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Experimental investigation of convective drying kinetics of switchgrass leaf in open sun and in a forced convection solar dryer

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Abstract: This paper discusses the thin layer drying characteristics of switch grass, which is an abundantly available energy crop. For this, an experimental study was performed to determine its thin layer drying characteristics in a solar dryer with forced convection and under open sun with natural convection. An indirect forced convection solar dryer consisting of a solar air collector and drying cabinet was used in the experiments. Natural sun drying experiments were conducted for comparison at the same time. Variation of drying rate with respect to size of the material is also studied. Selected six thin-layer drying models were fitted to the drying data. The performance of these models was investigated by comparing their coefficient of determination (R^2), Root Mean Square Error (RMSE) and Sum Squared Error (SSE) between the observed and predicted moisture ratios. From the analysis, Logarithmic model best describes drying process of switch grass leaves.
Keywords: switchgrass; drying kinetics; thin layer drying; drying curve; solar drying; open drying.

1. Introduction

Living organisms are important part of the ecosystem, prevailing everywhere on the Earth. The damage or degradation of any one of the link within the food system can lead to complete downfall of the ecosystem and possible ecosystem wide extinction. Man has since the discovery of fire; burned biomaterials like, wood and manure and fossil fuels like coal to produce energy and much needed heat to maintain body temperature. In the present age, uncontrolled and massive combustion of fuels towards the noble idea of energy for all; can be justified to some extent but, its consequences should be considered and possibly minimized.

Nowadays, people are moving from a form of economic development to sustainable development. Concern about global warming due to escalating air pollution has raised interest in alternative forms of energy. Many alternative sources of energy are being researched and extensively studied for their profitability and effectiveness. Chief among them include solar energy, tidal and wave energy, fuel calls and energy from biomass. Each one of them has their respective advantages and demands. Biomass is renewable and definitely less polluting than present petroleum based energy sources, further they do not add to environmental levels of greenhouse gases like carbon dioxide.

Organic matter can be transformed to usable energy by direct combustion, liquid fuel production (e.g. ethanol and butanol), and the manufacture of synthetic gases [1]. The method of direct combustion of biomass has been employed in many countries for a long time. India had its form of direct combustion of biomass like, wood and wall-dried manure of livestock. These have been useful to decrease the load on fossil fuels but, they do lead to various other unexpected problems like production of methane. Also to be considered here is the efficiency of the idea for direct combustion of biomass, it can may be ultimately lead to taking more toll on the environment due to the incomplete combustion of the carbon compounds. The pyrolysis method is currently being considered as a potential process to convert biomass to a liquid fuel suitable for automobile engines.

Switchgrass is considered as one of the high potential energy crops and a renewable source for transportation fuel and/or electricity [2]. It shows high yield across a wide geographic range; requires low water and nutrient requirements, can grow well in marginal quality land and have positive environmental benefits [3].Switchgrass is a perennial grass native to North America. [4,5]. It grows fast and can stand up to ten feet high after one growing season. One field of switchgrass yields from 5 to about 11 metric tons of grass bales per hectare. Aside from being turned into ethanol through a fermentation process, switchgrass can also be used for gasification and pyrolysis [4]. The energy produced from switchgrass primarily depends on the concentration of energy primarily derived from cell walls and particularly from lignin and cellulose [5]. To be effectively consumed towards the possible production of biomass energy, the reduction of moisture in the raw material is of utmost importance. It imparts a better efficiency for all the possible processes that may be employed and an increased productivity. Chief among the methods employed to produce energy from biomass would be a gasifier or an underground biogas plant. For all these processes, controlled drying of switchgrass to a moisture content of less than 10% weight is very important. This ultimately helps the productivity of biomass energy from the process and helps reduce the cost of maintenance that may occur due to operation.

Drying is an energy intensive process and energy requirements for drying in most of the industrialized countries account for 7-15% of nations industrial energy.[6]Drying can be accomplished by different methods like natural sun drying, convective drying, microwave drying, freeze drying and the use of solar or industrial dryers. Solar dryers are a good option of drying using alternate energy in areas of good sunshine and having long summer season. It is an age old household process used historically for easy long term storage. Various successful research works done have proved that the use of solar dryers has no effect on the final efficiency and mineral value of the substance. Various groups have applied these dryers for drying & cabbage [7], chilli [8], seedless grape [9], coffee [10], pupae of the silkworm [11], apricot [12], Dill and Spearmint [13] leafy green product [14].The use of an alternative source of energy that is abundantly available reduces the toll on the environment and thereby reduced the various ill effects of energy from fossil fuels' combustion.

Switchgrass can be used both for forage and biomass production. Biomass is anything produced from a living organism and switchgrass shows huge promise in conversion into electricity or fuel[15]. Bio-oil, a new fuel coming into the market [16] with about half the heating value of petroleum [17,18] (17 MJ per kg; wet weight basis), is produced from biomass pyrolysis. Bio-oil cannot be used directly as a fuel in heating applications or as a transportation fuel; however, by using suitable upgrading techniques it can be converted into usable fuels [18]. Even now, about 10% addition of switchgrass to coal provides cleaner emissions [3]. Also, it is acclaimed to be a great source of cellulosic ethanol.These are studies for the future, this team targets at the study of drying switchgrass in a chimney type forced convection solar dryer in varying process conditions. It aims ultimately to compare the effect of drying by open and solar air drying. Also, special importance is given to the effect of size of the sample in the drying rate.

Thin layer mathematical modeling is an approximate and viable method to predict the moisture content for the sample at a given time. The main target to be achieved by mathematical modeling is the approximation of various process considerations as a function of time. It also aids in understanding the experiment through a more theoretical outlook. The research done in this paper aims to understand the drying kinetics of switchgrass using both open air and solar drying. The experimental data has been fitted into four mathematical models for adequate theoretical studies and predictions.

2. Materials and Methods

2.1. Materials

Switch grass is harvested fresh and rinsed using a stream of water. Gratuitous surface moisture is dabbed off using blotting paper. For experiments, previously cut and weighed switch grass samples are taken both for half inch and one inch size and placed for drying in open sun and in the solar dryer.

2.2. Drying equipment and experimental procedure

The velocity of air is kept at an average of 1.2 m/s. The heating is done and weight loss is calculated on an hourly basis. The Pyranometer and the ambient temperature thermometer readings are appraised. The solar dryer used here is devised such that, the incident sunbeam falls directly on a surface area of $0.43m^2$. The plate is made of aluminum and is inclined at an angle of 17° to the floor. To improve the heating of the equipment, the plate is treated with black paint for maximum absorption of incident solar radiation. Forced Convection is done using the solar dryer with flat plate solar collectors. Rehydration of the grass is taken care to reduce the experimental errors. The experimental values are tabularized, plotted and fitted using various mathematical models.

2.3. Mathematical Modeling

The Moisture Ratio and Drying Rate were calculated using the following equations (1) and (2),

$$Moisture\ Ratio, MR = \frac{(M_t - M_e)}{(M_o - M_e)} \quad (1)$$

which can be simplified to $MR = \frac{Mt}{M_0}$ due to fluctuation of relative humidity of drying air.

$$Drying\ Rate, DR = \frac{(M_{t+dt} - M_t)}{(dt)} \quad (2)$$

Where MR is the Moisture Ratio, M_t is the moisture content at any time t, M_e is the equilibrium moisture content, M_o is the initial moisture content and M_{t+dt} is the moisture content in any time interval dt. For mathematical modelling, the theoretical drying equations in Table 1 were tested using statistical parameters to present the best model for illustrating the drying curve equation of switchgrass leaves drying by the solar dryer and under open sun.

Table 1. Mathematical models used to describe drying kinetics

Fitting model	**Model equation**
Henderson and Pabis	MR=a*exp(-bt)
Logarithmic	MR=a*exp(-bt)+c
Two Term	MR=a*exp(-bt)+ c*exp(-dt)
Wang and Singh	$MR=1+at+bt^2$
Two Term Exponential	MR= a*exp(b*x) + ((1-a)*exp(b*a*x))
Page	$MR = exp(-a*t^n))$

Where, MR stands for Moisture Ratio, t stands for the temperature, a, b, c and d are constants.

2.4. Data analysis and empirical modeling for Switch Grass drying

The regression was done using MATLAB R2011a. The primary comparison factor was the Regression Coefficient (R^2). Also, other parameters like, the Root Mean Square Error (RMSE), the Sum Squared Error (SSE) and Adjusted - R^2 values were scrutinized. Root Mean Square Error can be calculated using equation (3).

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(\mathbf{MR}_{\mathbf{pre,i}} - \mathbf{MR}_{\mathbf{exp,i}}\right)^2\right]^{1/2} \quad (3)$$

Sum Squared Error is calculated using equation (4),

$$SSE = \frac{1}{N}\sum_{i=1}^{N}(MR_{exp} - MR_{pred})^2 \quad (4)$$

Regression Coefficient can be found by equation (5),

$$R^2 = \frac{\sum_{i=1}^{n}(MR_i - MR_{pre,i}) - \sum_{i=1}^{n}(MR_i - MR_{exp,i})}{\sqrt{\left[\sum_{i=1}^{n}(MR_i - MR_{pre,i})^2\right]\cdot\left[\sum_{i=1}^{n}(MR_i - MR_{exp,i})^2\right]}} \quad (5)$$

The values of these parameters are discussed in the following sections. The selection of adequate Mathematical Model is done based on the closeness of experimental values to the theoretical ones.

3. Results and Discussion

3.1. Variation of Ambient Temperature and Solar Power

During the experimental period the temperature of the ambient air ranged from 32.5 to 24.5 °C while direct instantaneous solar insolation reached maximum value of 1000 W/m^2 during midday (figure 1 and figure 2). Air velocity was kept constant to be 1.21 m/s. Drying air temperature at the inlet of the drying cabinet ranged from 30.1 to 36.5 °C and outlet temperature of the drying air from drying cabinet varied from 38.5 to 43 °C.

The drying experiments were conducted to reduce the moisture content of switchgrass leaf from initial moisture content of more than 80% (d.b) to less than 10% (d.b). To augment the efficiency of the results, the procedure was triplicated and a variation of within 5% was observed. An hourly calculation of the ambient temperature ranged widely between 32.7 and 44°C during the duration of the experimental procedure for open air drying and between 24.6 and 34.8 °C for solar drying as shown in figure 2. During the trials, the maximum solar insolation reached 984.12 W/m^2 at 12 noon as in figure 3.The inlet air temperature of the solar dryer was 40.5 °C and the outlet temperature of air from solar dryer reached 48.5 °C. Air velocity was kept constant to be 1.21 m/s. Figure 2 and 3 depict the variation of ambient temperature and solar insolation with time, respectively. Since the drying process is a combination of heat and mass transfer, the drying rate increases with the increase in ambient air temperature and decrease in relative humidity.

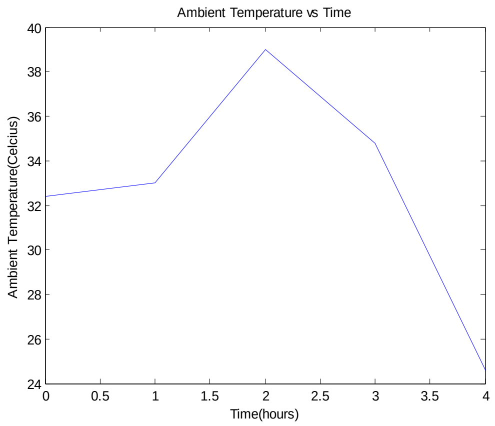

Figure 1. Variation of ambient temperature with time

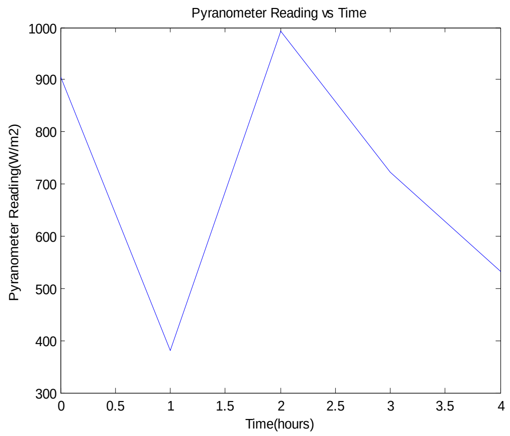

Figure 2. Variation of Pyranometer reading with time

3.2. Drying Curves

Drying curves describing the variation of moisture content and drying rate with time is shown in figures 3, 4, 5 and 6, both for 1″ and 1/2″ of switch grass leaf in open sun drying and solar drying conditions. As shown in figure 3, reduction in moisture content is 0.75 g/hr for 1/2″ switchgrass leaf while it is 0.7 g/hr for 1″ switchgrass leaf for open air drying, since smaller the size, higher will be the moisture removal rate as more drying area is exposed to air. It is observed that moisture content reduction is higher during initial stages of drying due to evaporation of free moisture from the outer surface layers and then it reduces due to internal moisture migration from inner layers to the surface which results in constant dehydration.

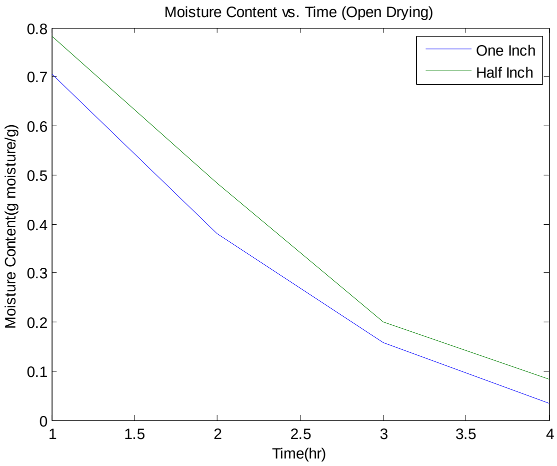

Figure 3. Variation of Moisture Content with time (Open air drying)

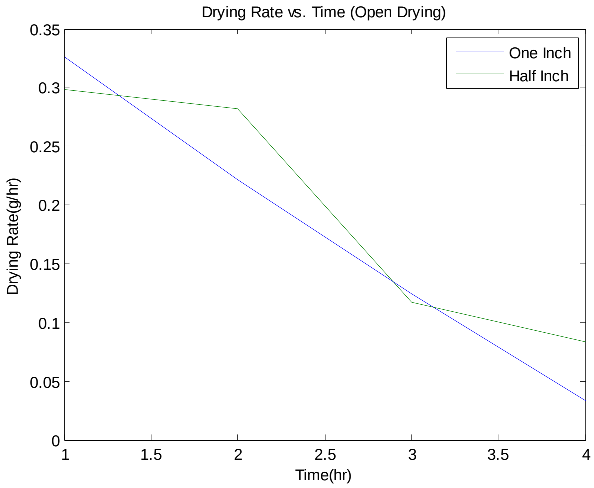

Figure 4. Variation of Drying Rate with time (Open air drying)

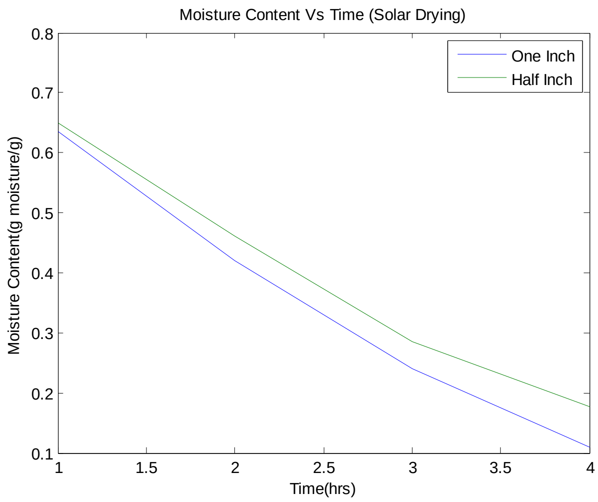

Figure 5. Variation of Moisture Content with time (Solar drying)

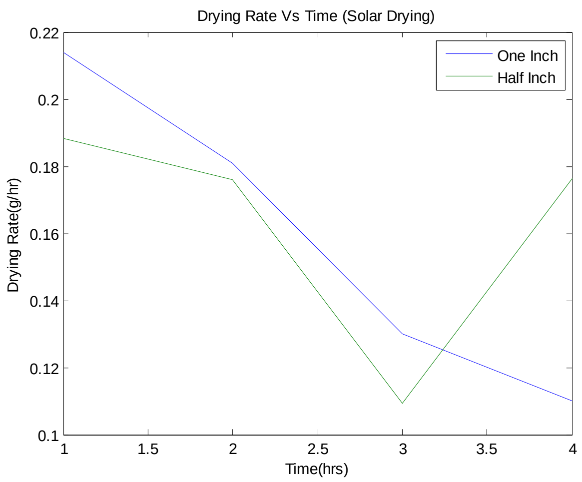

Figure 6. Variation of Drying Rate with time (Solar drying)

Variation of drying rate with time for open air drying is shown in figure 4. There is a constant variation of drying rate from 0.325 to 0.025 g/hr for 1″ switchgrass leaf while for 1/2″ switch grass leaf drying rate started from a maximum value of 0.3 g/hr and gradually it decreased to 0.085g/hr. Drying rate shows an increase of 6% for 1/2″ switchgrass leaf compared to 1″ showing the effect of size of the material in drying rate. Since there is a variation in ambient temperature in open air drying, drying rate also varies for the sample.

As shown figure 5, reduction in moisture content is 0.65 g/hr for 1/2″ switchgrass leaf while it is 0.625 g/hr for 1″ switchgrass leaf in solar air drying. It can be noted that reduction in moisture content is double in the case of solar drying as compared to open air drying and also 1/2″ switch grass leaf has a moisture reduction of 2.5% more than 1″ switch grass leaf as area exposed to drying air will be more. Moisture content is linearly decreasing in both the cases.

Variation of drying rate with time for solar air drying is shown in figure 6. Drying rate varied linearly from 0.215 to 0.11 g/hr for 1″ switchgrass leaf while for 1/2″ switchgrass leaf, it started from 0.19 g/hr reached a minimum value of 0.11 g/hr and then increased to 0.175g/hr. Drying rate is more by 2.5% for 1/2″ switchgrass leaf.

3.3. Fitting of drying curves using mathematical models

Table 2, 3,4 and 5 presents the parameters of equations applied to the experimental data obtained in the drying process of switch grass leaves for 1/2″and 1″ size both for open sun drying and solar drying methods. From the results it can be verified that 1/2″ switch grass leaf drying shows better fit with Two term model with an R^2 value of 0.9955 in open sun drying while for solar drying it shows a better fit with Page model with an R^2 value of 0.9951. 1″ switch grass leaf shows a better fit with Two Term model with an R^2 value of 0.9981 in open sun while in solar drying it shows a better fit with Henderson and Pabis Model.

Table 2. Estimated values of parameters of selected drying models used for the representation of thin-layer drying of 1/2″ switch grass leaf under open sun

Fitting Model	R^2	SSE	RMSE	Adj R^2	Constants			
					a	b	c	d
Henderson and Pabis	0.9774	0.01524	0.07128	0.9699	1.996	0.6617	-	-
Logarithmic	0.9344	0.0442	0.1487	0.8688	-196	0.001246	197.1	-
Two Term	0.9955	0.00303	0.05505	0.982	1432	0.2583	1433	0.2585
Wang and Singh	0.9062	0.06324	0.1452	0.8749	0.1972	-0.00322	-	-
Two Term Exponential	0.904	0.06468	0.1468	0.8721	-0.7006	0.1101	-	-
Page	0.9887	0.00759	0.05028	0.985	-0.0703	2.658	-	-

Table 3. Estimated values of parameters of selected drying models used for the representation of thin-layer drying of 1/2″ switch grass leaf in solar drying

Fitting Model	R^2	SSE	RMSE	Adj R^2	Constants			
					a	b	c	d
Henderson and Pabis	0.9153	0.05887	0.1401	0.887	1.746	-0.4835	-	-
Logarithmic	0.9879	0.00839	0.06478	0.9758	-53.65	0.0048	54.92	-
Two Term	0.9887	0.00786	0.08864	0.9548	1143	-0.02	-1141	0.0204
Wang and Singh	0.9567	0.03008	0.1001	0.9423	-0.066	0.029	-	-
Two Term Exponential	0.9404	0.04142	0.1175	0.9205	-0.1535	0.3587	-	-
Page	0.9951	0.00342	0.03375	0.9934	-0.025	3.081	-	-

Table 4. Estimated values of parameters of selected drying models used for the representation of thin-layer drying of 1″ switch grass leaf in open sun drying

Fitting Model	R^2	SSE	RMSE	Adj R^2	Constants			
					a	b	c	d
Henderson and Pabis	0.9858	0.00978	0.0571	0.981	2.173	0.757	-	-
Logarithmic	0.9005	0.06843	0.185	0.801	-268.6	0.0008883	269.7	-
Two Term	0.9981	0.00128	0.03578	0.9926	12410	0.3493	-	-
Wang and Singh	0.8886	0.07658	0.1598	0.8515	-0.2387	0.00471	-	-
Two Term Exponential	0.8882	0.0769	0.1601	0.8509	-3.987	0.009774	-	-
Page	0.9866	0.00921	0.05542	0.9821	-0.0818	2.709	-	-

Table 5. Estimated values of parameters of selected drying models used for the representation of thin-layer drying of 1″ switch grass leaf in solar drying

Fitting Model	R^2	SSE	RMSE	Adj R^2	Constants			
					a	b	c	d
Henderson and Pabis	0.9361	0.03946	0.1147	0.9148	1.724	-0.5246	-	-
Logarithmic	0.9685	0.01942	0.09854	0.9371	-99.47	0.0024	100.6	-
Two Term	0.7862	0.132	0.3633	0.1448	2.678	-0.876	0	-0.8769
Wang and Singh	0.9425	0.03548	0.1088	0.9234	-0.1296	0.01581	-	-
Two Term Exponential	0.9457	0.0335	0.1057	0.9276	2.456	-0.6223	-	-
Page	0.9562	0.02706	0.09497	0.9416	-0.0701	2.326	-	-

4. Conclusions

In this experimental study, the drying characteristics of Switchgrass leaf, in open sun and in a solar convective drier was investigated in two sample sizes. The rate of drying was improved with smaller sized samples. Solar convective drying can be considered a faster mode of drying from the drying curves. All the mathematical models used could sufficiently explain the kinetics involved. The Two Term Model has the best predictability for Switchgrass drying in the open sun. The Page and Henderson and Pabis Model are effective to explain the drying curves for solar drying of sample sizes ½" and 1" respectively.

Nomenclature

a,b,c,d	:	Empirical coefficients
M_t	:	Moisture content at specific time (g water/ g dry solids)
M_0	:	Moisture content at initial time (g water / g dry solids)
M_e	:	Moisture content at equilibrium time (g water / g dry solids)
MR	:	Moisture ratio
R^2	:	Coefficient of determination
RMSE	:	Root mean square error
SSE	:	Sum of squared Errors
T	:	Drying time (min)
Subscripts		
0	:	Initial
T	:	Specific time
th	:	Theoretical
exp	:	Experimental
pre	:	Predicted

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