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Experimental Investigation of Drying Ratesof Solar Photovoltaic and Thermal Dryers. II- Univaried Analysis

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Abstract

The signature of the equitorial zoneof the world commonly refered to as the 'Tropical Region' is charachterised by high temprature, rainfall and humidity where famers are predominantly subsistence with low per capital income. Increase in agricultural output leading to better living condition of the people in this region can be achieved with the aid of availabliy of more efficient drying equipment at cheaper cost: will definitly lead to increase in per capital income. To accomplish this, a good behavior of both the agricultural product and the dryng equipment can be achieved through modelling equations of experimental drying results . Many reseach works on mathematical modelling of drying curves were carried and thier resultswere fitted into known drying equations. Conclusion from drying curves fitted into these known equationswere drawn along the line of best fit or 'goodness of fit', using regression model, x-square, and the mean square deviation between the experimental and the calculated results. In this research work, modelling equation of the obtained experimental data were enumirated with the aid of graghs of moisture ratio and time (Univaried),and Ficks eqution's method of slop for seven system of dryers were enumerated.

Keywords: Tropical Region, Subsistence,Percapital income, Drying, Regression, Ficks Equation.

1.0 Introduction

Food shortage in developing countries does not arise entirely from low agricultural production but partly due to inability to preserve available agricultural products. Farmers in developing economy usually dry agricultural products with solar energy, which can be harnessed in thermal or photovoltaic (PV) forms. Solardrying is quite a simple and ancient skill. It is one of the easily accessible and the most widespread processing technology. Historically, the production of grapes by open sun drying can be traced back to 1490 BC in Greece [1].Solar drying is a dual process of heat transfer to the product from the heating source, mass transfer of moisture from the interior of the product to its surface and from the surface to the surrounding air [2].Experiments carried out in various countries have clearly shown that solar dryers can be effectively used for drying agricultural produce. Controlled solar crop drying can be traced to the United States of America by Lipper and Davis. They compared solar supplemented drying with natural drying which was followed by many other research works in the areas of solar energy utilisation for crop drying[3, 4]. The list is not exhaustive of numerous works on solar energy aimed at modifying the conventional energy to incorporate solar energy as partial or complete source of energy for heating the drying air, in which only few research works have been carried out in Nigeria [5]. 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). Others are the geometrical arrangement of the product in relation to the heat transfer in the surface or medium (for example, tray loading) and the characteristics of the drying equipment, heat transfer efficiency [6]. Weather data are not readily available to the farmers in developing economies due to the fact that there are few weather stations available hence the needs for weather prediction, modelling and simulation by scientists(who are mostly subsistence) for prediction of planting, harvesting and preservation through drying of their agricultural commodities [7].

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2.0 Mathematical Modelling of Solar Drying Curves

Many experimental works have been carried out on drying kinetics and modelling equation on drying curves over the years. Most of these works have concentrated on moisture ratio and drying time. Nanct and Tom [8],used moisture ratio of unshelled pistachios; in solar drying cupboard varying climatic conditions, the result at the end of the experiment shows that the moisture ratio of the shelled pistachios was 9.2% while that of the unshelled pistachios was 7.6%.

2.1 Drying Equations Unvaried Analysis

Based on the initial moisture content from oven drying, the weight loss was used to calculate the moisture content of the material in the dryer[8]. The moisture content was converted to moisture ratio (*MR*) using the following equation:

$$MR = \frac{(M_t - M_0)}{(M_0 - M_e)} \quad (1)$$

WhereM_0, M_e, M_t are the moisture content (kg water/kg dry matter) at a given time, beginning of the drying, when the equilibrium is reached and at time *t* (min), respectively.

The moisture ratio$MR = \frac{M_t}{M_o}$may be taken instead of $MR = \frac{(M_t - M_0)}{(M_0 - M_e)}$for mathematical modelling of the solar drying curves because of the continuous fluctuation of the relative humidity of the drying air during both the forced and natural solar drying processes[9,10,11]. According to [9],

$$\mathrm{MR} = \frac{x_t + x_{eq}}{x_0 + x_{eq}} \quad (2)$$

Where x_o, x_{eq}, x_t are the moisture content (kg water/kg dry matter) at a given time, beginning of the drying, when the equilibrium is reached and at time *t* (min), respectivelywhere x_{eq}.is determined from the absorption isotherms of prickly pear seeds and x_t was deduced from product weight, initial moisture content and dry matter content of the seeds. The dimensionless drying rate (f) was also determined for each drying experiment as follows:

$$f = \frac{\frac{-\mathrm{dMR}}{\mathrm{dt}}}{\left(\frac{-\mathrm{dMR}}{\mathrm{dt}}\right)_0} \quad (3)$$

Where $\left(\frac{-\mathrm{dMR}}{\mathrm{dt}}\right)_0$ is the initial drying rate. The values of $x_{eq}$are relatively little compared to those of $x_t$or x_0, the error involved in the simplification of equation (2) is negligible [12], thus Moisture Ratio was calculated as:

$$MR = \frac{M_t}{M_o} \quad (4)$$

Equation (4) was adopted as the Moisture ratio in this experiment.

2.2 Calculation of Moisture Diffusivity

Adnan *et al.* [13] conducted experiment on mathematical modelling of solar drying curves by fitting nine drying curves equations into nine different models equations (5) to (13).

Tale 1: Mathematical modelling of solar drying curves

Model name	Model	Equation No.	References
Newton	$MR = exp^{-kt}$	(5)	[14]
Page	$MR = exp^{-ktn}$	(6)	[9]
Modified page	$MR = exp^{(-kt)^n}$	(7)	[15]
Modified page	$\mathrm{MR} = \exp[-(\mathrm{kt})^{\mathrm{n}}]$	(8)	[16]
Henderson and Pabis	$MR = aexp^{-kt}$	(9)	[17]
Logarithmic	$MR = exp^{(-ktA)+c}$	(10)	[18]
Two term	$MR = aexp^{-k0t}$+$MR = bexp^{-k1t}$	(11)	[19]
Two-term Exponential	$MR = aexp^{-kt}$+$MR = (1-a)exp^{-kat}$	(12)	[20]
Wang and Singh	$MR = 1 + at$+bt^2	(13)	[21]

Fick's diffusion equation for particles with slab geometry was used for calculation of effective moisture diffusivity by method of slopesin this reseach work. Since the betel leaves are having a flat surface geometry and in this case, the average thickness of the leaves was 0.5 mm, the samples were considered of slab geometry [22]. The equation of Moisture Ratio (MR) relating to slab geometry was expressed according to [23].

$$MR = \frac{8}{\pi^2} exp\left[\frac{\pi^2 D_{eff} t}{4L^2}\right] \quad (14)$$

where*MR* is the dimensionless moisture ratio, D_{eff} is the effective moisture diffusivity in $\mathrm{m^2/min}$,

where $K = \frac{\pi^2 D_{eff}}{4L^2}$

t is the time of drying in minutes and

L is the slab thickness in meters

Regression analysis and correlation coefficient (R) were the primary criterion for selecting the best equation to describe the drying curve. In addition to R, the reduced χ-square and the mean square of the deviations between the experimental and calculated values for the models was used to determine the goodness of fit. The lower the values of the reduced χ-square, the better is the goodness of the fit. This can be calculated using equation (15) to (19):

$$x = \frac{\sum_{i=1}^{n}(MR_{exp,i} - MR_{pre,i})}{N-n} \quad (15)$$

$$R^2 = \frac{\sum_{i=1}^{n}(MR_i - MR_{pre,i}) * \sum_{i=1}^{n}(MR_i - MR_{\exp,i})}{\sqrt{\left[\sum_{i=1}^{n}(MR_i - MR_{pre,i})^2\right]} * \sqrt{\left[\sum_{i=1}^{n}(MR_i - MR_{pre,i})^2\right]}} \quad (16)$$

$$x^2 = \frac{\sum_{i=1}^{n}(MR_{exp,i} - MR_{pre,i})^2}{N-n} \quad (17)$$

$$\text{MBE} = \frac{\sum_{i=1}^{n}(MR_{pre,i} - MR_{exp,i})}{N} \quad (18)$$

$$\text{RMSE} = \left[\frac{\sum_{i=1}^{n}(MR_{pre,i} - MR_{exp,i})}{N}\right]^{1/2} \quad (19)$$

where$MR_{exp,}i$ is the *i*th experimental moisture ratio, $MR_{pre,}i$ is the *i*th predicted moisture ratio, *N* is the number of observations and *n* the number of predicted moisture ratios. The lower the Mean Biase Error (MBE) and Root Mean Square Error(RMSE) the better the agreement between experimental and predicted model.

3.0 Materials and Method

Cassava chip cut of average thickness 6.5 $X10^{-3}$m, lenght 4.9 $X10^{-3}$m and breadth 4.35 $X10^{-3}$mwas the material that was used to investigate the drying rate of the system of solar energy dryers in this research work(because of its importance as a source of food carbonhydrates for the average Nigerian). Six solar cabinet dryers were constructed (to be compared with the traditional open air drying) consisting of one Thermal Black (TBLK) and one integrated black (IBLK),oneThermal Green (TGRN) and one integrared green (IGRN) and oneThermal White (TWHT) and one integrated white (IWHT) dryers. Three solar thermal dryers were not 'assisted' and were made to respond only to the incoming solar radiation alone. The other three solar energy cabinet dryers were 'assisted'with solar PV as in shownFigure 1. These assisted solar energy dryers are referred to as 'integrated solar energy dryers.

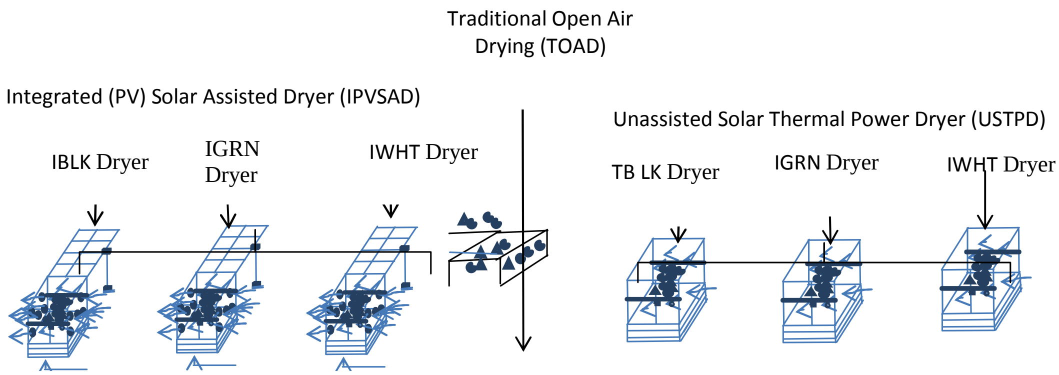


Figure1: Experimental Set-Up for Integrated (PV) Solar Assisted Dryer (IPVSAD) and Unassisted Solar Thermal Dryer (USTPD) Compared with Traditional Open Air Drying

Equal weight of cassava chips of 3344gms approximately was placed inside of each tray that was placed in each of the salar cabinet dryer.

4.0 Results and Discussion

The drying rated (lost of water in the cassava chips) were taken at specific time interval from each dryer by subctracting the weight at time t from weight at the begining of drying with the result recorded in Table 2. This recorded reading was taken as the moisture content (MC). The graphs of moisture content against time for the seven system of dryers were ploted in Figure 9. The data of moisture content was converted to moisture ratio (MR) using equation (4) and recorded in Table 3. The log of results in Table 3 is recorded in Table 4 as the log of moisture ratio. The graph of log of moisture ratio against the time gives a straight line graph with slope K, which is the moisture diffussivity andis useful in modelling out the drying eqution using Fick's method of slope.

Table 2: Falling weight (grms) of Cassava at specified time interval during drying process

TRIALS		Integrated Dryers		Open Air		Thermal Dryers		Time/Min.
	IBLK	IGRN	IWHT	open Air	TBLK	TGRN	TWHT	
1	3344	2939	3036	3041	3508	2937	2997	0
2	2703	2666	2912	2771	2006	2714	2850	60
3	2466	2434	2700	2676	2637	2637	2755	195
4	2286	2291	2398	2627	2606	2601	2722	360
5	2123	2167	2199	2580	3576	2569	2686	619
6	2031	2091	2152	2561	2555	2558	2672	640
7	1940	2008	1980	2551	2545	2548	2661	790
8	1848	1938	1891	2542	2530	2534	2641	860
9	1690	1802	1718	2495	2500	2499	2632	980
10	1600	1709	1637	2417	2445	2440	2535	1100
11	1452	1557	1510	2137	2260	2277	2366	1220
12	1389	1483	1464	1940	2111	2044	2201	1370
13	1333	1406	1425	1823	2011	2045	2108	1490
`14	1312	1380	1411	1789	2024	1823	2076	1610
15	1280	1339	1399	1738	1946	1979	2029	1880
16	1260	1311	1388	1717	1913	1959	2002	2000
17	1233	1232	1293	1260	1251	1243	1251	2060
18	1230	1266	1375	1706	1889	1931	1971	2190
19	1212	1242	1360	1707	1877	1920	1959	2330
20	1198	1229	1344	1653	1840	1878	1913	2570
21	1166	1167	1303	1437	1618	1654	1685	2630
22	1151	1149	1294	1338	1456	1491	1532	2980
23	1168	1164	1314	1344	1414	1432	1491	3220
24	1162	1154	1312	1268	1405	1421	1480	3620
25	1164	1154	1316	1369	1405	1426	1477	3940
26	1146	1129	1300	1252	1225	1259	1297	4120
27	1162	1138	1311	1240	1163	1206	1233	4300
28	1153	1130	1285	1282	1191	1226	1258	4930
29	1181	1158	1331	1300	1199	1233	1263	5320
30	1168	1142	1321	1282	1184	1215	1241	5980
31	1173	1148	1319	1234	1124	1163	1185	6550
32	1150	1134	1304	1265	1143	1179	1201	7300

Equation (4) was employed to calculate moisture ratio (MR) for all the seven system of dryers and recorded in Table 3.

Table 3: Moisture Ratio (Dimensionless)

IBLK	IGRN	IWHT	OPEN AIR	TBLK	TGRN	TWHT	Time Elapsed/Min.
1	1	1	1	1	1	1	0
0.80831	0.9071113	0.959156785	0.911213	0.785633	0.924072	0.950951	60
0.73744	0.8281728	0.889328063	0.879974	0.75171	0.897855	0.919253	195
0.68361	0.7795168	0.789855072	0.863861	0.742873	0.885598	0.908242	360
0.63487	0.7373256	0.7243083	0.848405	0.734322	0.874702	0.89623	619
0.60736	0.7114665	0.708827404	0.842157	0.728335	0.870957	0.891558	640
0.58014	0.6832256	0.652173913	0.838869	0.725485	0.867552	0.887888	790
0.55263	0.659408	0.622859025	0.835909	0.721209	0.862785	0.881215	860
0.50538	0.6131337	0.565876153	0.820454	0.712657	0.850868	0.878212	980
0.47847	0.5814903	0.539196311	0.794804	0.696978	0.83078	0.845846	1100
0.43421	0.529772	0.497364954	0.702729	0.644242	0.775281	0.789456	1220
0.41537	0.5045934	0.482213439	0.637948	0.601767	0.695948	0.734401	1370
0.39862	0.478394	0.469367589	0.599474	0.573261	0.696289	0.70337	1490
0.39234	0.4695475	0.464756258	0.588293	0.576967	0.620701	0.692693	1610
0.38278	0.4555971	0.460803689	0.571523	0.554732	0.673817	0.67701	1880
0.37679	0.4460701	0.457180501	0.564617	0.545325	0.667007	0.668001	2000
0.36872	0.4191902	0.425889328	0.414337	0.356613	0.423221	0.417417	2060
0.36782	0.4307588	0.452898551	0.561	0.538483	0.657474	0.657658	2190
0.36244	0.4225927	0.447957839	0.561329	0.535063	0.653728	0.653654	2330
0.35825	0.4181694	0.442687747	0.543571	0.524515	0.639428	0.638305	2570
0.34868	0.3970738	0.429183136	0.472542	0.461231	0.56316	0.562229	2630
0.3442	0.3909493	0.426218709	0.439987	0.415051	0.507661	0.511178	2980
0.34928	0.3960531	0.432806324	0.44196	0.403079	0.487572	0.497497	3220
0.34749	0.3926506	0.432147563	0.416968	0.400513	0.483827	0.493827	3620
0.34809	0.3926506	0.433465086	0.450181	0.400513	0.485529	0.492826	3940
0.3427	0.3841443	0.428194993	0.411707	0.349202	0.428669	0.432766	4120
0.34749	0.3872065	0.431818182	0.407761	0.331528	0.410623	0.411411	4300
0.3448	0.3844845	0.423254282	0.421572	0.33951	0.417433	0.419753	4930
0.35317	0.3940116	0.438405797	0.427491	0.34179	0.419816	0.421421	5320
0.34928	0.3885675	0.435111989	0.421572	0.337514	0.413687	0.414081	5980
0.35078	0.3906091	0.434453228	0.405788	0.32041	0.395982	0.395395	6550
0.3439	0.3858455	0.429512516	0.415982	0.325827	0.40143	0.400734	7300

The log of moisture ratio was taken and shown in Table 4.

Table 4: Log of Mosture Ratio (Dimensionless)

IBLK	IGRN	IWHT	OPEN AIR	TBLK	TGRN	TWHT	Hrs Elapsed/MINS
0	0	0	0	0	0	0	O
-0.04234	-0.04234	-0.01811	-0.04038	-0.10478	-0.03429	-0.09242	60
-0.08188	-0.08188	-0.05094	-0.05553	-0.12395	-0.04679	-0.13227	195
-0.10817	-0.10817	-0.10245	-0.06356	-0.12909	-0.05276	-0.16519	360
-0.13234	-0.13234	-0.14008	-0.0714	-0.13411	-0.05814	-0.19732	619
-0.14785	-0.14785	-0.14946	-0.07461	-0.13767	-0.06	-0.21656	640
-0.16544	-0.16544	-0.18564	-0.07631	-0.13937	-0.0617	-0.23646	790
-0.18085	-0.18085	-0.20561	-0.07784	-0.14194	-0.0641	-0.25756	860
-0.21244	-0.21244	-0.24728	-0.08595	-0.14712	-0.07014	-0.29638	980
-0.23546	-0.23546	-0.26825	-0.09974	-0.15678	-0.08051	-0.32015	1100
-0.27591	-0.27591	-0.30332	-0.15321	-0.19095	-0.11054	-0.3623	1220
-0.29706	-0.29706	-0.31676	-0.19521	-0.22057	-0.15742	-0.38156	1370
-0.32021	-0.32021	-0.32849	-0.22223	-0.24165	-0.15721	-0.39944	1490
-0.32832	-0.32832	-0.33277	-0.23041	-0.23885	-0.20712	-0.40633	1610
-0.34142	-0.34142	-0.33648	-0.24297	-0.25592	-0.17146	-0.41706	1880
-0.3506	-0.3506	-0.33991	-0.24825	-0.26334	-0.17587	-0.4239	2000
-0.37759	-0.37759	-0.3707	-0.38265	-0.4478	-0.37343	-0.4333	2060
-0.36577	-0.36577	-0.344	-0.25104	-0.26883	-0.18212	-0.43436	2190
-0.37408	-0.37408	-0.34876	-0.25078	-0.2716	-0.1846	-0.44076	2330
-0.37865	-0.37865	-0.3539	-0.26474	-0.28024	-0.19421	-0.44581	2570
-0.40113	-0.40113	-0.36736	-0.32556	-0.33608	-0.24937	-0.45757	2630
-0.40788	-0.40788	-0.37037	-0.35656	-0.3819	-0.29443	-0.46319	2980
-0.40225	-0.40225	-0.36371	-0.35462	-0.39461	-0.31196	-0.45682	3220
-0.40599	-0.40599	-0.36437	-0.3799	-0.39738	-0.31531	-0.45906	3620
-0.40599	-0.40599	-0.36305	-0.34661	-0.39738	-0.31378	-0.45831	3940
-0.41551	-0.41551	-0.36836	-0.38541	-0.45692	-0.36788	-0.46508	4120
-0.41206	-0.41206	-0.3647	-0.38959	-0.47948	-0.38656	-0.45906	4300
-0.41512	-0.41512	-0.3734	-0.37513	-0.46915	-0.37941	-0.46244	4930
-0.40449	-0.40449	-0.35812	-0.36907	-0.46624	-0.37694	-0.45202	5320
-0.41053	-0.41053	-0.3614	-0.37513	-0.47171	-0.38333	-0.45682	5980
-0.40826	-0.40826	-0.36206	-0.3917	-0.49429	-0.40232	-0.45497	6550
-0.41359	-0.41359	-0.36702	-0.38093	-0.48701	-0.39639	-0.46357	7300

The graph of moisture content against time for the seven system of dryers were plotted in Figures 2 to 8. The graph of log of moisture ratio againt time gives a straight line graph with slope K, which is the moisture diffussivity and is useful in modelling out the drying eqution using Fick's method of slope.

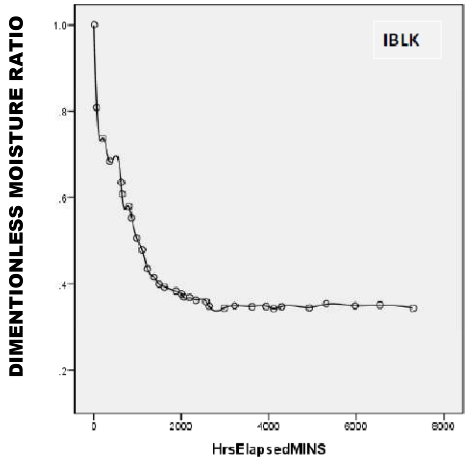


Figure 2: Moisture Ratio against Time (Integrated Black dryer)

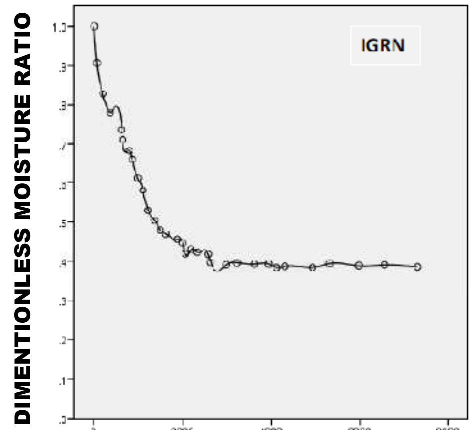
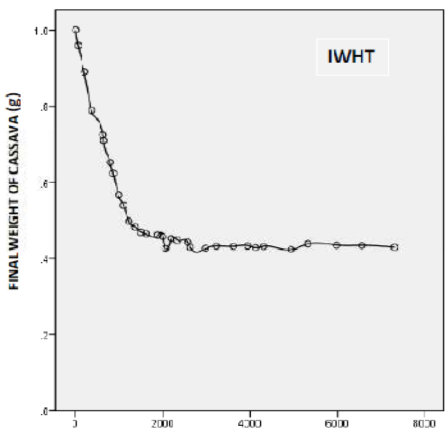


Figure 3: Moisture Ratio against Time (Integrated Green dryer)



TIME/MIN.

Figure 4: Moisture Ratio against Time (Integrated White Dryer)

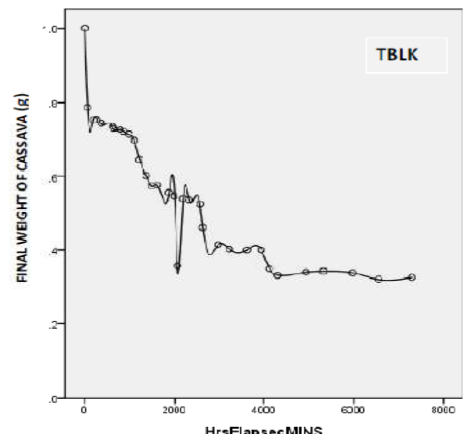
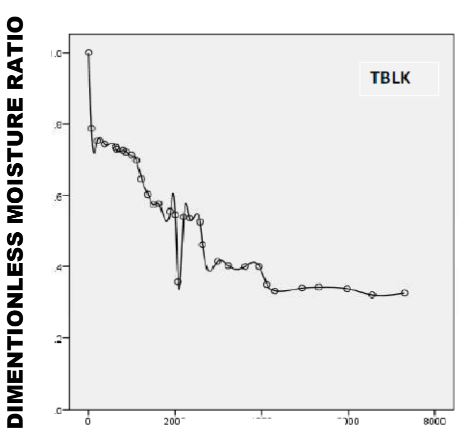


Figure 5: Moisture Ratio against Time (Traditional Open Air Dryer)



TIME/MIN.

Figure 6: Moisture Ratio against Time (Solar Thermal Black Dryer)

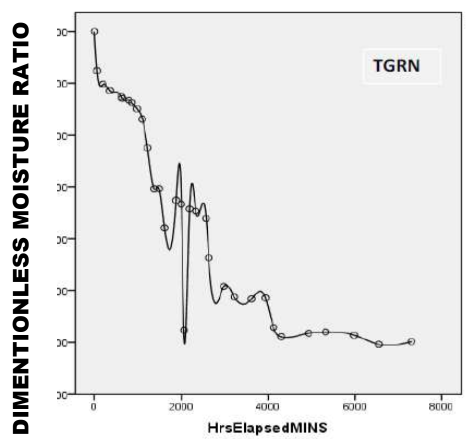


Figure 7: Moisture Ratio against Time (Solar Thermal Green Dryer)

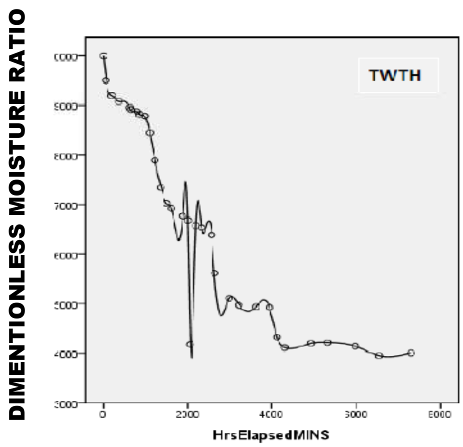


Figure 8: Moisture Ratio against Time (Solar Thermal White Dryer)

Figures 9 and 10 explained the behaviour of the seven systems of dryers under investigation. Figure9 is plot of combined drying rates of seven dryer systems weight against serial number (s/no) of experiment while Figure 10 is the group comparative plots of combined drying rates of seven dryer systems,moisture ratio agaist time.

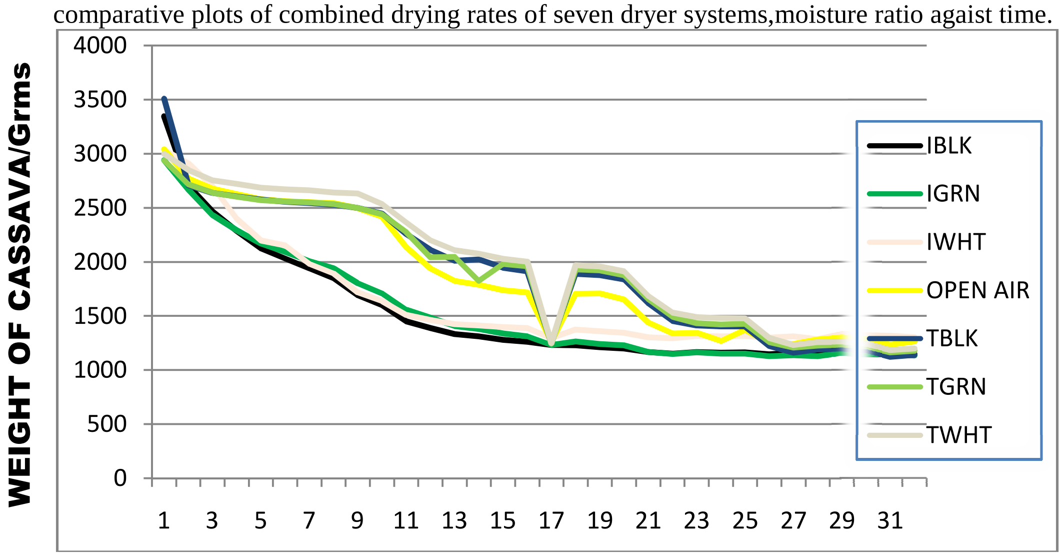


Figure 9: Plot of combined Drying Rates of Seven Dryer Systems Weight against S/No of experiment.

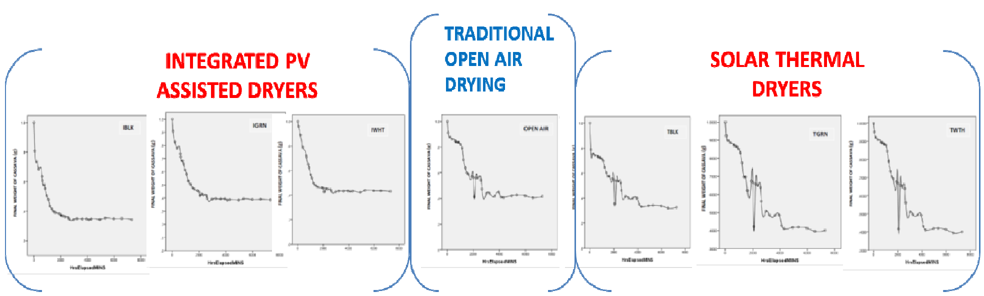


Figure 10: Comparative Plots of combined Drying Rates of Seven Dryer Systems,Moisture Ratio Agaist Time

5.0 Conclusion

Equaion (14) was used to derived model for drying commodities with slab geometry as in the case of cassava chips that was used in this drying experiment, by applying Fick's equation method of slope.The expression obtained from equation (14) can simply be employed tocalculate moisture diffusivity which is an important determining factor in modelling equation of solar drying curves. From equation (14),the Log of both sides of the equation gives a straight line graphwhereby k is the gradient. In equation (14), L is the thickness of the slab. Figures2 to 8 is the graphs of mosture ratio against drying time which described the drying rates of the systems of the dryers and Figure (9)was used to descbribe the peformance of the combined seven system of dryers along the influencing parameters such as the color paints of the inside of the dryer cabinets painted black, green and white.The graph of dimentionless mosture (MR) ratio against time is exponiential and displayed in Figures (2) to (8). The modelling equation governing the seven system of dryers can simply be written inform of:

$$y = Aexp^{-kt} \tag{20}$$

where $y = MR$and

$$-K = Slope = \frac{\pi^2 D_{eff}}{4L^2} \tag{21}$$

This modelling equation enumerated above using Fick's by method of slope make it very easy to derive, and can be applied to both thin layer and slab geometry types of agricultural commodity.

6.0 References

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