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Experimental Investigation of Drying Ratesof Solar Photovoltaic and Thermal Dryers III: MultivariateModelling Equation

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Abstract

Drying process is influenced by many factors which include environmental parameters like temperature, humidity, wind speed and pressure; type of the equipment employedand properties of the materials being dried, such as moisture content and surface area. Many studies have been carried out on drying technologies, especially drying curves and modelling equations, most of which havefocused on univariate analysis employing only mosture ratio and time as variables as dependent and independent variables, respectively. This paper focuses on multivariate drying analysis with the modelling equationincorporating physicalparameters such as Humidity, Temperature and wind speed, using constructedsolar energy thermal dryer and solar Photovoltaic assisted dryer equipment.The experimental data obtained were used to model the drying rate as a function of identified influencing factors. Multivariatedrying equationsand related error analyses,which can assist in the prediction of behavior and performance of both the agriculural product and the dryer equipment under different climatic conditions, were obtained for each of a system of seven colour-differentiateddryersconsidered in the study.

Keywords: Climatic conditions, Drying technologies, Modelling Equation, Photovoltaic, Dryers.

1.0 Introduction

Convective solar energy drying operation is governed mainly by the properties of the drying medium (heat energy, air movement, humidity, atmospheric pressure and vacuum) and that of the product properties (moisture content, thickness, surface area and nature of the material) being dried. Other properties are the geometrical arrangement of the product in relation to the heat transfer on the surface of the drying medium (for example, tray loading), characteristics of the drying equipment, and heat transfer efficiency [1]. Drying is essential for processing andpreserving agricultural crops and industrial products, such as textiles, dairy processing, cement, clay bricks, tiles, wood and timber processing, waste water treatment, and biomass treatment.Although solar radiation for drying has existed since antiquity, it has not yet been widely commercialised, particularly in the industrial sector. Considering the rapid depletion of natural fuel resources, solar drying is expected to become indispensable in the future. Moreover, environmental considerations and damages caused by human beings due to increasing consumption of fossil fuel prompt governments and industries to use renewable energies as a clean and sustainable resource, thus, the use of solar energy for drying. Numerous solar drying applications are classified into two main categories, namely agricultural and industrial.

2.0 Related Literature

Many benefits could be exploited from solar energy for drying applications [2]. Up to 70 per cent of agricultural products get spoilt during the traditional process of open-air drying, especially in tropical and subtropical regions [3].Average electricity prices for companies have jumped from 60% over the past five years because of costs passed along as part of government subsidies to renewable energy producers[4].The sun is the largest available carbon-free energy resource for human being. Many investigations have been conducted to learn how to harvest and apply solar energy as a primary source of energy [5].Convective Solar Energy drying is the transfer of heat energy from the surrounding environment to evaporate surface

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moisture[6]. Kays [7] and Joshi*et al.*[1] define the drying rate in bean samples and other agricultural commodities as the amount of water removed per unit time from thin layer drying at 50, 60 and 70 °C. It was apparent that the drying rate decreased continuously with increasing drying time. The results indicated that diffusion is the most likely physical mechanism governing moisture movement in the bean samples, which is generally in agreement with some previous studies on drying of various food products [8-10].Okpari*et al.*[11] developed a model for Global Solar Radiation for Enugu using maximum temperature. They conducted comparative statistical testsof model fitness using Root Mean Square Error (RMSE) and the Mean Bias Error (MRE). These errorswere found to be 1.95% and 8.71% which means that the model can be used for both long term and short term prediction of solar radiation.
Adnan*et al.*[12] conducted experiment on mathematical modelling of solar drying curves by *fitting* eight drying curvesusing moisture ratio of unshelled pistachios as the dependent variable. This paper investigates the effect of meteorological parameters such as temperature, humidity and windspeed on the drying rate (reduction in moisture content) of cassava with time. It models the response variable (weight of drying material) as a function of meteorologicalparameters (temperature, humidity, windspeed and time) using multivariate techniques, which can predict the behavior and performance of the agriculural product and drying equipment under different climatic conditions.

3.0 Materials and Methods

Six solar cabinet dryers were constructed (to be compared with the traditional open air drying (TOAD)) Fig. 1. Three out of the six solar dryers were Unassisted Solar Thermal Dryers (USTPD), such as Thermal Black (TBLK), Thermal Green (TGRN) and Thermal White (TWHT), while the remaining three were Integrated Assissted Photovoltaic Solar Dryers (IPVSAD) such as Assisted Black (IBLK), Assisted Green (IGRN) and assisted White (IWHT) dryers respectively. It means that thefirst three solar thermal dryers and the Traditional Open Air Drying (TOAD)were not 'assisted' but were made to respond only to the incoming solarradiation alone. The other remaining three solar energy cabinet dryers were 'assisted' with solar Photovolyaic (PV). These assisted solar energy dryers are referred to as 'integrated solar energy dryers'.
One each of the three integrated assisted solar (IPVSAD) and the unassited (USTPD) cabinet dryers was painted black (IBLK), the second one green (IGRN), while the third (remaining) uassited and the integrate dryer was fabricated with (white) aluminium sheet (IWHT). At the three sides of each (IPVSAD) were located three low power consuming and highly efficient fans which remove moisture from the inside of the dryer chamber to the outside of the solar cabinet dryer. The process of expelling moisture continues until the required moisture content of the commodity is reached.

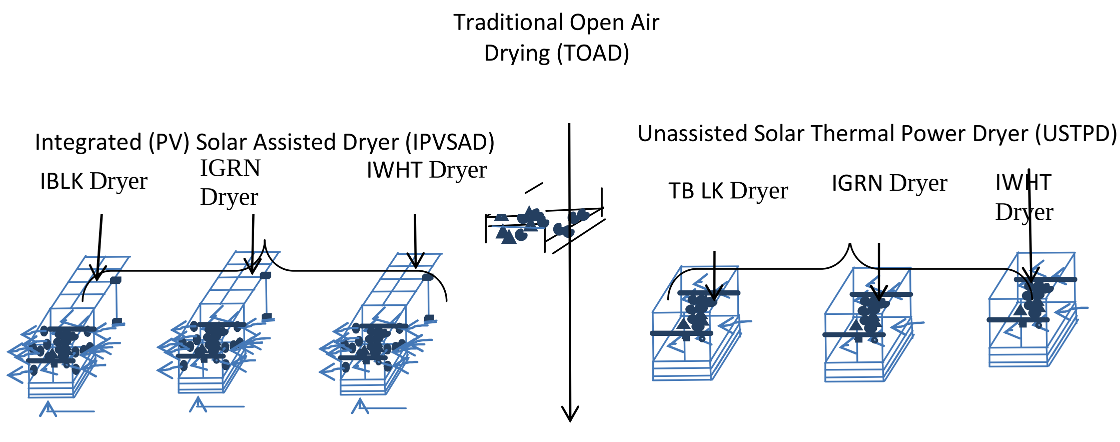

Figure1: Experimental Set-Up for Integrated (PV) Solar Assisted Dryer (IPVSAD) and Unassisted Solar Thermal Dryer (USTPD) Compared with Traditional Open Air Drying (TOAD)
The attached thermostat attached to IPVSAD performs the action of make and break at the pre-set temperature for the commodity to dry. A PV module power assembly was also incorporated to produce electric current for the attached electric heater for generation of additional heat when the solar radiation becomes chaotic during the day or when it is not available in the night.

4.0 Resultsand Discussion

4.1 Results

Thirty two recordings were made at various time intervals which started at time t equals to 0 corresponding to the initial weight of cassava before the start of drying. Recording of the falling weight of cassava in all the seven trays contained in the seven system of dryer were taken simultaneously and the measured results of time,humidity, temperature and wind speed were recorded in Table 1 (for brevity only the first ten sets of observations are displayed out of a total of 32 sets). A model involving Multivariate Modelling Equations, Graphs or Drying curves and Error Analysis which combined influencing parameters like Humidity, Temperature, Wind Speed, Moisture and Time were generated using MATLAB and recorded as multivariate equations 1 to 7 below.The drying curves are presented in Figures 2to8. Actual and predicted errors are recorded in Tables 2 to8. Again for brevity, only the first 5 error observations are shown.

Table 1: Result of Drying Experiment.

		INTEGRATE DRYER			OPEN AIR DRYING	THERMAL DRYER			
S/NO		IBLK	IGRN	IWHT	OPEN AIR DRYING	TBLK	TGRN	TWHT	
1	FINAL Wt OF CASA	3344	2939	3003	3041	3508	2937	3011	O
	HUMIDITY	48.4	47.7	49	43	46.1	59	58.8	
	TEMPT.	34.31	35.4	35.3	43.2	43.2	42.2	42.2	
	WIND SPD	2.1	3.2	1.2	0.1	0.001	0.001	0.001	
2	FINAL Wt OF CASA	2703	2666	2916	2771	2006	2714	2850	60
	HUMIDITY	44.1	54	50.1	61	65.1	61	63	
	TEMPT.	44.1	44.1	42.1	34.1	34.1	34	53	
	WIND SPD	3.2	3.2	1.2	0.1	0.001	0.001	0.001	
3	FINAL Wt OF CASA	2466	2434	2700	2676	2637	2637	2755	195
	HUMIDITY	86.6	76.5	77.6	64.8	79.6	78.5	77.6	
	TEMPT.	29.1	29	29.1	30.2	29.3	28.9	28.8	
	WIND SPD	1.2	2.3	3.3	0.1	0.001	0.001	0.001	
4	FINAL Wt OF CASA	2286	2291	2398	2627	2606	2601	2722	360
	HUMIDITY	81.2	81.2	82.5	75	79.3	79.5	81.4	
	TEMPT.	28.8	28.8	29.4	29.2	29.2	29.2	28.8	
	WIND SPD	1.9	1.1	3.6O	0.1	0.001	0.001	0.001	
5	FINAL Wt OF CASA	2123	2167	2199	2580	3576	2569	2686	619
	HUMIDITY	85	82	87.4	60.7	82.9	82.6	85	
	TEMPT.	27.6	27..5	37.5	27	27.1	27.1	26.8	
	WIND SPD	1.2	0.8	0.8	0.3	0.001	0.001	0.001	
6	FINAL Wt OF CASA	2031	2091	2152	2561	2555	2558	2672	640
	HUMIDITY	84.1	83.9	90.8	79.6	81.7	83.1	85.1	
	TEMPT.	26.4	26.4	28.2	25.9	26.9	25.9	25.7	
	WIND SPD	1.2	0.9	0.8	0.1	0.001	0.001	0.001	
7	FINAL Wt OF CASA	1940	2008	1980	2551	2545	2548	2661	790
	HUMIDITY	73.2	89	86	84.3	86.6	86.7	90.5	
	TEMPT.	35.8	29.3	30.5	29.3	25.8	25.6	25.5	
	WIND SPD	3.2	3.2	1.2	0.1	0.001	0.001	0.001	

8	FINAL Wt OF CASA	1848	1938	1891	2542	2530	2534	2641	860
	HUMIDITY	93.1	93.6	94.1	83.4	88.6	88.3	90.1	
	TEMPT.	25.7	26	26.3	25.1	25.2	25.1	25.1	
	WIND SPD	1.5	1.6	2.5	0.1	0.001	0.001	0.001	
9	FINAL Wt OF CASA	1690	1802	1718	2495	2500	2499	2632	980
	HUMIDITY	81.6	89.3	74	53.1	78.1	81.2	80.8	
	TEMPT.	35.8	34.1	41	35	31	20.9	30.6	
	WIND SPD	1.3	3	3	0.1	0.001	0.001	0.001	
10	FINAL Wt OF CASA	1600	1709	1637	2417	2445	2440	2535	1100
	HUMIDITY	75.6	65.2	54.8	43.8	62.4	66	67.1	
	TEMPT.	37.2	37.5	39.6	38.9	38.2	37.7	36	
	WIND SPD	1.2	1.8	2.9	0.1	0.001	0.001	0.001	

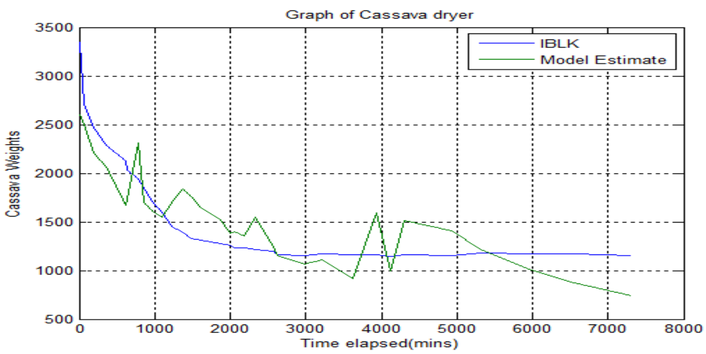

Figure 2: Graph of Integrated Black Dryer (Assisted IBLK) Showing Fall in Weight against Time, for Experimental and Predicted values

Table 2: Measured Weight, Estimated Weight, Weight Error, and the Weight Error (%) for Integrated Black Dryer (Assisted IBLK)

Measured Weight	Estimated Weight	Weight Error	Weight Error(%)
3344	2604.861108	739.138892	-22.1
2703	2508.757372	194.242628	-7.19
2466	2208.56421	257.43579	-10.44
2286	2063.126684	222.873316	-9.75
2123	1674.467644	448.532356	-21.13
2031	1730.408647	300.591353	-14.8
1940	2314.805517	-374.805517	19.32
1848	1697.881392	150.118608	-8.12
1690	1604.326633	85.673367	-5.07
1600	1548.024577	51.975423	-3.25
1452	1696.096077	-244.096077	16.81

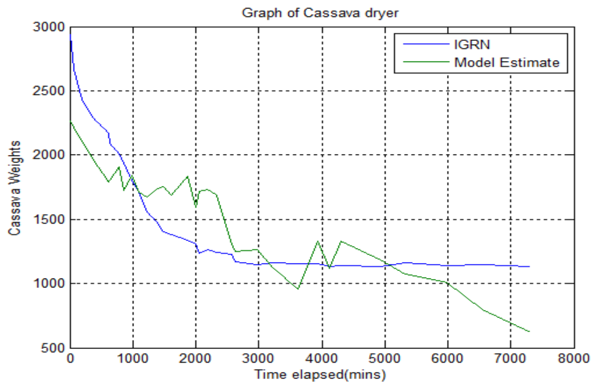

Figure 3: Graph of Integrated Green Dryer (Assisted IGRN) Showing Fall in Weight against Time, for Experimental and Predicted values

Table 3: Measured Weight, Estimated Weight, Weight Error, and the Weight Error (%) for Integrated Green Dryer (Assisted IGRN)

Measured Weight	Estimated Weight	Weight Error	Weight Error(%)
2939	2266.29658	672.70342	-22.89
2666	2215.293134	450.706866	-16.91
2434	2114.985011	319.014989	-13.11
2291	1969.982111	321.017889	-14.01
2167	1791.529129	375.470871	-17.33
2091	1803.669125	287.330875	-13.74
2008	1907.314342	100.685658	-5.01
1938	1722.723149	215.276851	-11.11
1802	1842.57974	-40.57974	2.25

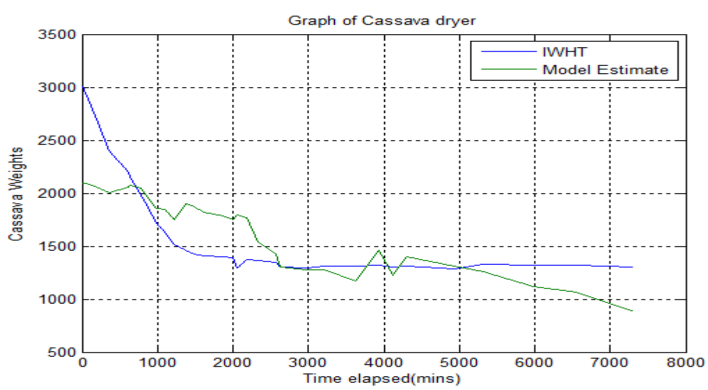

Figure 4: Graph of Integrated Green Dryer (Assisted IWHT) Showing Fall in Weight against Time, for experimental and predicted values

Table 4: Measured Weight, Estimated Weight, Weight Error, and the Weight Error (%) for Integrated White Dryer (Assisted IWHT)

Measured Weight	Estimated Weight	Weight Error	Weight Error(%)
3003	2094.547831	908.452169	-30.25
2916	2091.962124	824.037876	-28.26
2700	2057.368207	642.631793	-23.8
2398	2004.717008	393.282992	-16.4
2199	2055.951633	143.048367	-6.51
2152	2074.342348	77.657652	-3.61
1980	2047.594042	-67.594042	3.41
1891	1970.731237	-79.731237	4.22
1718	1851.028688	-133.028688	7.74
1637	1845.332361	-208.332361	12.73

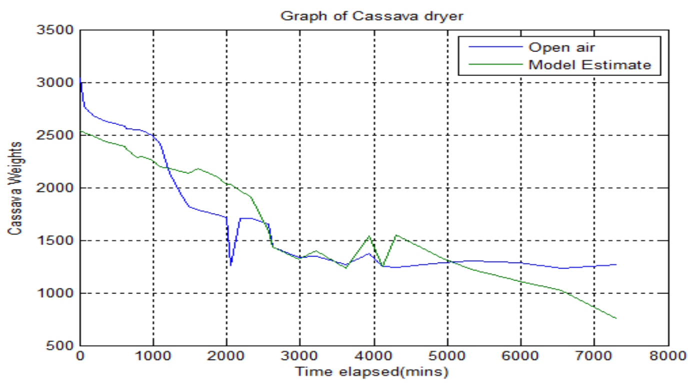

Figure 5: Graph of Traditional Open Air Dryer Showing Fall In Weight against Time, for experimental and predicted values.

Table 5: Showing Measured Weight, Estimated Weight, Weight Error, and the Weight Error (%) for Open Air

Measured Weight	Estimated Weight	Weight Error	Weight Error(%)
3041	2543.739953	497.260047	-16.35
2771	2524.632352	246.367648	-8.89
2676	2488.003018	187.996982	-7.03
2627	2435.678108	191.321892	-7.28
2580	2390.390854	189.609146	-7.35
2561	2362.334096	198.665904	-7.76
2551	2288.415894	262.584106	-10.29
2542	2296.28173	245.71827	-9.67
2495	2255.129488	239.870512	-9.61

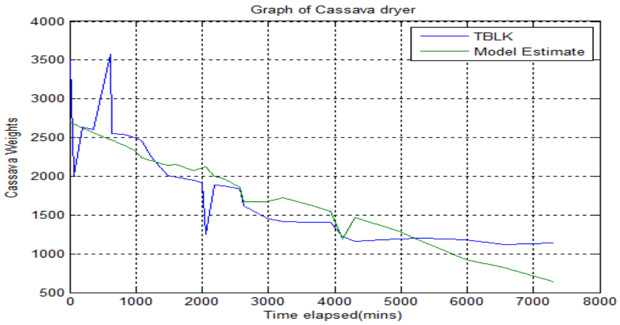

Figure 6: of Graph Thermal Black (TBLK) Dryer Showing Fall In Weight against Time, for experimental and predicted values

Table6: Measured Weight, Estimated Weight, Weight Error, and the Weight Error (%) for Thermal Black (TBLK)

Measured Weight	Estimated Weight	Weight Error	Weight Error(%)
3508	2700.307988	807.692012	-23.02
2006	2674.955532	-668.955532	33.35
2637	2624.672824	12.327176	-0.47
2606	2562.056558	43.943442	-1.69
3576	2470.587317	1105.412683	-30.91
2555	2465.441748	89.558252	-3.51
2545	2412.908629	132.091371	-5.19
2530	2390.022788	139.977212	-5.53
2500	2322.857707	177.142293	-7.09

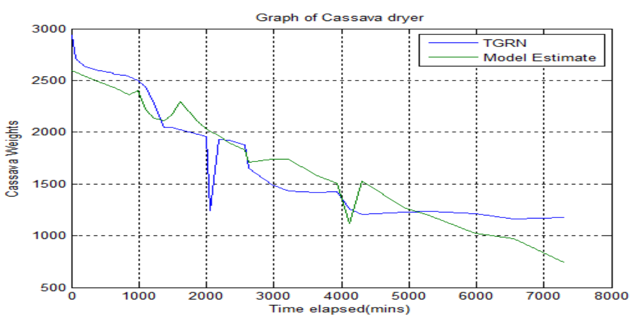

Figure 7: Graph of Thermal Green (TGRN) Dryer Showing Fall in Weight Against Time, for experimental and predicted values

Table7: Measured Weight, Estimated Weight, Weight Error, and the Weight Error (%) for Thermal Green (TGRN)

Measured Weight	Estimated Weight	Weight Error	Weight Error(%)
2937	2596.745293	340.254707	-11.59
2714	2580.570277	133.429723	-4.92
2637	2544.223747	92.776253	-3.52
2601	2496.897597	104.102403	-4
2569	2432.00837	136.99163	-5.33
2558	2433.628407	124.371593	-4.86
2548	2384.502486	163.497514	-6.42
2534	2363.637331	170.362669	-6.72
2499	2404.574608	94.425392	-3.78
2440	2219.502314	220.497686	-9.04

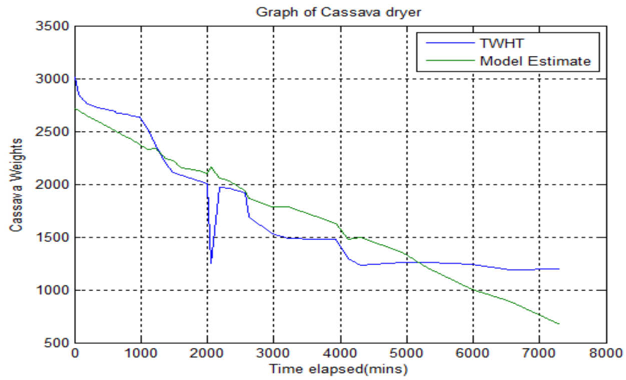

Figure8: Graph Thermal White (TWHT) Dryer Showing Fall In Weight against Time, for experimental and predicted values

Table 8: Measured Weight, Estimated Weight, Weight Error, and the Weight Error (%) for Thermal White

Measured Weight	Estimated Weight	Weight Error	Weight Error(%)
3011	2718.60909	292.39091	-9.71
2850	2696.144079	153.855921	-5.4
2755	2647.244054	107.755946	-3.91
2722	2589.349849	132.650151	-4.87
2686	2500.263545	185.736455	-6.91
2672	2493.388464	178.611536	-6.68
2661	2446.479697	214.520303	-8.06
2641	2423.168353	217.831647	-8.25
2632	2373.835167	258.164833	-9.81
2535	2326.995752	208.004248	-8.21
2366	2339.22064	26.77936	-1.13
2201	2242.263782	-41.263782	1.87

5.0 Conclusion

Predictive multivariate models of cassava drying rates models were obtained as functions of Humidity, Temperature, Wind Speed, Moisture and Time. The models are as follows.

Response ~ b1 - Humidity^2*b2*Time + Temperature^2*b3*Time + ind_Speed^2*b4*Time - Moisture^2*b5*Time, where b1, b2, b3, b4 and b5 are to be determined via multivariate regression and Humidity, Temperature, Wind_Speed, Moisture and Time are actual data from the colour dataset. Hence, multivariate solar energy drying equations wereobtained for each single unit dryer above which may be applied to equivalent system of dryers.

The result of the experiment also showed that it is possible to have a drying Modelling Equation that takes into consideration many other parameters (equations 1 to 7), such as temperature, humidity, windspeed in addition to the conventional Models which is usually presented only in form of Moisture Ratio (MR) against Time. The Modelled equations associated with each system of dryers are as follows.

Integrated (PV) Black Dryer (IBLK):

y = 2604.861108 - Humidity^2*0.000009*Time + Temperature^2*-0.000169*Time + Wind_Speed^2*0.109650*Time - Moisture^2*3.640153*Time (1)

Integrated (PV) Green Dryer (IGRN):

y = 2266.296581 - Humidity^2*0.000020*Time + Temperature^2*-0.000118*Time + Wind_Speed^2*0.028047*Time - Moisture^2*1.032327*Time (2)

Integrated (PV) White (IWHT):

y = 2094.547831 - Humidity^2*0.000003*Time + Temperature^2*-0.000057*Time + Wind_Speed^2*-0.018712*Time - Moisture^2*-0.100445*Time (3)

Open Air Dryer:

y = 2543.739953 - Humidity^2*0.000018*Time + Temperature^2*-0.000141*Time + Wind_Speed^2*-0.033829*Time - Moisture^2*0.105006*Time (4)

Thermal Black Dryer (TBLK):
y = 2700.307988 - Humidity^2*0.000005*Time + Temperature^2*-0.000110*Time + Wind_Speed^2*-135159.425944*Time - Moisture^2*0.224041*Time (5)
Thermal Green Dryer (TGRN):
y = 2596.745295 - Humidity^2*0.000028*Time + Temperature^2*-0.000213*Time + Wind_Speed^2*85642.475016*Time - Moisture^2*0.005633*Time (6)
Thermal White (TWHT):
y = 2718.609091 - Humidity^2*-0.000007*Time + Temperature^2*0.000007*Time + Wind_Speed^2*-300898.130260*Time - Moisture^2*0.133765*Time (7)

This paper introduces multivariate drying equation modelling for cassava across seven different drying systems. This is a novelty that can be adapted to solar drying of other crops. Also, a Half-life concept (Time taken by 50% of moisture content to dry) Table 14 (not displayed here) was used to get am intuitively meaningful picture of the drying rates.

Due to the fact that almost all the factors responsible for solar energy drying (Temperature, Humidity and Wind Speed) were taken into consideration by the Multivariate drying equations 1 to 7 within the limit of error analysis in tables 2 to 8, it can further be used as a predicting tool during drying of agricultural commodity.

The model equation obtained for the drying rates (R) as a function of time (t) are: R(IPSAPD) = [2604.861108 - Humidity^2*0.000009t + Temperature^2*-0.000169t + Wind_Speed^2*0.109650t - Moisture^2*3.640153t],R(USTPD) = [2700.307988 - Humidity^2*0.000005t + Temperature^2*-0.000110t + Wind_Speed^2*-135159.425944t - Moisture^2*0.224041t),R(TOAD) = [2543.739953 - Humidity^2*0.000018t + Temperature^2*-0.000141t + Wind_Speed^2*-0.033829t - Moisture^2*0.105006t], for black IPVSAD, black USTPD and black TOAD, respectively.

The experiment shows that the Integrated PV assisted Solar Dryer was not affected by natural parameters such as precipitation or fluctuating weather condition.We can conclude that drying of agricultural commodities were affected by physical parameters such as colour of the dryer; hence the dryer with the inside compartment painted with black colour dried commodities faster than other test coloured dryers (green, red, blue and white).

6.0 References

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