind speed is given below in Table 3.3, 3.4 and 3.5.

Table 3.3. Difference between calculated switchgrass foliage temperature and air temperature for different levels of vapor pressure deficit and wind speed at radiation intensity of 590 watt/m^2

Radiation intensity of 590 watt/m^2					
Seed development stage			**Seed shattering and seed shattered stage**		
VPD (KPa)	Wind speed (m/s)	Tc-Ta (°C)	VPD (KPa)	Wind speed (m/s)	Tc-Ta (°C)
1.93	5.83	-2.46	1.5	5.83	-2.59
1.93	3.25	-1.10	1.5	3.25	-1.00
1.93	1.30	4.04	1.5	1.30	4.86
1.44	5.83	-0.58	1.04	5.83	0.80
1.44	3.25	1.16	1.04	3.25	1.93
1.44	1.30	6.30	1.04	1.30	8.24
0.64	5.83	2.41	0.47	5.83	2.10
0.64	3.25	3.80	0.47	3.25	1.24
0.64	1.30	13.48	0.47	1.30	10.91

Table 3.4. Difference between calculated switchgrass foliage temperature and air temperature for different levels of vapor pressure deficit and wind speed at radiation intensity of 350 watt/m^2

Radiation intensity of 350 watt/m^2					
Seed development stage			**Seed shattering and seed shattered stage**		
VPD (KPa)	Wind speed (m/s)	Tc-Ta (°C)	VPD (KPa)	Wind speed (m/s)	Tc-Ta (°C)
1.93	5.83	-3.58	1.5	5.83	-3.02
1.93	3.25	-2.87	1.5	3.25	-2.19
1.93	1.30	-1.03	1.5	1.30	0.76
1.44	5.83	-2.72	1.04	5.83	-1.28
1.44	3.25	-1.27	1.04	3.25	-0.70
1.44	1.30	1.46	1.04	1.30	2.15
0.64	5.83	0.22	0.47	5.83	1.12
0.64	3.25	1.58	0.47	3.25	2.75
0.64	1.30	6.72	0.47	1.30	7.97

Table 3.5. Difference between calculated switchgrass foliage temperature and air temperature for different levels of vapor pressure deficit and wind speed at radiation intensity of 160 watt/m^2

Radiation intensity of 160 watt/m^2					
Seed development stage			**Seed shattering and seed shattered stage**		
VPD (KPa)	Wind speed (m/s)	Tc-Ta (°C)	VPD (KPa)	Wind speed (m/s)	Tc-Ta (°C)
1.93	5.83	-4.57	1.50	5.83	-4.66
1.93	3.25	-4.73	1.50	3.25	-4.58
1.93	1.30	-3.32	1.50	1.30	-3.00
1.44	5.83	-3.79	1.04	5.83	-2.92
1.44	3.25	-4.55	1.04	3.25	-4.02
1.44	1.30	-2.24	1.04	1.30	-2.24
0.64	5.83	-1.31	0.47	5.83	-0.07
0.64	3.25	-0.72	0.47	3.25	0.83
0.64	1.30	1.09	0.47	1.30	3.06

During drying of switchgrass, several transport phenomenon are occurring simultaneously. The drying rate of switchgrass is influenced by radiation intensity, vapor pressure deficit, and wind speed during drying. It was observed that when the vapor pressure deficit was high, an increase in wind speed helped to improve the drying potential of switchgrass. A negative temperature difference between switchgrass foliage and ambient air temperature at high vapor pressure deficit indicates that the switchgrass foliage is at lower temperature than the drying air. The higher vapor pressure deficit drives water from the switchgrass foliage at a higher rate, and evaporative cooling reduces leaf temperature accordingly. The rate of water removal from the surface of switchgrass increases with wind speed. At a radiation intensity of 590 watts/m^2 and vapor pressure deficit of 1.93 KPa, an increase in wind speed from 1.3 to 5.83 m/s resulted in a temperature drop between switchgrass and drying air and indicates increased drying rate. At higher vapor pressure deficit, as the wind speed decreases, evaporative cooling also decreases and the temperature drop between the switchgrass surface and air also decreases (Table 3.3). Also, it can be observed that when the vapor pressure deficit is low (0.64 KPa and 0.47 KPa), evaporative cooling is also low as the driving force for moisture removal decreases. Since less water leaves the plant surface, the temperature drop between switchgrass and drying air decreases (Table 3.3). At low wind speed (1.3 m/s), the radiation falling on the switchgrass surface increases its temperature several degrees above the temperature of air. From Table 3.3 it can be observed that at low vapor pressure deficit of 0.64 KPa and wind speed of 1.3 m/s, the temperature of switchgrass was higher than the temperature of drying air by 13.48 °C compared to a 3.80 °C increase in surface temperature over air temperature, when wind speed was 3.25 m/s. The increase in temperature of switchgrass at high radiation intensity and low wind speed drives moisture loss at higher rate from switchgrass than what can be drawn at higher wind speed. At high radiation intensity, an increase in wind speed convectively cools the switchgrass removing some of the radiation heating.

The effect of wind speed on drying rate can be observed more clearly at low radiation intensity conditions. At 160 watts/m^2 and vapor pressure deficit of 1.93 KPa, switchgrass temperature was 4.57 and 4.73 °C lower than the temperature of drying air, which indicated higher evaporative cooling due to removal of more moisture from the switchgrass surface (Table

3.5). At low radiation intensity of 160 watt/m^2 temperature of switchgrass were lower than temperature of drying air for high (1.93 KPa) and medium (1.44 KPa) vapor pressure deficit vapor pressure deficit. However, at low vapor pressure deficit (0.64 KPa) and low wind speed (1.30 m/s), the temperature of switchgrass foliage was higher than the temperature of drying air due to a lower rate of water evaporation from the surface (Table 3.5). This phenomenon explains the improvement in drying rate of switchgrass with an increase wind speed at low radiation intensity conditions.

In the present study, wind speed was found to be negatively correlated (r=-0.31) with switchgrass drying rate. When, radiation intensity and VPD were held constant, switchgrass dried under high wind speed, dried slower than switchgrass dried under low wind speed (Figure 3.7). This can be explained due to higher temperature of switchgrass at low wind speed as discussed earlier. A negative effect (r=-0.20 to -0.43) of wind speed on the drying rate of late harvested corn stover was also observed by Womac et al. (2005). However, at low radiation intensity, a positive effect of wind speed was also observed on drying rate of switchgrass. In the present study, at radiation intensity of 168 watt/m^2 and VPD of 0.64 KPa, drying rate at wind speed of 5.83 m/s was 0.00037 min^{-1} compared to 0.00023 min^{-1} at 3.25 m/s. A variable effect of wind speed was also observed by Wright et al. (2000) during lab drying of ryegrass. When the solar radiation intensity was low, the wind speed of 3 ms^{-1} increased the drying rate of ryegrass. These findings suggest that during cloudy days, when solar radiations are low, an increase in wind speed can improve the drying rate of the crop. Effect of radiation intensity, wind speed and vapor pressure deficit on switchgrass drying rate is also shown in Figures 3.6, 3.7 and 3.8. The graphs for other environmental conditions tested during the drying study are provided in Appendix V. Initial moisture content of switchgrass was also significantly correlated (p=0.0358) with the drying rate but the correlation was not strong (r=0.23) as observed for radiation and vapor pressure deficit. Faster drying rates were observed for switchgrass having higher initial moisture content. Moore & Peterson (1995) also reported that immature plants have higher initial moisture content, higher leaf to stem ratio, thinner stems and less cuticle layer thickness, which results in faster drying rate.

During seed shattering and seed shattered stage of maturity, radiation had the most significant effect ($p<0.0001$) on the drying rate constant of switchgrass. Radiation intensity was more strongly correlated ($r=0.70$) with the drying rate constant than any other environmental variable tested in this study. Air temperature was also strongly and positively correlated ($r=0.44$, $p<0.0001$) with drying rate. A strong negative correlation ($r=-0.43$, $p<0.0001$) of wind speed with drying rate constant was also observed for later stages of maturity, which was analogous to previous maturity stage tests. A variable effect of wind speed at low radiation level was also observed similar to previous maturity stage testing. High wind speed helped to improve the drying rate under low radiation. Even though the effect was not significant, switchgrass had a slightly higher drying rate of 0.00063 min^{-1}at a wind speed of 5.83 m/s compared to 0.0006 min^{-1} at 3.25 m/s at the radiation intensity of 132.58 watt/m^2. Unexpectedly, during later stages of maturity, vapor pressure deficit was found to be weakly correlated ($r=0.13$) with drying rate and the effect was not significant. The effect of initial moisture content was also not significant ($p=0.1704$) and was weakly correlated ($r=-0.15$) with drying rate. These findings suggest that during later stages of maturity, solar radiation is the most significant factor that can increase the drying potential of crop. The crop should be dried in wide swaths to intercept maximum solar insolation for faster drying rates.

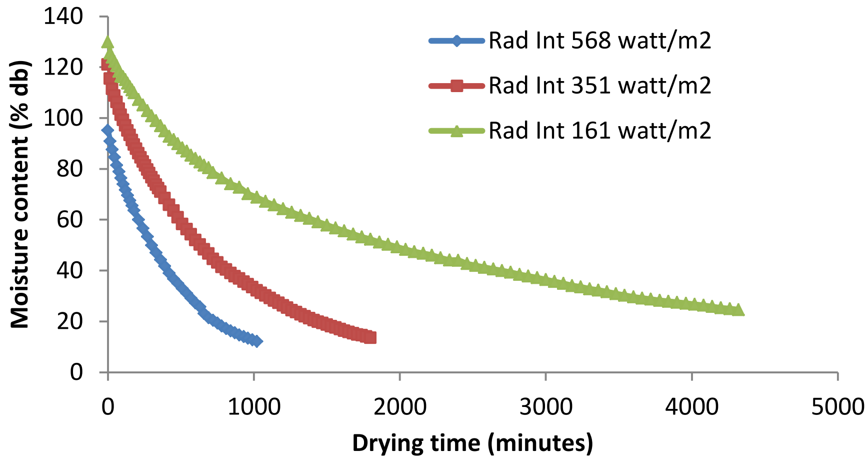

Figure 3.6. Effect of radiation intensity on drying rate of switchgrass when the vapor pressure deficit and wind speed were held at 1.44 KPa and 3.25 m/s

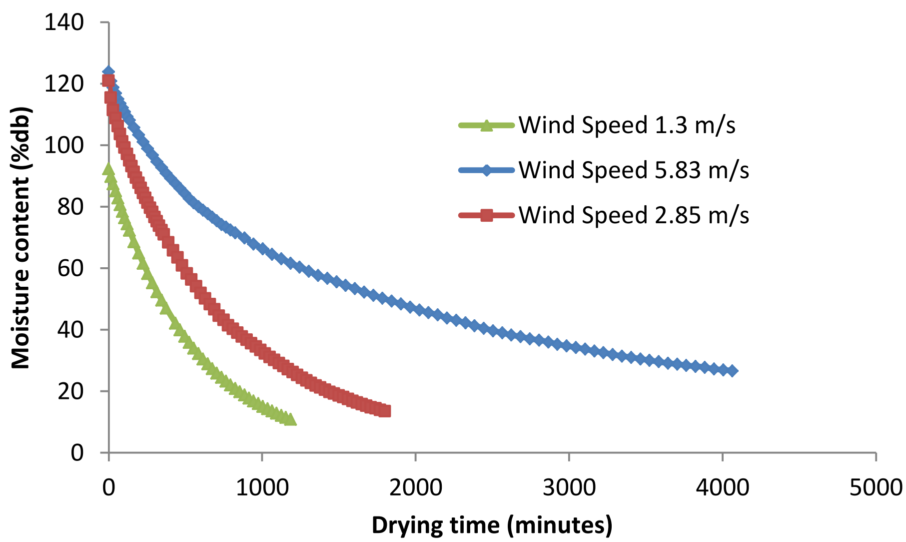

Figure 3.7. Effect of change of wind speed on drying rate of switchgrass when the vapor pressure deficit and radiation intensity were held constant at 1.44 KPa and 351 watt/m^2

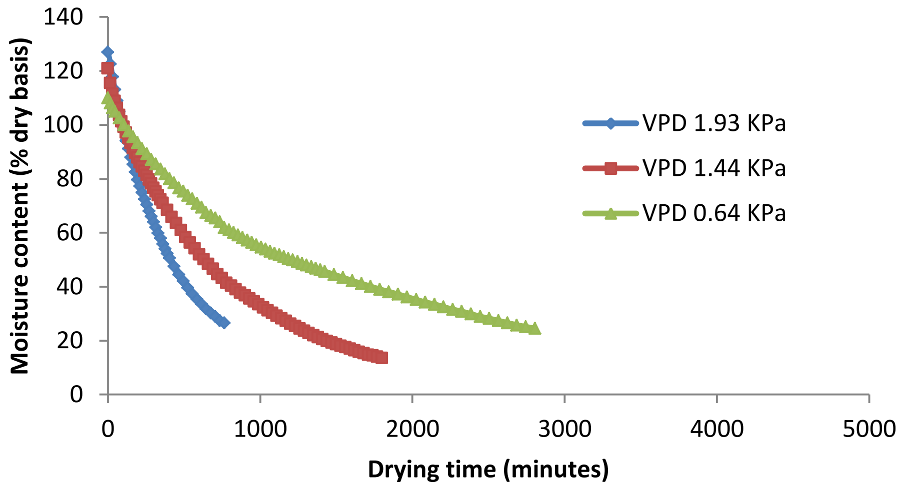

Figure 3.8. Effect of change of vapor pressure deficit on drying rate of switchgrass when the wind speed and radiation intensity were held constant at 3.25 m/s and 351 watt/m^2

3.2.2. Regression equations to predict moisture content of switchgrass

Table 3.6 lists the exponential model and regression equations relating drying rate of switchgrass with initial moisture content of switchgrass and environmental variables of radiation intensity, vapor pressure deficit, and wind speed. Separate equations for drying rate constants were provided based on the maturity stage of switchgrass. To calculate the drying rate constants from each experiment, moisture ratio data was fitted with drying time and was described by the exponential model given in equation (3). R^2 values obtained during calculation of drying rate constant from the 27 drying experiments in the seed development stage had a mean and standard deviation of 0.97 and 0.03, respectively. For seed shattering and seed shattered stage, R^2 values had a mean and standard deviation of 0.96 and 0.05, respectively. The drying constants obtained from the experiments based on the specific weather conditions and maturity stages were then used to develop the empirical model given in Table3.6.

Since, the experiments were carried only on thin layers of switchgrass; the model can closely predict the drying rates of switchgrass placed in wide swaths. In order to predict, drying rates of narrow windrows, further experimentation and calculations are required.

Table 3.6. Drying rate model and drying rate constant equations developed for different maturity stage of switchgrass based on environmental conditions of radiation intensity, vapor pressure deficit, wind speed and initial moisture content

Drying rate model used	Drying rate constant equation [a]	R^2	RMSE
$\boldsymbol{M = M_o e^{-k(t)}}$	*For* Seed development stage (Aug., Sept.): k= exp $(0.00339\,Rad + 0.5281\,VPD - 0.1511\,WS - 0.00007635\,MC - 8.74856)$	0.83	0.37
	For seed shattering and seed shattered stage (Oct., Nov.): k= exp $(0.00333\,Rad + 0.11141\,vpd - 0.14002\,WS - 0.00993\,MC - 6.64547)$	0.84	0.29

[a] k= Drying rate constant (min^{-1}), Rad= Average daily radiation intensity ($watts/m^2$), VPD= vapor pressure deficit (KPa), WS= Wind speed (m/s) at 2 m height above ground, MC= Moisture content (% dry basis)

3.3 Model validation

Both models were validated by plotting the predicted drying rate of switchgrass as a linear function of the experimental drying rate. A perfect model will have a slope of 1.0, intercept of 0.0 and correlation coefficient of 1.0 (Rotz & Chen, 1985; Wright et al., 2001). In the present study, drying rates obtained from 54 drying experiments were used for model formulation and eight separate experiments were conducted for model validation. The graph between predicted and experimental drying rates is shown in Figure 3.9 and 3.10 for both maturity stages. During seed development stage, a correlation of 0.71 was observed with an intercept and slope of 0.0003 and 1.16, respectively. R^2 value of 0.71 indicates that some error occurred, which might be due to measurement error during experimentation or model development. However, during seed shattering and seed shattered stage, a correlation of 0.96 was observed with an intercept and slope of 0.0005 and 0.82, respectively. The graphs between predicted and experimental values are also shown in Figure 3.11 and 3.12 for both maturity stages.

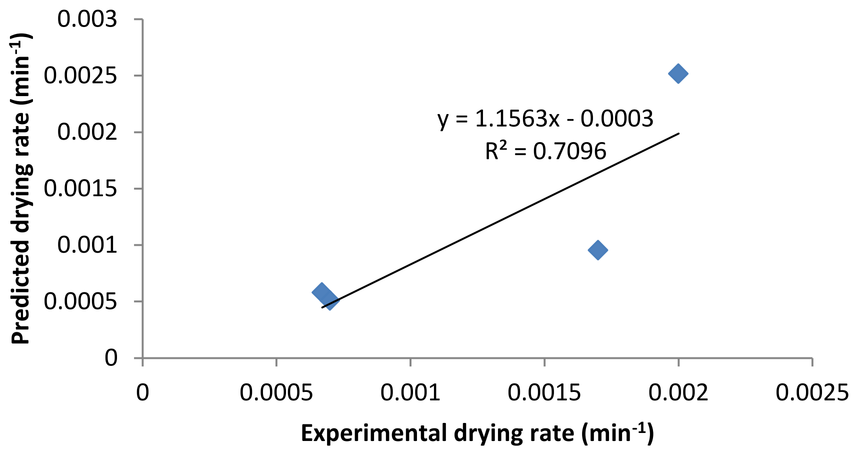

Figure 3.9. A plot between experimental and predicted drying rates of switchgrass obtained during seed development of maturity

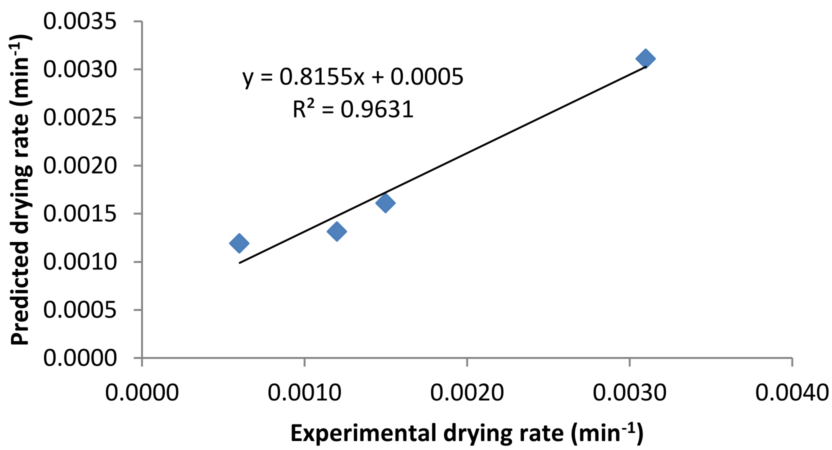

Figure 3.10. A plot between experimental and predicted drying rates of switchgrass obtained during seed development of maturity

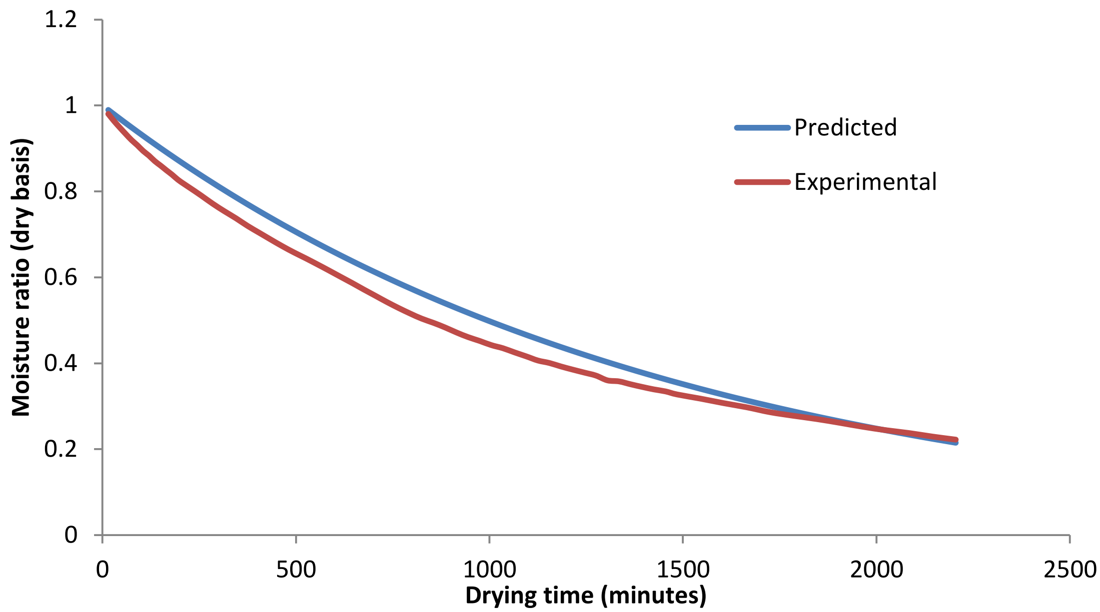

Figure 3.11. Moisture ratio vs drying time plot for predicted and experimental values of switchgrass dried at a radiation intensity of 185 watts/m2, vapor pressure deficit of 1.04 KPa, wind speed of 1.56 m/s, and initial moisture content of 126.74% on dry basis dried in Aug. and Sep.

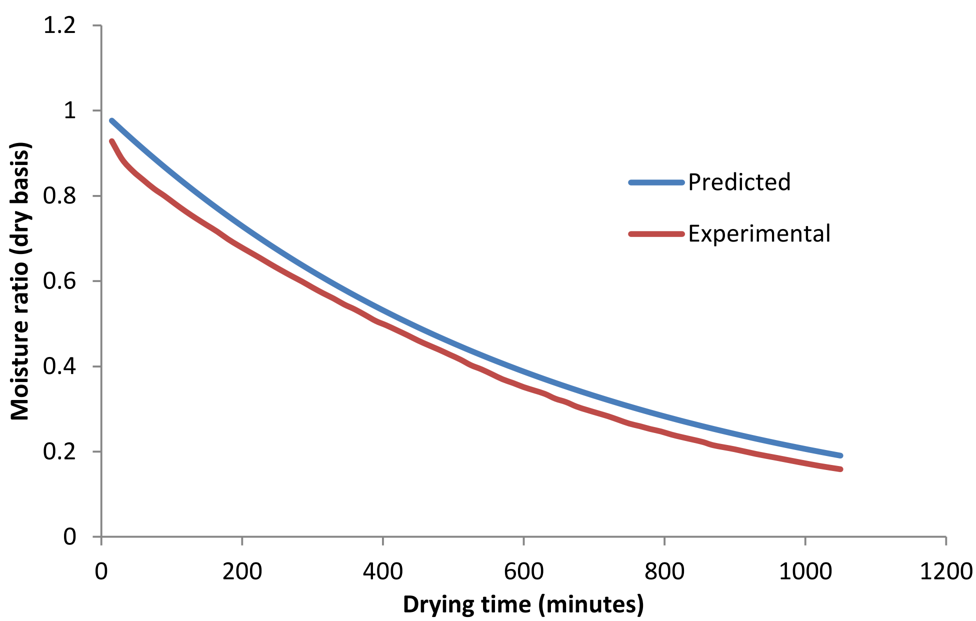

Figure 3.12. Moisture ratio vs drying time plot for predicted and experimental values of switchgrass dried at a radiation intensity of 496 watts/m2, vapor pressure deficit of 0.75 KPa, wind speed of 5.58 m/s, and initial moisture content of 81.72 % on dry basis, dried in Nov. and Oct.

3.4. Conclusions

The following conclusions were drawn from this study:

- An environmental chamber was built to evaluate the effect of weather parameters that affect the drying rate of grass during field drying. The chamber can also be used to test the effect of various conditioning treatments and swath structure under different environmental conditions.
- During drying, solar radiation was found to be the most significant factor in seed development stage and seed shattering and seed shattered stage of maturity. Vapor pressure deficit was also positively correlated with drying rate of switchgrass but the affect was not statistically significant during later maturity stages. Wind speed was negatively correlated with drying potential and a variable affect was observed during low solar radiations. When the radiation intensity was low, increase in wind speed helped to improve the drying potential of switchgrass. Initial moisture content was weakly correlated during both maturity stages.
- An empirical model was developed which can predict the drying rates of thin layers of switchgrass based on the wide range of environmental conditions (Table 3.1) tested in the present study.

Evaluating the effect of individual weather parameters on the drying rate of switchgrass helps us to better understand the drying process in the field. In the present study, it was observed that solar radiation was the most significant factor in improving the drying rate of switchgrass at seed shattering and seed shattered maturity stage. Therefore, drying switchgrass in wide swath to intercept the maximum amount of radiation at these stages of maturity is recommended. Moreover, it was observed that under low radiation intensity conditions, wind speed helps to improve the drying rate of switchgrass. Field operations such as raking or turning of the windrows are recommended to improve air circulation within a swath on cloudy days. Additionally, in the present study it was found that the effect of individual weather parameters on the drying rate of switchgrass was dependent on maturity stage. Vapor pressure deficit was strongly correlated with the drying rate during seed development stage whereas, vapor pressure deficit was weakly correlated during seed shattering and seed shattered stage. Moreover, the initial moisture content was found to be positively correlated with the drying rate at the initial maturity stage, and negatively correlated at the later stages of maturity. These findings suggest the importance of using separate drying rate models for each maturity stage of switchgrass. The empirical models developed in this study can predict the drying time of switchgrass based on the forecasted weather conditions so that the appropriate decisions can be made.

However, in the present study only the effect of maturity stage and environmental conditions of solar radiation intensity, vapor pressure deficit, and wind speed were considered. Drying rate can be dependent on several other factors such as variety, amount of leaves on plant, cuticle thickness, degree of conditioning, and swath porosity. Soil moisture levels can also negatively affect the drying rate of switchgrass. Moreover, the drying rate could also be changed if rewetting by precipitation or dew occurs during the curing period. Field operations such as raking or turning of windrows also improve the drying potential of the crop. To evaluate the effects of these parameters on the drying rate of switchgrass, the environmental chamber developed for the present study can be used in future experiments.

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CHAPTER IV

QUANTITATIVE AND QUALITATIVE LOSSES IN ROUND AND SQUARE SWITCHGRASS BALES STORED FOR BIOFUEL PURPOSES

Abstract.

Storage studies were conducted in 2009 and 2010 on large round (1.83m×1.53 m) and square (1.22 m×1.22 m×2.44 m) switchgrass bales stored for 6 months. Round and square bales were stored outside under different conditions: inside, tarped (on pallets, gravel and ground) and untarped (on pallets, gravel and ground). During both years, outside tarped bales resisted moisture accumulation and thus dry matter losses were equivalent to bales stored inside. Untarped square bales consistently had higher moisture contents than untarped round bales. In 2010, average bale moisture content increased from 11.86% (wet basis) in initial samples to 63.2, 64.06, and 44.2% on wet basis in outer, core and bottom layers of uncovered square bales. Under similar conditions, average bale moisture increased from 13.27% (wet basis) to 18.98, 13.64, and 21.88% on wet basis in outer, core and bottom layers of uncovered round bales, respectively. Highest dry matter loss (38.47%) was observed in uncovered square bales stored outside on gravel. Hemicellulose content was more severely affected than the cellulose content during storage. In 2010, untarped square bales stored on gravel, ground and pallets lost 30%, 24% and 16% of hemicellulose content, respectively.

Keywords: Switchgrass, storage, losses, cellulose, hemicellulose, lignin, ash, compositional changes, dry matter loss

4.0. Introduction

With expected rise in fossil fuel prices, there is increased interest for alternative energy sources that are cheap, renewable, and particularly derived from plant materials. Herbaceous and woody crops together with crop residues that are not direct sources of food are being considered for conversion to fuel ethanol, and other useful chemicals (Sanderson et al., 2007).

According to USDA/DOE Billion Ton Study, 189 billion liters of ethanol a year is required to replace 30% of the nation's transportation fuel requirement. This would require 454-544 million metric tons (400-500 million dry tons) of biomass from different crop sources (Gale et al., 2008). To ensure continuous availability of raw material at this scale would require storage of biomass at biorefineries or nearby sites for 6 to 12 months (Wiselogel et al., 1996). Switchgrass has a wide harvest window starting from July to February of the following year (Thorsell et al., 2004). During the harvest season from July to February, switchgrass can be harvested and directly transported to the biorefinery. For the remaining months, from March to June, biorefineries will be dependent on stored biomass or alternate sources. The main concerns in a biomass storage system are the cost of storage and the dry matter losses during the storage period. Outside unprotected storage results in higher dry matter losses, changes in composition, and loss of both structural and nonstructural components (Wiselogel et al., 1996).

Spoilage of bales during storage is mainly due to biochemical reactions of respiration by microbes (Greenlees et al., 2000). Such spoilage mainly results from high moisture content in the bales during storage. The major portion of biomass lost during storage is the water soluble part called extractives. Carbohydrates such as sucrose, glucose, and fructose are a major component of switchgrass and account for 18 to 27% of the dry weight of these extractives (Chen et al., 2010). Total monomeric and oligomeric sugars in switchgrass contribute to 25-32% of the dry weight of extractives (Chen et al., 2010). Except for the carbon content, these extractable sugars are not so important in gasification processes, but they are critical in ethanol fermentation by biochemical conversion processes (Wiselogel et al., 1996). There are several other factors which affect the quality of bales during storage such as weathering, storage surface, length of storage, erosion, bale density, and bale orientation (Wiselogel et al., 1996). Weathering and biochemical reactions which occur during storage may produce chemical compounds that affect the conversion process and efficiency of feed stock conversion to ethanol.

Various researchers have studied bale storage losses in different crops such as alfalfa (Huhnke, 1988; Huhnke et al., 1992; Huhnke, 1993; Shinners et al., 2009a), wheat straw (Huhnke, 1990), corn stover (Kevin and Ben, 2004), and bermudagrass (Mandebvu et al., 1998). These studies were directed towards the forage industry with emphasis on digestibility by ruminants and not for biofuel conversion. There are only a few studies that consider bale storage of lignocellulosic biomass to meet the needs of biorefineries. Wiselogel et. al. (1996) studied the compositional changes in round switchgrass bales stored outside and unprotected for 6.5 months in Stephenville, Texas. They reported significant changes in the extractives (+3%), cellulose (-4%) and hemicellulose (-1.4%) components of switchgrass. Sanderson et. al. (1997) also studied storage of round switchgrass bales (unprotected outside) for a period of 6 months in August, 1992 and for a period of 12 months in 1993 and 1994 in Stephenville, Texas. Dry matter loss of 13% was reported in 1992 and dry matter loss of 5% in 1993 and 1994.

There are various advantages associated with square bales such as higher density, lower transportation costs and ease of handling compared to round bales. However, there is minimal information available on storage losses associated with large square bales of switchgrass. To minimize the cost of delivery of biomass to biorefineries, both square bales and round bales may be required (Wang et al., 2009). The specific objectives of the present study are:

- Evaluate dry matter loses in round and square switchgrass bales subjected to different storage treatments.
- Study moisture variation in round and square switchgrass bales
- Evaluate compositional changes in round and square switchgrass bales after storage

Additional outside treatments with storage on wooden pallets, gravel, and ground with covered and uncovered storage were studied to obtain a possible alternative to expensive inside storage.

4.1. Materials and Methods

4.1.1. Experimental crop

A two-year storage study was conducted on switchgrass (*Panicum virgatum* L.) bales stored at the Samuel Roberts Noble Foundation research station at Burneyville, Oklahoma. In the first year of the study, switchgrass was harvested and baled in winter on 8th January, 2009. In the second year, harvest and baling occurred in spring on 18th March, 2010. Switchgrass was cut using a John Deere rotary disc mower conditioner (Model 946). Average moisture content at the time of cutting was 11% wb in 2009 and 13% in 2010. Switchgrass was baled into round and square bales without a windrow drying period. A John Deere variable chamber round baler (Model 568) and a Hesston square baler (Model 4900) were used. Each bale was wrapped with a plastic twine spaced approximately 10.16 cm (4 in) apart on round bales and 17.74 cm (7 in) apart on square bales.

4.1.2. Baling, sampling and storage

In both years, switchgrass was baled into 21 round bales (average weight of 435 kg per bale in 2009 and 414 kg in 2010) and 21 square bales (average weight of 540 kg per bale in 2009 and 507 kg in 2010). Average bale densities for round and square bales were 109 kg/m^3 and 149 kg/m^3, respectively in 2009 and 103 kg/m^3 and 148 kg/m^3, respectively in 2010 (Table 4.1). On average, round bale dimensions were 1.8 m in diameter and 1.5 m in length and square bales were 1.2 m in width 1.2 m in height and 2.4 m in length. Initial bale moisture content determined by the oven drying method, ranged from 8.8 to 15.1 % with an average of 10.9% w.b. in 2009 and varied from 9.4 to 16.6% with an average of 12.5% w.b. in 2010. The storage area consisted of a well-drained fine sandy loam soil. Spacing between bales was approximately 1.5 m to allow for air circulation and sunlight penetration, which helped to keep them dry during the storage period. Round and square bales were subjected to seven treatments:

- Inside a barn
- Stored on ground with no tarp
- Stored on ground and covered with tarp
- Stored on gravel with no tarp
- Stored on gravel and covered with tarp
- Stored on pallet with no tarp
- Stored on pallet and covered with tarp

Three replications of each treatment were stored in both years. Bales stored outside were placed on pallets, gravel and ground whereas those stored inside were placed directly on concrete. The individual polyethylene tarps used to cover the top half of the round and square bales were 2.7 m by 3.7 m. Wooden pallets and gravel kept the bales about 15 and 10 cm, respectively above the ground for those bales subjected to that storage treatment. The bales stored on ground were placed on grass sod.

Table 4.1. Comparison of round and square bale characteristics in 2009 and 2010

Bale Characteristics	Round Bale		Square Bale	
	2009	2010	2009	2010
Average weight (kg)	435	414	540	507
Average bale density (kg/m^3)	109	103	149	148
Bale dimensions (m)	1.8 diameter X 1.5 length		1.2 wide x 1.2 height X 2.4 length	
Initial moisture content (% w.b.)	9.9	13.25	11.84	11.65

4.1.3. Sampling in 2009

Before storage, all bales were weighed and sampled using a core sampler 5.1 cm in diameter and 61 cm in length. A total of six core samples were taken from each bale. In the case of round bales, three samples were taken from both directions, along the curved surface of the bale. In case of square bales, three samples were taken from both directions along the side (2.4 m X 1.2 m) forming the length and height of the bale. After initial sampling, the holes from where the samples were collected were filled with form material to avoid any moisture accumulation. Samples were combined to make one composite sample and analyzed for moisture and composition. After 6 months in storage, samples were taken from each bale for compositional and dry matter analysis, using the procedure followed during initial sampling of the bales. Moisture contents initially and then after 6 months in storage was analyzed by the oven drying method. The six month storage study was completed on July 7, 2009.

4.1.4. Sampling in 2010

In 2010, a total of six core samples were taken at the start of the storage study from each bale, as was done in 2009. Compared to 2009, a more extensive sampling approach was followed in 2010 during final sampling at the end of six months. A corer which was 2.5 cm in diameter and 61 cm in length was used to take core samples (Uni-Forage Sampler; Star Quality Samplers, Edmonton, AB, Canada). For round bales, samples were collected from 30 equally spaced locations around the bales (Figure 4.1). Outer layer samples were taken from the outer 20 cm. Deep core samples were then extracted from the same sampling locations to a depth of 61 cm. Finally, bottom layer samples were taken from the outer 20 cm of the bale bottom, in contact with ground, pallets and gravel. Samples from the outer layer, inner core and bottom were stored in sealed polyethylene bags and analyzed separately for moisture content and chemical composition.

Similarly, for square bales, 30 equally spaced sampling locations were selected, 15 of which were at top and 15 at bottom of the bales (Figure 4.2a, b). Samples were collected from the outer 20 cm of the sampling locations at the top and evaluated as outer layer samples (Figure 4.2b). Similarly, bottom 20 cm layer samples were collected from the bottom 15 sampling locations which were in contact with ground, pallet or gravel. Inner layer samples up to a depth of 61cm were extracted from the top and bottom layer sampling locations and were pooled and evaluated as core samples (Figure 4.2b).

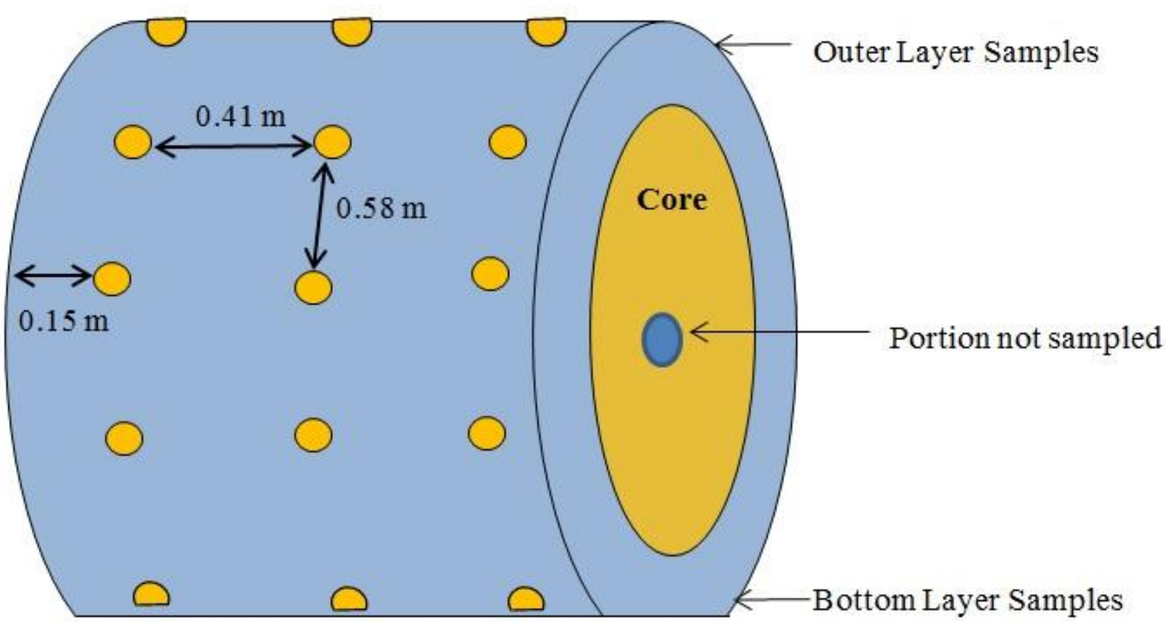

Figure 4.1. Final sampling locations of large round switchgrass bales taken after 6 months in storage at Burneyville, OK in 2010. Samples were taken from 30 locations all over the curved sides of the bales.

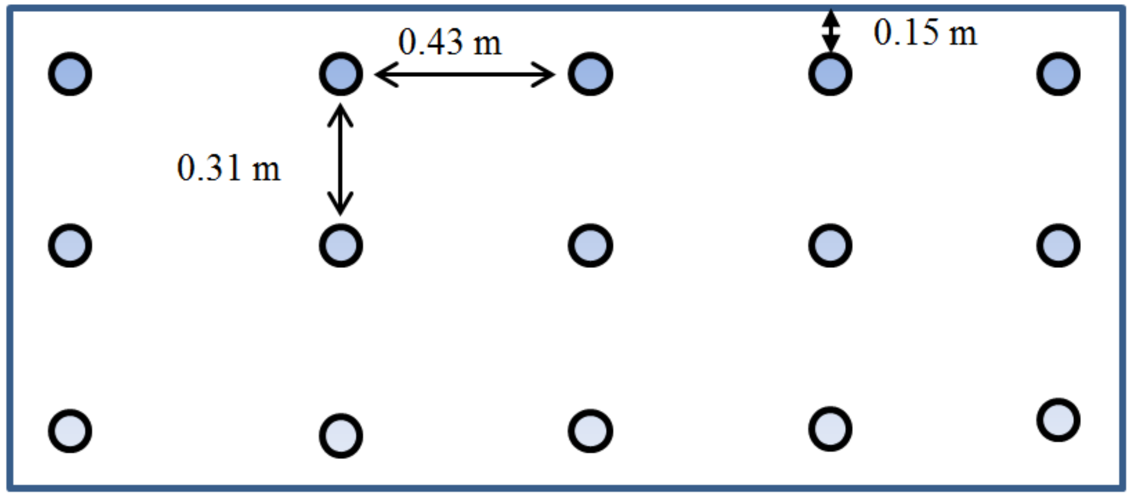

Figure 4.2a. Top and bottom views of sampling locations

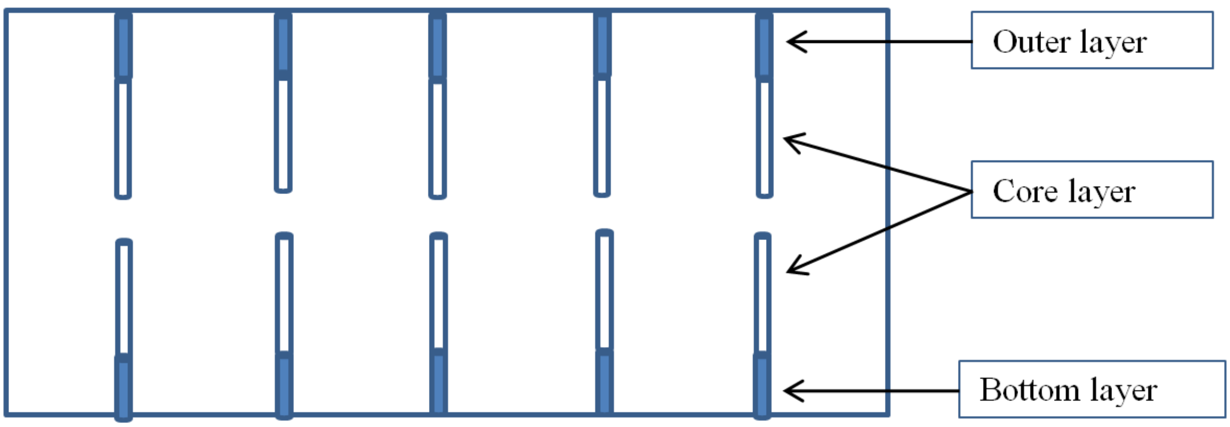

Figure 4.2b. Side view. Sampling locations of large square switchgrass bales taken after 6 months in storage at Burneyville, OK in 2010. Samples from two depths were taken from 15 locations on top and 15 locations on the bottom of each bale.

4.1.5. Temperature and rainfall

During 2009, a total of 688 mm of rainfall was received during the periods from January through July. A major rainfall event was recorded in April 2009 with a total precipitation of 390 mm. During 2010, a total of 586 mm of rainfall was received from March to September. Mean monthly temperatures for storage months are also compared in Table 4.2.

Table 4.2. Monthly total rainfall and mean temperature at Burneyville, OK for the storage period in 2009 and 2010

Month	**Total Rainfall (mm)**		**Mean Temperature (°C)**	
	2009	**2010**	**2009**	**2010**
January	8		5.11	
February	40		10.99	
March	48	22	13.61	11.00
April	390	74	16.83	17.28
May	124	107	20.22	21.72
June	63	55	27.22	28.00
July	14	129	27.39	27.89
August		25		29.44
September		173		24.22
Total	688	586		

4.1.6. Laboratory analysis of switchgrass samples

Change in bale weights and moisture contents from beginning to end of the study were used to calculate dry matter losses. Since separate samples were collected in 2010 from outer 20 cm, core and bottom 20 cm of the bales, the samples were analyzed separately for moisture content and chemical changes. Analyzing samples separately provided the advantage of adjusting the final moisture content according to the volume occupied by each layer; thus resulting in better estimation of dry matter loss and chemical composition. The volume adjusted moisture content of each bale was calculated by:

$$M_f = \frac{(M_{ol} \,.\, V_{ol} + M_c \,.\, V_c + M_b \,.\, V_b)}{V_t}$$

Where, M is the moisture content on wet basis, V is the volume of the bale section and the subscripts represents (f) the final adjusted, (ol) the outer layer, (c) the core, (b) the bottom, and (t) the total volume of the bale.

For dry matter loss and compositional analysis, samples were oven dried at 65 $^{\circ}$C for 72 h to calculate moisture content. Dried samples were ground to 1mm using a Wiley mill and passed through a 1.0 mm screen before ADL (Acid Detergent Lignin), ADF (Acid Detergent Fiber), protein, minerals content and ash analysis. Cell wall fractions such as cellulose, hemicellulose and lignin are left in NDF portion after extraction with a detergent, at neutral pH. The ADF fraction primarily consists of cellulose and lignin portion and was developed as a preliminary step for calculation of lignin content as ADL. Hemicellulose content is often calculated as a difference of NDF and ADF fraction whereas, cellulose is calculated as the difference of ADF and ADL fraction (Jung & Lamb, 2004; Wolfrum & Lorenz, 2009). Crude proteins included mixtures of true proteins (composed of amino acids) and non-protein nitrogen. The crude protein in the samples was derived by multiplying the nitrogen content by a factor of 6.25 (Hames et al., 2003). Lignin found in cell walls was determined by using standard ADL procedures.

4.1.7. Statistics

Dry matter loss data was statistically analyzed by using Randomized Complete Block Design in SAS 9.3 (SAS Institute,NC, 2010). For changes in chemical composition, differences between the treatments as well as their retention ratios were compared after 6 months in storage using SAS.

4.2. Results and discussion

4.2.1. Moisture content

Initial moisture content of the switchgrass bales was less than 15% w.b. for all the treatments in both years (Table 4.3, 4.4). Bales below this moisture content are generally stable during storage, if protected from rainfall (Harrigan and Rotz, 1994). Hay baled above 18% w.b. heats during the storage period due to microbial respiration, resulting in dry matter losses and low quality biomass (Moore and Peterson, 1995).

<u>2009</u>

No significant difference ($p=0.9592$) was observed in moisture content, between inside stored round and square bales (10.62% w.b.) and outside stored round and square bales covered with tarps (10.35% w.b.). Round bales stored outside and covered with a tarp (9.02% w.b.) had significantly (p=0.0468) lower moisture content than untarped round bales (19.75% w.b.). Also, square bales covered with a tarp (11.68% w.b.) had significantly (p<0.0001) lower moisture content than untarped square bales (50.20% w.b.). No significant difference was observed between tarped round and tarped square bales. Whereas, uncovered square bales (50.20% w.b.) had significantly higher moisture content than uncovered round bales (19.75% w.b.). These results confirmed that covering round and square bales was important to resist moisture accumulation during storage. Also, in comparison to initial moisture content, a significant increase in final moisture content was observed for square untarped bales (Table 4.3).

Table 4.3. Moisture content in switchgrass bales stored under different storage conditions in 2009

Storage treatment		Initial MC*		MC after 6 months*	
		Round	**Square**	**Round**	**Square**
Tarped	Pallet	9.97 ab	12.10 ab	9.85 b	9.16 b
	Ground	10.5 a	10.80 b	8.38 b	15.63 b
	Gravel	9.53 ab	11.87 ab	8.82 b	10.26 b
Untarped	Pallet	9.73 ab	12.4 ab	22.14 a	48.07 a†
	Ground	10.53 a	11.63 ab	19.13 a	52.32 a†
	Gravel	9.10 b	11.23 ab	17.98 a	-
Inside		10.00 ab	12.87 a	10.24 b	10.99 b
LSD		1.10	2.00	6.31	21.10

[*] Means within columns followed by different letters are significantly different at the 95% confidence level. † Significant at the 0.05 and 0.01 probability levels, respectively, using paired t-test comparing initial and final values for each storage method. LSD is the least significant difference of mean values above which the treatments are statistically different from each other.

2010

Similar trends in moisture content variations were observed between the storage treatments, when compared to 2009. In case of square bales, no significant difference was observed in moisture content, between inside storage treatments (9.80% w.b.) and outside tarped treatments (11.96% w.b.). However, in case of round bales, the bales stored on ground and covered with tarp had a significant higher moisture content of 13.47% w.b. compared to 8.91%

w.b. in inside stored round bales. Round bales stored on pallet and gravel and covered with tarp had statistically similar moisture content of 10.32% w.b. compared to 8.91% w.b. in inside stored bales. This finding suggest that covering bales with a tarp and storing them on elevated surface such as pallet or gravel was equally affective as inside storage in terms of resisting moisture accumulation during storage. During the last month of storage, the tarp from one of the square bale stored on gravel was blown off by the wind. This incident resulted in higher moisture content of 22.65% w.b. compared to other tarped treatments having moisture content of 11.67% w.b. Therefore, the replication was not included for moisture content estimation. Round bales stored untarped (15.94% w.b.) had significantly ($p=0.0005$) higher moisture content than round tarped bales (11.37% w.b.). A highly significant difference ($p<0.0001$) was observed between untarped square bales and tarped square bales. Untarped square bales had much higher moisture content of 60.13% w.b. compared to tarped square bales having a moisture content of 11.96% w.b. In addition, round untarped bales (15.94% w.b.) had significantly less moisture than untarped square bales (60.13% w.b.). These results confirmed that untarped square bales accumulate more moisture than untarped round bales. No significant difference was observed between round tarped and square tarped bales. A significant increase in final moisture content was also observed in untarped square bales when compared to initial moisture content.

Table 4.4. Moisture content in switchgrass bales stored under different storage conditions in 2010

Storage treatment		Initial Moisture*		MC after 6 months*	
		Round	**Square**	**Round**	**Square**
Tarped	Pallet	12.66 bc	10.35 c	9.28 c	10.93 b
	Ground	13.82 ab	11.14 bc	13.47 ab	13.34 b
	Gravel	13.14 abc	10.42 c	11.35 bc	11.62 b
Untarped	Pallet	12.57 c	10.58 c	16.92 a	61.32 a[†]
	Ground	14.23 a	13.31 ab	16.49 a	57.37 a[†]
	Gravel	13.31 abc	11.69 abc	14.41 ab	61.69 a[†]
Inside		13.03 abc	14.12 a	8.91 c	9.80 b
LSD		1.24	2.67	4.07	4.93

[*] Mean within columns followed by different letters are significantly different at the 95% confidence level. [†] Significant at the 0.05 and 0.01 probability levels, respectively, using paired t-test comparing initial and final values for each storage method. LSD is the least significant difference of mean values above which the treatments are statistically different from each other.

4.2.1.1. Moisture variation in outer, core and bottom of round and square bales in 2010

The moisture content variation in the outer layer, core and bottom of switchgrass bales stored in 2010 are presented in Figure 4.3 and Table 4.5.

<u>Outer layer</u>

In the outer layer of the bales, tarped round and square bales had statistically similar moisture content as inside stored bales. However, in case of untarped round and square bales, the outer layers had significantly higher moisture content than tarped round and tarped square bales. In the outer layers, untarped round bales had a moisture content of 18.98% w.b. and was significantly higher than tarped round bales having a moisture content of 10.56% w.b. Similarly, untarped square bales had a significantly higher moisture content of 63.44% w.b. in outer layers compared to 8.58% w.b. in tarped square bales. Also, untarped square bales (63.44% w.b.) had a significantly higher moisture content in outer layers compared to untarped round bales (18.98% w.b.). However, no significant difference in moisture content was observed between the outer layers of tarped round and tarped square bales. A significant increase in final moisture content was also observed for untarped round and square bales when compared to initial moisture content.

Core

Core of the round bales was slightly less affected during storage compared to the outer layer. Statistically similar moisture content variation was observed in tarped round (10.92% w.b.) and untarped round (13.64% w.b.) bales, except for tarped round bales stored on pellet. However, moisture content in the core of untarped square bales (64.06% w.b.) was significantly higher than core of tarped square bales (11.05% w.b.). Due to geometry and higher density of square bales, moisture was trapped inside the core of the square bales resulting in more spoilage. Round bales tend to shed moisture along the sides of the bales, keeping the core less affected. A highly significant difference in moisture content was also observed between untarped round (13.64% w.b.) and untarped square bales (64.06% w.b.). A significant increase in moisture content was also observed in the core of untarped square bales when compared to initial moisture content.

Bottom layer

In the bottom layers of the bales, untarped square bales (44.2% w.b.) had significantly ($p<0.0001$) higher moisture than tarped square bales (18.19% w.b.). Tarped round bales stored on pallets (10.68% w.b.) and gravel (15.06% w.b.) had significantly less moisture in bale bottom than tarped round bales stored on ground (31.26% w.b.). These findings confirmed that storing bales on pallets and gravel helped to protect the bale bottom from moisture accumulation. The bale area that was in contact with the ground had visible decay compared to bales stored on gravel or a pallet. Also, bales stored on pallets (21.32% w.b.) had significantly ($p=0.002$) lower moisture in the bale bottom than bales stored on gravel (25.7% w.b.). In addition, for the bottom layer, untarped square bales (44.2% w.b.) had significantly higher moisture content than untarped round bales (21.88% w.b.).

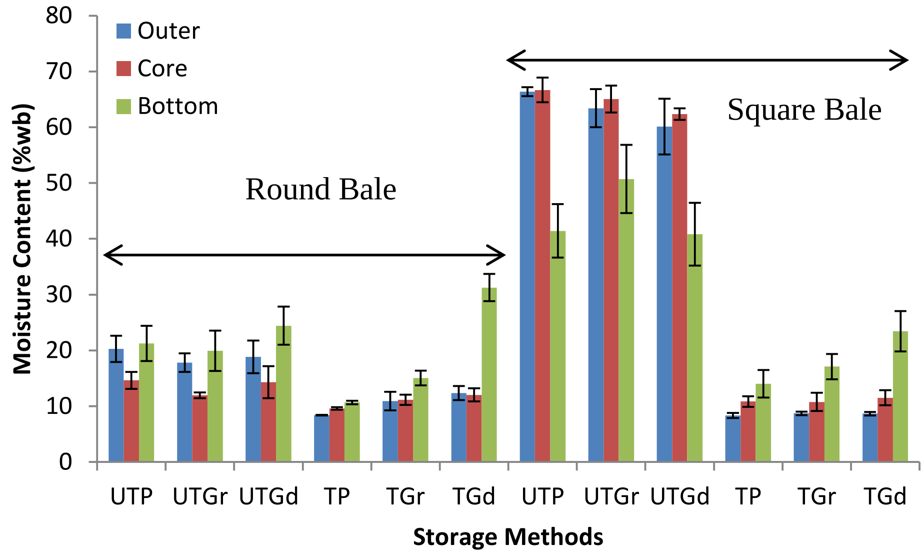

Figure 4.3. Moisture content shown with error bars in outer, core and bottom of round and square switchgrass bales stored for 6 months in 2010. Storage method indicates UTP=untarped on pallet, UTGr=untarped on gravel, UTGd=untarped on ground, TP=tarped on pallet, TGr=tarped on gravel, TGd=tarped on ground

Table 4.5. Moisture content in outer layer, core and bottom of switchgrass bales stored under different storage conditions in 2010

		Moisture content after 6 months*					
Storage treatment		Round	Square	Round	Square	Round	Square
		Outer Layer		Core		Bottom	
Tarped	Pallet	8.40 c	8.34 b	9.59 b	10.85 b	10.68 d	14.03 bc
	Ground	12.35 bc	8.67 b	12.02 ab	11.51 b	31.26 a†	23.45 b†
	Gravel	10.92 c	8.72 b	11.15 ab	10.78 b	15.06 dc	17.10 bc
Untarped	Pallet	20.27 a†	66.08 a†	14.64 a	64.79 a†	21.27 bc$^{\Theta}$	41.05 a†
	Ground	18.85 a$^{\Theta}$	60.12 a†	14.32 a	62.35 a†	24.44 ab†	40.83 a†
	Gravel	17.81 ab$^{\Theta}$	63.4 a†	11.96 ab	65.05 a†	19.92 bc	50.72 a†
Inside		8.91 c	9.8 b	8.91 b	9.80 b	8.91 d	9.8 c
LSD		5.58	7.14	4.40	12.33	7.52	13.58

[*] Means within columns followed by different letters are significantly different at the 95% confidence level. $^{\Theta, \dagger}$ Significant at the 0.05 and 0.01 probability levels, respectively, using paired t- test comparing initial and final values for each storage method. LSD is the least significant difference of mean values above which the treatments are statistically different from each other.

4.2.2. **Dry matter loss**

2009

No statistical difference (p=0.8456) in dry matter loss was observed between inside (1.78% d.b.) and tarped storage treatments (2.49% d.b.) which suggested that tarped treatments were affective in resisting dry matter loss. Most of the trends observed for dry matter loss were similar to moisture trends, as high moisture results in higher dry matter loss. Dry matter loss results for 2009 are presented in Table 4.6. Round tarped bales (1.12% d.b.) lost significantly (p<0.0001) less dry matter than round untarped bales (16.66% d.b.). Similarly, square tarped bales (3.85% d.b.) lost significantly (p<0.0001) less dry matter than untarped square bales (28.39% d.b.). Untarped square bales (28.39% d.b.) lost significantly higher dry matter than untarped round bales (16.66% d.b.) and no significant difference was observed between tarped round and tarped square bales.

Table 4.6. Dry matter loss from round and square switchgrass bales stored under different storage conditions for 6 months in 2009.

Storage treatment		**Dry Matter Loss (% of total)***	
		Round	Square
Tarped	Pallet	0.37 b	0.61 b
	Ground	1.41 b	10.59 b
	Gravel	1.58 b	0.3 b
Untarped	Pallet	15.38 a	25.62 a
	Ground	17.34 a	31.15 a
	Gravel	17.27 a	-
Inside		0.83 b	3.13 b
LSD		12.66	11.76

[*] Means within columns followed by different letters are significantly different at the 95% confidence level. LSD is the least significant difference of mean values above which the treatments are statistically different from each other.

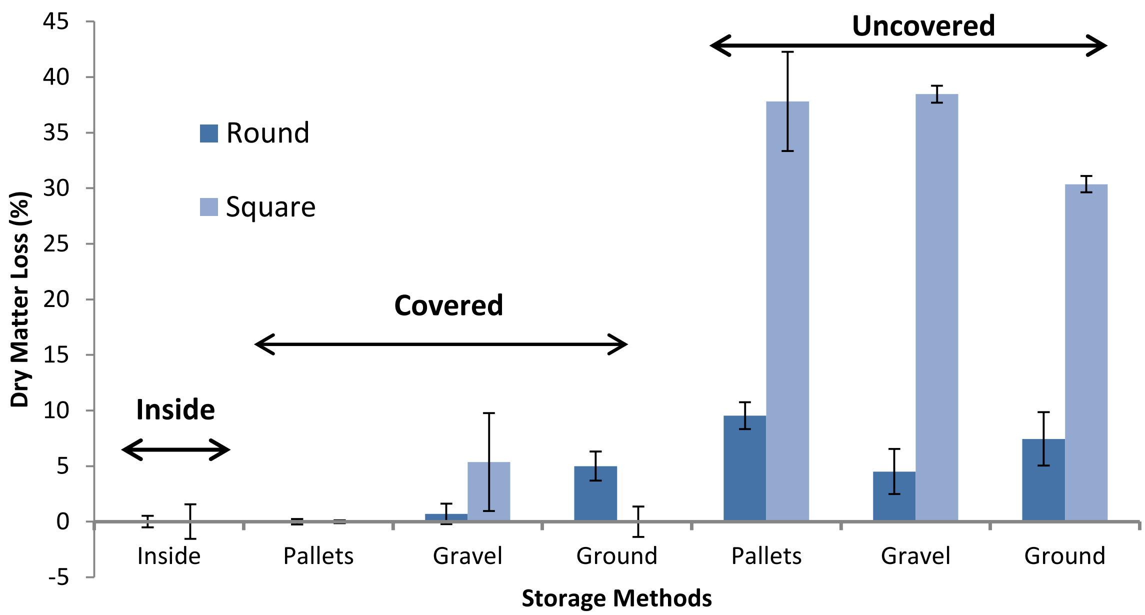

Figure 4.4. Dry matter loss from round and square switchgrass bales stored under different storage conditions for 6 months in 2010.

<u>2010</u>

Dry matter loss data for 2010 is presented in Figure 4.4 and Table 4.7. A negligible amount of dry matter was lost from bales stored inside and bales stored on pallets and covered with tarp. Bales stored outside and protected with tarps lost on an average of 1.11% of dry matter during storage and were similar ($p= 0.13$) to losses observed in inside stored bales (0% dry matter basis). Round bales stored under a tarp lost on average 0.42% of dry matter and was significantly ($p=0.002$) lower than 6.07% dry matter lost from untarped round bales. Tarped square bales also lost significantly ($p<0.0001$) less dry matter, 1.79%, compared to 35.55% from untarped square bales. No significant difference ($p=0.2214$) was observed between elevated bales stored on pallets or gravel and bales stored on ground. These results indicate that under similar weather conditions, storing round and square bales protected with polyethylene tarp is affective in resisting dry matter loss similar to inside barn storage. Under similar conditions, untarped round bales lost significantly less dry matter (average 6.09% dry matter basis) than untarped square bales (average 35.55% dry matter basis). Also, no significant difference in dry matter loss was observed between tarped round and tarped square bales. Dry matter loss observations suggest that square bales stored outside should be protected with tarps to avoid quantitative and qualitative losses.

Table 4.7. Dry matter loss from round and square switchgrass bales stored under different storage conditions for 6 months in 2010.

Storage treatment		**Dry Matter Loss (% of total)** [*]	
		Round	Square
Tarped	Pallet	0 c	0 c
	Ground	1.44 c	0.61 c
	Gravel	0.5 c	5.82 c
Untarped	Pallet	8.82 a	37.81 a
	Ground	5.42 ab	30.36 a
	Gravel	3.52 bc	38.47 a
Inside		0 c	0.19 c
LSD		4.38	8.71

[*] Means within columns followed by different letters are significantly different at the 95% confidence level. LSD is the least significant difference of mean values above which the treatments are statistically different from each other.

4.2.3. Compositional changes

4.2.3.1. Storage compositional changes in 2009

Initial NDF content of switchgrass bales varied from 77.46% to 84.77% on dry basis with an average of 81.38% (Table 4.8). A slight increase in NDF content was observed for most of the treatments. This increase in fiber content is consistent to the results obtained by Shinners et al. (2009a, b). These increases might be due to loss of extractives and carbohydrates which are more severely affected than the fiber portion. Cellulose content also increased slightly during storage (Table 4.9). However, no significant difference was observed between inside and outside tarped bales (p=0.6465) and round tarped and round untarped bales (p=0.2836). A significant difference in cellulose content was obtained between square bales, but no particular trend was observed.

Table 4.8. Assessment of NDF content variation in switchgrass bales stored for 6 months and 27.07 in. of accumulative rainfall in 2009.

Storage treatment		**Final NDF Content* (% d.m. basis)**		**[r] Retention ratio***	
		Round	Square	Round	Square
Tarped	Pallet	83.5 a	83.56 a	1.05 a	1.01 a
	Ground	84.09 a	84.24 a	1.06 a	1.01 a
	Gravel	82.27 a	82.39 a	1.05 a	0.99 a
Untarped	Pallet	83.13 a	82.52 a	1.05 a	0.99 a
	Ground	83.08 a	84.06 a	1.06 a	1.01 a
	Gravel	84.05 a	84.84 a	1.06 a	1.02 a
Inside		81.76 a	86.61 a	0.98 a	1.04 a
LSD		5.79	4.80	0.05	0.07

[*] Means within columns followed by different letters are significantly different at the 95% confidence level. [r] Ratio of constituent value after 6 months in storage to initial value into storage. LSD is the least significant difference of mean values above which the treatments are statistically different from each other. Since the results are presented on dry matter basis, small increase in NDF content is due to decrease of soluble components, rather than an actual increase in NDF content.

Table 4.9. Assessment of cellulose content variation in switchgrass bales stored for 6 months and 27.07 in. of accumulative rainfall in 2009.

Storage treatment		**Final Cellulose Content* (% d.m. basis)**		**[r] Retention ratio***	
		Round	Square	Round	Square
Tarped	Pallet	40.08 a	45.86 a	0.88 b	1.05 a
	Ground	42.41 a	42.70 ab	0.96 ab	1.00 a
	Gravel	39.64 a	41.82 b	0.95 ab	1.07 a
Untarped	Pallet	42.66 a	43.37 ab	1.04 a	1.02 a
	Ground	41.01 a	44.22 ab	0.99 ab	1.02 a
	Gravel	42.61 a	43.87 ab	1.00 ab	1.03 a
Inside		40.36 a	43.58 ab	0.88 b	1.02 a
LSD		5.28	3.88	0.14	0.13

[*] Means within columns followed by different letters are significantly different at the 95% confidence level. [r] Ratio of constituent value after 6 months in storage to initial value into storage. LSD is the least significant difference of mean values above which the treatments are statistically different from each other. Since the results are presented on dry matter basis, small increase in cellulose content is due to decrease of soluble components, rather than an actual increase in cellulose content.

Hemicellulose content was found to be more affected than the cellulose content during storage. Initial hemicellulose content varied from 25.10% to 34.11% with an average of 29.04%

on dry basis. Significant differences (p=0.0002) were found between round and square bales with square bales being more affected than round bales (Table 4.10). No significant change was observed in inside and tarped bales stored on pallets, gravel and ground (p=0.9604) suggesting covering bales was helpful to resist hemicellulose losses during storage. No significant difference (p=0.3717) was observed between round tarped (31.26% d.b.) and round untarped bales (30.25% d.b.) but a highly significant difference (p<0.0001) was observed between square tarped (29.29% d.b.) and square untarped bales (23.92% d.b.). On average, hemicellulose content decreased by 22% in untarped square bales stored on pallets, gravel and ground when compared to initial values. Also, untarped square bales (23.92% d.b.) had significantly lower hemicellulose content than uncovered round bales (30.25% d.b.).

Table 4.10. Assessment of hemicellulose content variation in switchgrass bales stored for 6 months and 27.07 in. of accumulative rainfall in 2009.

Storage treatment		**Final Hemicellulose Content* (% d.m. basis)**		**[r] Retention ratio***	
		Round	Square	Round	Square
Tarped	Pallet	30.28 a	27.40 abc	1.17 a	0.94 abc
	Ground	31.72 a	30.82 a	1.24 a	0.79 a
	Gravel	31.78 a	29.64 ab	1.16 a	0.88 ab
Untarped	Pallet	29.67 a	23.67 c	0.99 a	0.77 bc
	Ground	31.18 a	31.18 c	1.11 a	0.94 c
	Gravel	29.91 a	24.42 bc	1.08 a	0.79 abc
Inside		30.16 a	32.92 a	1.03 a	1.09 ab
LSD		2.53	5.60	0.14	0.24

[*] Means within columns followed by different letters are significantly different at the 95% confidence level. [r] Ratio of constituent value after 6 months in storage to initial value into storage. LSD is the least significant difference of mean values above which the treatments are statistically different from each other.

An increase in lignin content was also observed for all the treatments except for square bales stored inside and square bales stored on pallets and covered with tarp (Table 4.11). Lignin content in initial samples varied from 6.76% on dry matter basis to 10.95% with an average of 9.2%. In the final samples lignin content varied from 7.97% to 17.51% with an average of 12% on dry matter basis. An increase in lignin content was in agreement to several studies done on the bales by Agblevor et al. (1994) and Wiselogel et al., (1996). There was a highly significant difference ($p<0.0001$) observed for lignin content in tarped and untarped square bales. Uncovered square bales stored on pallets, gravel and ground had an average initial lignin content of 9.72% on dry basis, which increased to 16.07% after storage. This increase in lignin content in uncovered square bales was due to the loss of sugars and extractives caused by precipitation and microbial growth. Humic substances can also form during storage if the bales are unprotected from precipitation and sunlight (Agblevor et al., 1994). Humic compounds are partially water insoluble and they are formed by the browning reactions between amino compounds and decomposed carbohydrate products due to weathering (Agblevor et al., 1994). These humic substances are insoluble in hydrolysis liquor and thus analyzed as lignin by the wet chemical methods resulting in an increase in lignin content. Consequently, increase in lignin content can also be associated with sugar losses and excessive weathering of biomass. It can be observed from Table 4. 11 that covered treatments have less increase in lignin content than uncovered treatments, specifically in the case of square bales. The result confirms that covering square bales is important to avoid weathering and maintaining quality when stored outside.

Table 4.11. Assessment of lignin content variation in switchgrass bales stored for 6 months and 27.07 in. of accumulative rainfall in 2009.

Storage treatment		**Final Lignin Content* (% d.m. basis)**		**[r] Retention ratio***	
		Round	Square	Round	Square
Tarped	Pallet	13.14 a	10.31 b	1.69 a	0.98 c
	Ground	9.96 a	10.72 b	1.06 b	1.11 c
	Gravel	10.86 a	10.94 b	1.22 ab	1.25 bc
Untarped	Pallet	10.80 a	15.49 a	1.4 ab	1.58 ab
	Ground	10.90 a	16.17 a	1.2 ab	1.66 a
	Gravel	11.53 a	16.55 a	1.26 ab	1.72 a
Inside		11.24 a	10.11 b	1.47 ab	0.94 c
LSD		3.80	3.14	0.61	0.33

[*] Means within columns followed by different letters are significantly different at the 95% confidence level. [r] Ratio of constituent value after 6 months in storage to initial value into storage. LSD is the least significant difference of mean values above which the treatments are statistically different from each other.

Initial crude protein content varied from 1.46% to 5.60% with an average of 2.66% on dry basis. There was an increase in crude protein content for most of the storage treatments (Table 4.12) but no significant differences were observed between taped and untarped square bales treatments. A significant difference was observed in round bale treatments, but no identifiable trend was observed. An increase in protein content was also reported by other researchers (Harrigan and Rotz, 1994b; Huhnke, 1988, 1990b; Huhnke et al., 1992; Shinners et al., 2009a, b).

Table 4.12. Assessment of crude protein content variation in switchgrass bales stored for 6 months and 27.07 in. of accumulative rainfall in 2009.

Storage treatment		**Final Crude protein Content* (% d.m. basis)**		**[r] Retention ratio***	
		Round	Square	Round	Square
Tarped	Pallet	5.66 bc	6.72 a	2.30 ab	3.01 a
	Ground	4.87 c	6.18 a	2.05 ab	3.07 a
	Gravel	6.83 ab	5.44 a	2.32 ab	2.17 a
Untarped	Pallet	5.70 bc	6.19 a	2.12 ab	2.96 a
	Ground	5.46 bc	5.30 a	1.86 b	2.2 a
	Gravel	7.59 a	6.59 a	2.92 a	2.37 a
Inside		5.84 abc	6.17 a	2.32 ab	2.56 a
LSD		1.78	2.4	1.18	2.21

[*] Means within columns followed by different letters are significantly different at the 95% confidence level. [r] Ratio of constituent value after 6 months in storage to initial value into storage. LSD is the least significant difference of mean values above which the treatments are statistically different from each other. Since the results are presented on dry matter basis, increase in protein content is due to decrease of soluble components, rather than an actual increase in protein content.

Ash is considered to be the most stable part of biomass, not changing significantly with time. An average of 3.83% ash was recorded in initial samples and an average of 3.9% was observed in final samples (Table 4.13). No statistical difference was observed in ash content. Minor changes were observed which could be due to leaching and losses of sugars and extractives in weathered portions (Agblevor et. al., 1994).

Table 4.13. Assessment of ash content variation in switchgrass bales stored for 6 months and 27.07 in. of accumulative rainfall in 2009.

Storage treatment		**Final Ash Content * (% d.m. basis)**		**[r] Retention ratio***	
		Round	Square	Round	Square
Tarped	Pallet	3.38 a	2.06 a	1.00 a	0.86 a
	Ground	2.73 a	2.72 a	0.78 a	1.00 a
	Gravel	3.55 a	3.93 a	0.99 a	1.16 a
Untarped	Pallet	3.35 a	2.71 a	1.12 a	0.88 a
	Ground	3.60 a	2.82 a	0.87 a	1.24 a
	Gravel	2.94 a	4.95 a	0.89 a	1.19 a
Inside		3.61 a	3.07 a	1.27 a	1.14 a
LSD		1.85	2.93	0.84	1.06

[*] Means within columns followed by different letters are significantly different at the 95% confidence level. [r] Ratio of constituent value after 6 months in storage to initial value into storage. LSD is the least significant difference of mean values above which the treatments are statistically different from each other. Since the results are presented on dry matter basis, small increase in ash content is due to decrease of soluble components, rather than an actual increase in ash content.

4.2.3.2. Storage compositional changes in 2010

A more thorough sampling approach was followed in year 2010. Samples were taken and analyzed separately from the outer layer, core and bottom of the bales and then were adjusted according to the volume occupied by each layer. Trends observed in compositional changes were generally similar to what were observed in 2009. Initial NDF content in all treatments varied from 79.78% to 89% on dry basis, with an average of 82.97%. Final NDF content after storage had an average of 85.63% on dry basis in untarped round bales and 78.26% in untarped square bales (Table 4.14). Initial and final NDF contents during storage were found to be similar. Differences were small and not necessarily identifiable as trends.

Table 4.14. Assessment of NDF content variation in switchgrass bales stored for 6 months and 23.07 in. of accumulative rainfall in 2010

Storage treatment		**Final NDF Content* (% d.m. basis)**		**[r] Retention ratio***	
		Round	Square	Round	Square
Tarped	Pallet	80.76 b	82.27 a	0.95 bc	0.96 ab
	Ground	83.32 ab	80.54 a	0.97 bc	0.99 ab
	Gravel	83.01 ab	81.91 a	0.98 bc	0.95 ab
Untarped	Pallet	85.36 ab	81.72 a	1.07 a	1.01 a
	Ground	83.87 ab	74.4 ab	0.97 bc	0.98 ab
	Gravel	87.66 a	78.68 b	1.05 ab	0.92 b
Inside		86.67 ab	81.37 a	1.05 ab	1.02 a
LSD		6.35	4.65	0.08	0.07

[*] Means within columns followed by different letters are significantly different at the 95% confidence level. [r] Ratio of constituent value after 6 months in storage to initial value into storage. LSD is the least significant difference of mean values above which the treatments are statistically different from each other.

Cellulose content increased slightly in all the treatments after 6 months (Table 4.15). Initial cellulose content varied from 38.39% to 44.60% on dry basis, with an average of 40.50%. After 6 months in storage, cellulose content had an average of 46.64% on dry basis in untarped round bales and 41.45% in untarped square bales. This increase might be due to loss of other constituents that are more severely affected during storage as discussed in earlier section.

Table 4.15. Assessment of cellulose content variation in switchgrass bales stored for 6 months and 23.07 in. of accumulative rainfall in 2010

Storage treatment		Final Cellulose Content* (% d.m. basis)		[r] Retention ratio*	
		Round	Square	Round	Square
Tarped	Pallet	41.32 b	43.46 a	1.02 c	1.03 a
	Ground	44.4 ab	42.76 a	1.06 bc	1.03 a
	Gravel	43.49 ab	43.16 a	1.05 c	1.03 a
Untarped	Pallet	47.86 ab	43.22 a	1.28 a	1.12 a
	Ground	44.66 ab	39.44 b	1.06 bc	1.02 a
	Gravel	47.41 ab	41.69 ab	1.17 abc	1.01 a
Inside		48.94 a	43.10 a	1.27 ab	1.09 a
LSD[*]		6.72	2.69	0.21	0.13

[*] Means within columns followed by different letters are significantly different at the 95% confidence level. [r] Ratio of constituent value after 6 months in storage to initial value into storage. LSD is the least significant difference of mean values above which the treatments are statistically different from each other. Since the results are presented on dry matter basis, small increase in cellulose content is due to decrease of soluble components, rather than an actual increase in cellulose content.

Initial hemicellulose content varied from 29.03% to 37.30% on dry basis with an average of 33.17%. A decrease in hemicellulose content was observed for all the treatments stored in 2010 except for square bales stored inside (Table 4.16). A 2% decrease in hemicellulose content was also reported for round switchgrass bales during the first year of a 2- year storage study by Wiselogel et al. (1996). In the present study, significant decrease (p=0.0009) were observed between tarped (30.05% d.b.) and untarped square bales (24.35% d.b.). A loss of 30%, 24% and 16% in hemicellulose content on % dry basis was observed in square untarped bales stored on gravel, ground and pallets, respectively. Also, untarped square bales stored on gravel lost significantly higher hemicellulose content than untarped square bales stored on pallets. The loss in hemicellulose content is much higher than the loss observed by Wiselogel et al. (1996) in uncovered round bales. This might be due to higher moisture content and thus higher degradation in uncovered square bales compared to uncovered round bales (Table 4.3). No significant difference (p=0.2873) was observed between round tarped and round untarped bales. The trend was similar to what was observed in 2009.

Table 4.16. Assessment of hemicellulose content variation in switchgrass bales stored for 6 months and 23.07 in. of accumulative rainfall in 2010

Storage treatment		**Final Hemicellulose Content* (% d.m. basis)**		**[r] Retention ratio***	
		Round	Square	Round	Square
Tarped	Pallet	32.2 a	30.46 a	0.92 a	0.92 abc
	Ground	31.36 a	30.55 a	0.9 a	0.97 ab
	Gravel	31.11 a	29.14 a	0.91 a	0.86 bcd
Untarped	Pallet	28.9 a	27.72 ab	0.85 a	0.84 bcd
	Ground	29.7 a	23.2 bc	0.89 a	0.76 cd
	Gravel	31.11 a	22.13 c	0.95 a	0.95 d
Inside		30.1 a	31.53 a	0.87 a	1.02 a
LSD		6.55	4.81	0.22	0.17

[*] Means within columns followed by different letters are significantly different at the 95% confidence level. [r] Ratio of constituent value after 6 months in storage to initial value into storage. LSD is the least significant difference of mean values above which the treatments are statistically different from each other.

Lignin content was comparatively less affected in year 2010 than in year 2009. This can be due to less accumulated rainfall in 2010 compared to 2009. Initial lignin content varied from 7.95% to 11.10% on dry basis, with an average of 9.30%. After 6 months in storage, lignin content varied from 7.25% to 9.52% in round bales and 6.73% to 12.82% in square bales (Table 4.17). Lignin content decreased in round bales and tarped square bales but increased in untarped square bales. Increase in lignin content is an indication of excessive weathering as discussed previously. No significant difference was observed between inside stored bales and tarped bales. Significant differences were observed between tarped and untarped round bales (p=0.0015) and tarped and untarped square bales (p<0.0001). Also, untarped square bales (12.47% d.b.) had significantly higher lignin content in comparison to untarped round bales (9.09% d.b.). Higher lignin content in untarped square bales suggests that covering square bales is important to prevent weathering during storage.

Table 4.17. Assessment of lignin content variation in switchgrass bales stored for 6 months and 23.07 in. of accumulative rainfall in 2010

Storage treatment		**Final Lignin Content* (% d.m. basis)**		**[r] Retention ratio***	
		Round	**Square**	**Round**	**Square**
Tarped	Pallet	7.25 c	8.36 cd	0.78 c	0.79 cd
	Ground	7.56 bc	8.2 cd	0.88 abc	0.92 cd
	Gravel	8.41 abc	8.65 c	0.85 bc	0.70 c
Untarped	Pallet	8.6 ab	10.78 b	1.01 a	1.23 b
	Ground	9.52 a	13.8 a	0.99 a	1.53 a
	Gravel	9.14 a	12.82 a	0.94 ab	1.28 b
Inside		7.63 bc	6.73 d	0.85 bc	0.75 d
LSD		1.29	1.69	0.14	0.18

[*] Means within columns followed by different letters are significantly different at the 95% confidence level. [r] Ratio of constituent value after 6 months in storage to initial value into storage. LSD is the least significant difference of mean values above which the treatments are statistically different from each other.

Initial crude protein varied from 2.02 to 5.10% with an average of 3.61% on dry basis. Crude protein also increased in all the treatments in 2010 (Table 4.18); however, the increase was not as prominent as in 2009. Significant differences ($p<0.0001$) were observed between untarped and tarped square bales, showing signs of weathering in uncovered square bales. The mechanism driving this trend is likely to be similar to fiber components. Sugars and other extractives are leached or oxidized by microbial respiration, which increases the crude protein content indirectly during storage (Coblentz, 2009). Untarped bales stored on pallets, gravel, and ground had a significantly higher crude protein content of 6.95, 6.94, and 6.46%, respectively compared to 4.48, 4.83, and 4.90% in tarped square bales stored on pallets, gravel, and ground, respectively.

Table 4.18. Assessment of crude protein content variation in switchgrass bales stored for 6 months and 23.07 in. of accumulative rainfall in 2010

Storage treatment		**Final Crude Protein Content* (% d.m. basis)**		**[r] Retention ratio***	
		Round	**Square**	**Round**	**Square**
Tarped	Pallet	6.34 a	4.48 b	1.6 a	1.31 b
	Ground	5.54 bcd	4.90 b	1.55 a	1.60 ab
	Gravel	4.66 e	4.83 b	1.4 a	1.42 b
Untarped	Pallet	6.25 ab	6.95 a	1.38 a	2.05 a
	Ground	5.05 de	6.46 a	1.53 a	2.03 a
	Gravel	5.41 cde	6.94 a	1.54 a	2.06 a
Inside		5.99 abc	6.06 a	1.60 a	1.58 ab
LSD		0.77	1.11	0.30	0.60

[*] Means within columns followed by different letters are significantly different at the 95% confidence level. [r] Ratio of constituent value after 6 months in storage to initial value into storage. LSD is the least significant difference of mean values above which the treatments are statistically different from each other. Since the results are presented on dry matter basis, increase in protein content is due to decrease of soluble components, rather than an actual increase in protein content.

Ash content varied from 2.31% to 6.77% on dry basis with an average of 4.07% in initial samples due to field variation. Ash content varied from 2.73% to 6.94% on dry basis with an average of 4.23% in final samples (Table 4.19). A significant increase ($p<0.0001$) in ash content was observed in square untarped (4.78% d.b.) treatments. A slight increase in ash content from 4.8% in initial samples to 5.8% on dry basis in final samples was also reported by Wiselogel et al. (1996) in round switchgrass bales stored unprotected for 6.5 months. Increase in ash content is also an indication of excessive weathering. A significant difference was observed between square tarped and square untarped treatments with square untarped treatments having higher ash content after storage.

Table 4.19. Assessment of ash content variation in switchgrass bales stored for 6 months and 23.07 in. of accumulative rainfall in 2010

Storage treatment		**Final Ash Content* (% d.m. basis)**		**[r] Retention ratio***	
		Round	**Square**	**Round**	**Square**
Tarped	Pallet	3.26 b	2.73 d	0.94 a	0.78 b
	Ground	4.86 a	3.03 d	1.22 a	0.84 b
	Gravel	3.33 b	6.94 cd	0.86 a	0.85 b
Untarped	Pallet	3.79 b	4.34 ab	1.07 a	1.34 ab
	Ground	5.11 a	5.06 a	1.05 a	1.8 a
	Gravel	3.52 b	4.95 ab	1.07 a	1.42 ab
Inside		4.21 ab	4.06 bc	0.94 a	0.98 b
LSD		1.00	0.91	0.66	0.64

[*] Means within columns followed by different letters are significantly different at the 95% confidence level. [r] Ratio of constituent value after 6 months in storage to initial value into storage. LSD is the least significant difference of mean values above which the treatments are statistically different from each other. Since the results are presented on dry matter basis, small increase in ash content is due to decrease of soluble components, rather than an actual increase in ash content.

4.3. Conclusions

1. Dry matter loss from round and square switchgrass bales during storage was dependent on the storage method. The highest dry matter loss, 38.47%, was observed in uncovered square bales stored outside on gravel. In 2010, uncovered round bales stored on pallets, ground and gravel lost 8.82, 5.92, and 3.52% of dry matter, respectively, and were significantly less than untarped square bales stored on pallets, ground and gravel which lost 37.81, 30.36, and 38.47% of dry matter, respectively.
2. During storage, a substantial increase in moisture content was observed in uncovered square bales which were significantly higher than uncovered round bales. In 2010, uncovered round bales stored on pallets, ground and gravel had a moisture content of 16.92, 16.49, and 14.41% on wet basis, respectively and were significantly less than

untarped square bales stored on pallets, ground and gravel which had a moisture content of 61.32, 57.37, and 61.69% on wet basis, respectively. Tarped square bales, stored on pallets (14.03% w.b.) and gravel (17.1% w.b.) had less moisture in bale bottom than tarped square bales stored on ground (23.45% w.b.) but the difference was not significant.

3. A slight increase in cellulose content was observed in both years. However, there was no significant difference between the storage methods. During both years, hemicellulose content decreased in untarped square bales. In 2010, untarped square bales stored on gravel, ground and pallets lost 30%, 24% and 16% of hemicellulose content, respectively. An increase in lignin content was also recorded for untarped square bales stored outside in both years, indicating excessive weathering during storage.
4. Ash content increase slightly in untarped square bales, which might be due to leaching of water soluble portion and microbial respiration during storage.

In the present study, both round and square bales stored well outside when covered with protection such as polyethylene tarps and stored above ground on pallets or gravel. Bales stored on pallets and covered with tarp had least amount of dry matter loss and compositional changes. These findings confirmed that it can be used as an alternative to expensive barn storage. During the storage period, untarped square bales held more moisture than untarped round bales and thus resulted in higher losses in untarped square bales. Also during storage, hemicellulose content of switchgrass was more severely affected than cellulose content. Both cellulose and hemicellulose components are important for biofuel production. Storage losses will directly affect the economics of biofuel production from both conversion processes and thus should be protected in as high a yield as possible.

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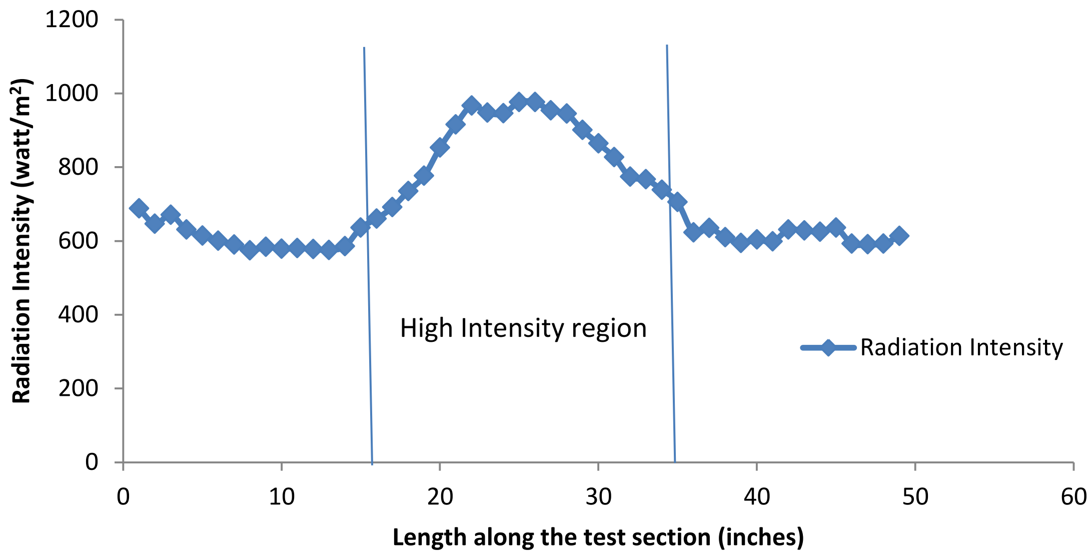
Appendix I

Radiation intensity variation along the length of test section



Appendix II

Daily variation of absorptivity for the month of September

Date	Absorptivity (%)
1st Sept	0.464
2nd Sept	0.464
3rd Sept	0.464
4th Sept	0.464
5th Sept	0.464
6th Sept	0.464
7th Sept	0.464
8th Sept	0.464
9th Sept	0.464
10th Sept	0.463
11th Sept	0.463
12th Sept	0.463
13th Sept	0.463
14th Sept	0.463
15th Sept	0.463
16th Sept	0.463
17th Sept	0.463
18th Sept	0.462
19th Sept	0.462
20th Sept	0.462
21st Sept	0.462
22nd Sept	0.462
23rd Sept	0.462
24th Sept	0.462
25th Sept	0.461
26th Sept	0.461
27th Sept	0.461
28th Sept	0.461
29th Sept	0.461
30th Sept	0.461
31st Sept	0.460

Appendix III

Sampling schedule for switchgrass harvesting used during the drying study

Maturity stage	Experiment No.	Date of harvesting
Seed development stage	1	12-Aug-2011
	2	16-Aug-2011
	3	20-Aug-2011
	4	18-Aug-2011
	5	19-Aug-2011
	6	20-Aug-2011
	7	22-Aug-2011
	8	25-Aug-2011
	9	27-Aug-2011
	10	5-Sep-2011
	11	7-Sep-2011
	12	10-Sep-2011
	13	14-Sep-2011
	14	18-Sep-2011
	15	19-Sep-2011
	16	21-Sep-2011
	17	23-Sep-2011
	18	24-Sep-2011
	19	25-Sep-2011
	20	25-Sep-2011
	21	27-Sep-2011
	22	28-Sep-2011
	23	30-Sep-2011
	24	4-Oct-2011
	25	6-Oct-2011
	26	8-Oct-2011
	27	10-Oct-2011
Seed shattering stage	1	11-Oct-2011
	2	12-Oct-2011
	3	13-Oct-2011
	4	14-Oct-2011
	5	16-Oct-2011
	6	17-Oct-2011
	7	18-Oct-2011
	8	20-Oct-2011
	9	23-Oct-2011
	10	29-Oct-2011
	11	30-Oct-2011
	12	30-Oct-2011
Seed shattered stage	13	1-Nov-2011
	14	3-Nov-2011

15	8-Nov-2011
16	10-Nov-2011
17	11-Nov-2011
18	13-Nov-2011
19	18-Nov-2011
20	18-Nov-2011
21	19-Nov-2011
22	19-Nov-2011
23	21-Nov-2011
24	22-Nov-2011
25	24-Nov-2011
26	27-Nov-2011
27	28-Nov-2011

Appendix IV

Difference between calculated switchgrass foliage temperature and air temperature for different levels of radiation intensity, vapor pressure deficit, and wind speed calculated for the drying experiments in seed development stages of maturity

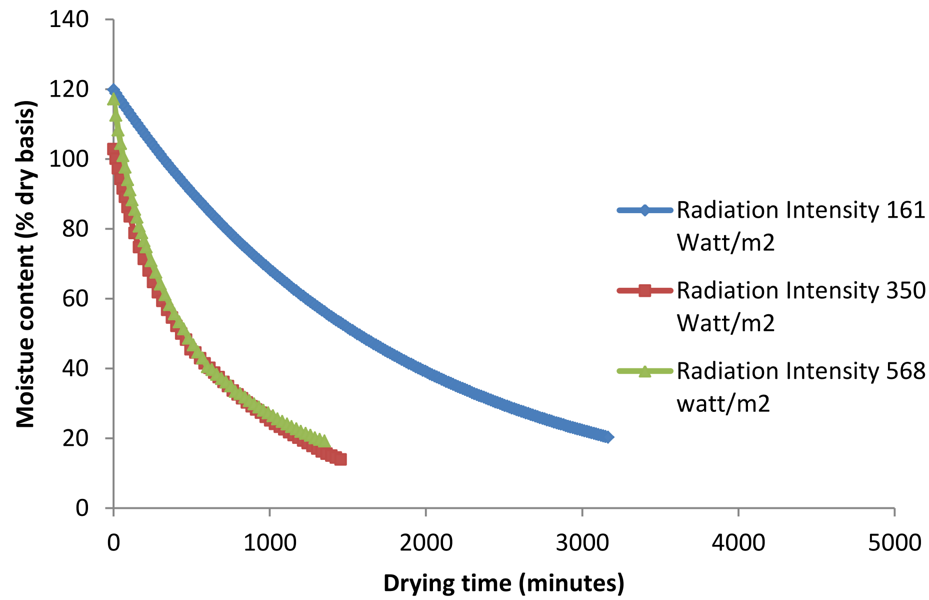
Radiation Intensity (watt/m^2)	Vapor pressure deficit (Kpa)	Wind speed (m/s)	Switchgrass Temperature (°C)	Air temperature (°C)	Tc-Ta (°C)
590	1.93	5.83	40.16	42.63	-2.46
590	1.93	3.25	42.33	43.43	-1.10
590	1.93	1.30	47.48	43.44	4.04
590	1.44	5.83	33.45	34.03	-0.58
590	1.44	3.25	34.88	33.73	1.16
590	1.44	1.30	40.86	34.57	6.30
590	0.64	1.30	37.91	24.44	13.48
590	0.64	3.25	30.46	26.66	3.80
590	0.64	5.83	26.85	24.44	2.41
351	1.93	1.30	40.73	41.76	-1.03
351	1.93	3.25	40.44	43.32	-2.87
351	1.93	5.83	39.86	43.44	-3.58
351	1.44	5.83	32.05	34.77	-2.72
351	1.44	3.25	32.65	33.92	-1.27
351	1.44	1.30	35.94	34.48	1.46
351	0.64	1.30	31.15	24.44	6.72
351	0.64	3.25	26.02	24.44	1.58
351	0.64	5.83	24.66	24.44	0.22
161	1.93	1.30	39.98	43.30	-3.32
161	1.93	3.25	38.91	43.64	-4.73
161	1.93	5.83	38.87	43.44	-4.57
161	1.44	5.83	30.53	34.32	-3.79
161	1.44	3.25	38.89	43.45	-4.55
161	1.44	1.30	32.08	34.32	-2.24
161	0.64	5.83	21.99	23.30	-1.31
161	0.64	3.25	22.46	23.18	-0.72
161	0.64	1.30	25.31	24.22	1.09

Difference between calculated switchgrass foliage temperature and air temperature for different levels of radiation intensity, vapor pressure deficit, and wind speed calculated for the drying experiments in seed shattering and seed shattered stages of maturity

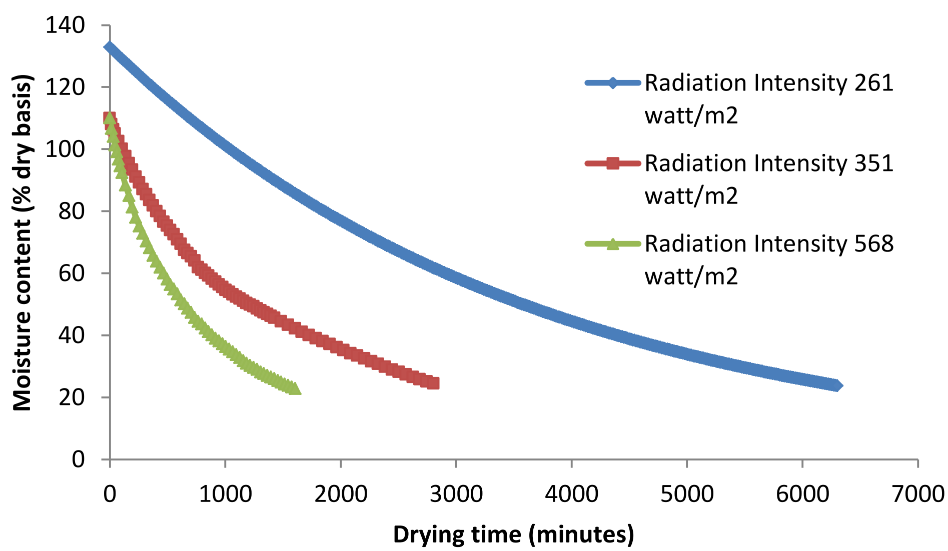
Radiation Intensity ($watt/m^2$)	Vapor pressure deficit (Kpa)	Wind speed (m/s)	Switchgrass Temperature (°C)	Air temperature (°C)	Tc-Ta (°C)
590	1.5	5.83	31.44	34.04	-2.59
590	1.5	3.25	33.25	34.25	-1.00
590	1.5	1.30	38.47	33.60	4.86
351	1.5	5.83	27.94	30.95	-3.02
351	1.5	3.25	28.96	31.14	-2.19
351	1.5	1.30	32.86	32.10	0.76
161	1.5	1.30	29.00	31.99	-3.00
161	1.5	3.25	26.91	31.49	-4.58
161	1.5	5.83	26.90	31.56	-4.66
590	1.04	5.83	31.08	30.28	0.80
590	1.04	3.25	33.05	31.12	1.93
590	1.04	1.30	39.35	31.11	8.24
351	1.04	5.83	24.78	26.06	-1.28
351	1.04	3.25	30.41	31.12	-0.70
351	1.04	1.30	28.55	26.40	2.15
161	1.04	5.83	23.30	26.22	-2.92
161	1.04	1.30	24.47	26.72	-2.24
161	1.04	3.25	22.96	26.99	-4.02
590	0.47	5.83	32.12	30.02	2.10
590	0.47	3.25	31.64	30.40	1.24
590	0.47	1.30	42.30	31.39	10.91
351	0.47	5.83	24.88	23.76	1.12
351	0.47	3.25	26.08	23.33	2.75
351	0.47	1.30	31.30	23.33	7.97
161	0.47	1.30	25.29	22.24	3.06
161	0.47	5.83	21.66	21.73	-0.07
161	0.47	3.25	22.15	21.31	0.83

Appendix V

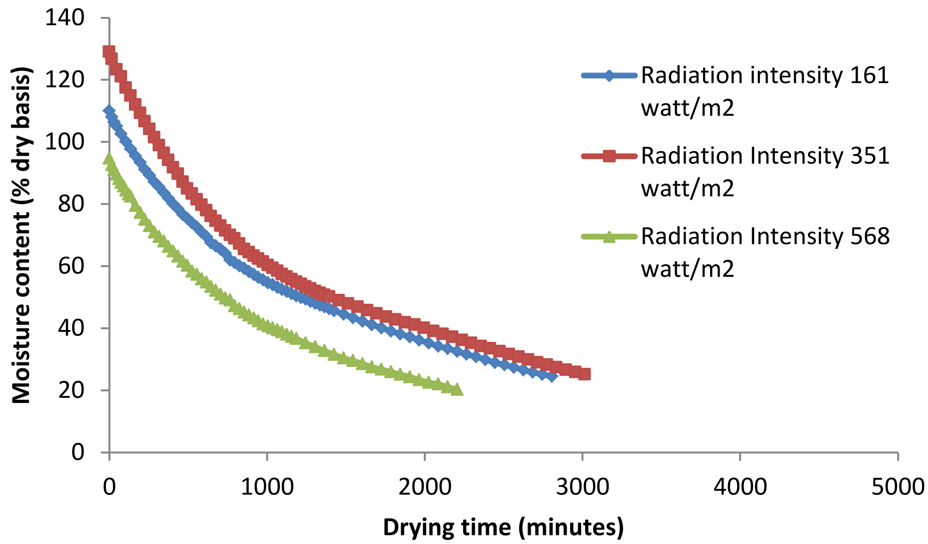
Variation of moisture content with drying time under different conditions of radiation intensity, vapor pressure deficit and wind speed



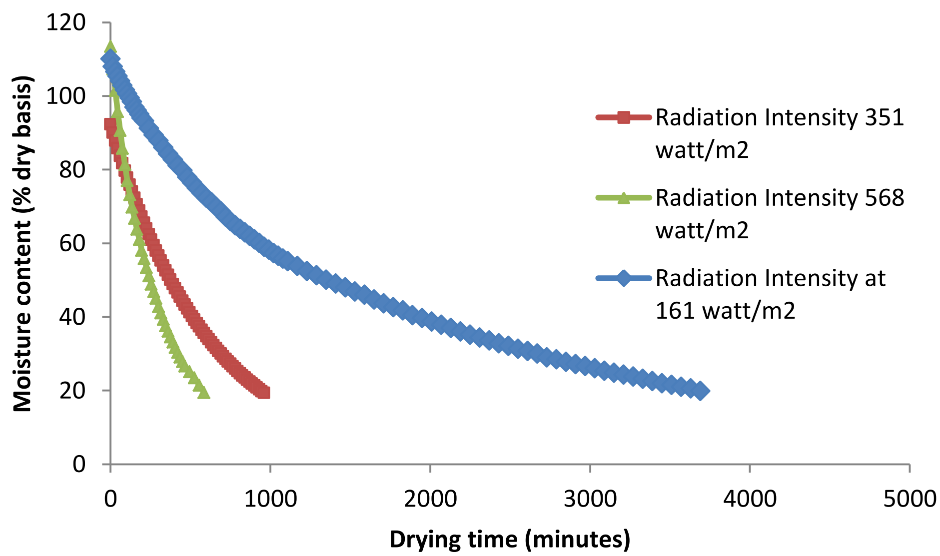
Effect of radiation intensity on drying rate of switchgrass when the vapor pressure deficit and wind speed were held at 0.64 KPa and 1.3 m/s



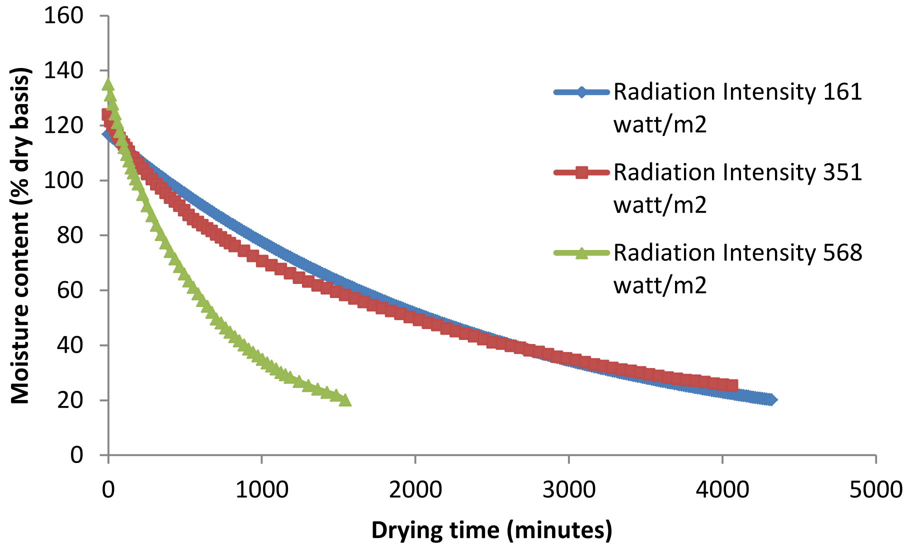
Effect of radiation intensity on drying rate of switchgrass when the vapor pressure deficit and wind speed were held at 0.64 KPa and 3.25 m/



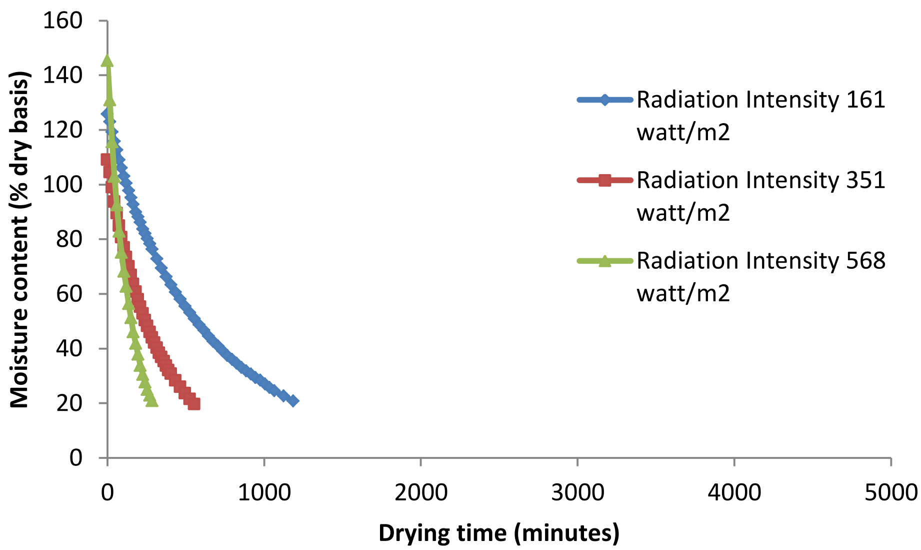
Effect of radiation intensity on drying rate of switchgrass when the vapor pressure deficit and wind speed were held at 0.64 KPa and 5.83 m/s



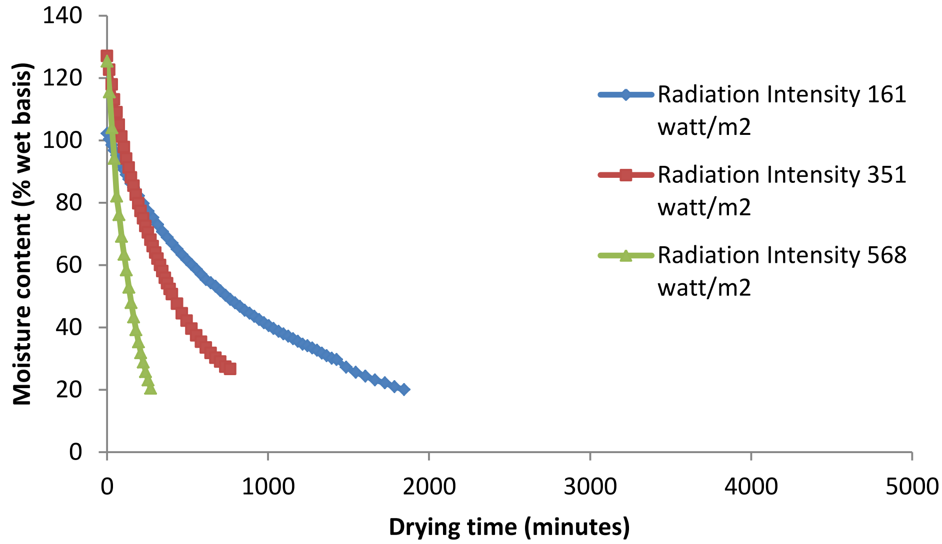
Effect of radiation intensity on drying rate of switchgrass when the vapor pressure deficit and wind speed were held at 1.44 KPa and 1.3 m/s



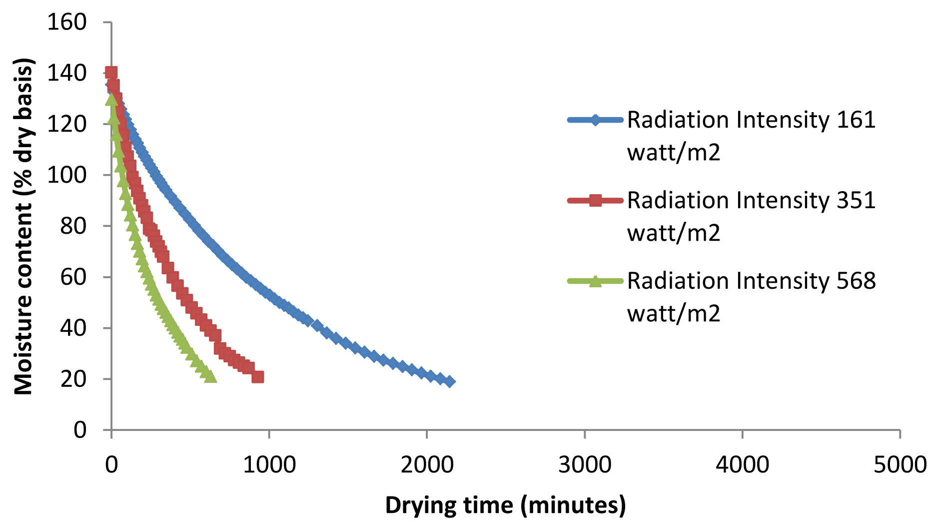
Effect of radiation intensity on drying rate of switchgrass when the vapor pressure deficit and wind speed were held at 1.44 KPa and 5.83 m/s



Effect of radiation intensity on drying rate of switchgrass when the vapor pressure deficit and wind speed were held at 1.93 KPa and 1.3 m/s



Effect of radiation intensity on drying rate of switchgrass when the vapor pressure deficit and wind speed were held at 1.93 KPa and 3.25 m/s



Effect of radiation intensity on drying rate of switchgrass when the vapor pressure deficit and wind speed were held at 1.93 KPa and 5.83 m/s

VITA

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Scope and Method of Study: Switchgrass is recognized as potential bioenergy crops for bioethanol production. Economic analysis, and biomass supply chain and logistics planning require estimation of storage losses as well as drying time needed for safe storage of biomass. The broad research objectives were to develop an empirical model to predict drying rate of switchgrass based on environmental variables, and evaluate the effect of individual weather parameter on the drying rate of switchgrass. The second broad objective includes assessment of qualitative and quantitative losses in round and square switchgrass bales stored under different conditions.

Findings and Conclusions: For the drying study, an environmental chamber was fabricated that can simulate field drying conditions. An empirical drying model based on maturity stage of switchgrass was developed which was dependent on the environmental conditions of solar radiation, vapor pressure deficit and wind speed. During both maturity stages, radiation intensity was positively and strongly correlated with drying rate. Vapor pressure deficit was also positively correlated (r=0.50) with drying rate during the seed development stage of maturity, but the effect was not significant for later stages of maturity. In environmental chamber, the effect of air speed was found to be dependent on radiation intensity. Under high radiation intensity, increase in wind speed decreased the drying rate of switchgrass. However, under low radiation intensity, increase in wind speed increased the drying potential of switchgrass.

In the storage study, outside tarped bales resisted moisture accumulation and thus dry matter losses were equivalent to bales stored inside. Untarped square bales consistently had higher moisture contents than untarped round bales. Highest dry matter loss (38.47%) was observed in uncovered square bales stored outside on gravel. Hemicellulose content was more severely affected than the cellulose content during storage. In 2010, untarped square bales stored on gravel, ground and pallets lost 30%, 24% and 16% of hemicellulose content, respectively.

ADVISER'S APPROVAL: Dr. Carol L. Jones