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INFLUENCE OF WEATHER VARIABILITY ON DRYING CHARACTERISTICS OF AIR- AND SOLAR KILN-SEASONED GMELINA ARBOREA ROXB. WOOD

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ABSTRACT

Plantation-grown *Gmelina arborea* trees were felled and corewood (3500 mm long) from the base of the logs were sawn. Flatsawn, FS planks (25 mm x 125 mm x 2500 mm) were processed for the experiment. Initial moisture content (IMC%) of planks was determined using the ovendry method. A total of 33 samples each were under air drying shed (ADS, 2.5 m^2) and greenhouse-type solar kiln (SK, $4.00m^3$) located at the Forestry Research Institute of Nigeria (FRIN) for 21 days. Drying rate (DR%/day) and Final moisture content, FMC% of planks were calculated with reference to moisture content above and below fibre saturation point (FSP). Daily measurement on temperature-T°C and relative and humidity-RH% of the atmospheric condition of the study area, and internal environmental condition of the drying facilities were measured. Data were analysed using descriptive statistics, ANOVA and regression analysis at $\alpha_{0.05.}$ Average DR%/day ranged from 0.42 to 155.46 and 0.02 to 157.46 in ADS and SK, respectively. Average FMC was 19.42 and 10.40 in ADS and SK, respectively. Atmospheric T°C ranged from 28.11 to 34.91 while internal T°C ranged from 31.27 to 38.00 and 32.63 to 40.18 in ADS and SK, respectively. Solar powered-kiln improved final moisture content and drying rate of *Gmelina arborea* wood.

KEY WORDS

Wood, temperature, relative humidity, drying rate, fibre saturation point, planks.

Wood drying (seasoning) is referred to as a process of removing water from wood under a specific drying environment (Moya et al., 2012; Owoyemi et al., 2015). It is imperative to dry wood to required moisture content prior to manufacture of desired wood product(s) or further processing (Bond et al., 2011). Drying is of fundamental importance in the production chain. It is a vital stage in wood products manufacturing process because it adds value to the manufactured wood products. Wood seasoning improves wood dimensional stability, workability, adhesive application and so on. Furthermore, acoustic, mechanical, electric insulation and thermal properties of wood improves when wood is seasoned (Tenorio et al., 2012). According to Pedro et al. (2015) for desirable wood processing procedures which ultimately improve end uses, wood should be dried to avoid unwanted development in service. Dried/seasoned wood are less prone to avoidable shrinkage and fungal attack which causes stains or decay. Hence, incidence of seasoning defects such as, warp, collapse, honeycombing, splits and checks reduce drastically.

Air-and solar kiln drying of wood are common wood drying methods which have been practiced for a number of years. The air shed and solar kiln environments are nonisothermal conditions in which drying factors (temperature relative humidity) are nature-based and unregulated. Hence, wood drying rate is unstable and uncontrollable. According to Gan and Choo, 2001; and Owoyemi et al. (2015) temperature and relative humidity are among major variables that influence drying processes. Drying factors play vital role in influencing the wood drying rate and final moisture content of wood. Report by Simo-Tagne et al. (2017) submitted that wood drying under different environments yielded varying outcomes. Variation in drying factors (temperature, relative humidity and air circulation) influenced drying rate, moisture ration and final moisture content of dried board (Pedro et al., 2015; Owoyemi et al., 2015). Based on these findings, outcomes of drying procedures or field experiment at different locations cannot be rigidly compared (Teppo 2015).

According to Bauer (2003) and Pedro et al. (2015) temperature is a major and crucial factor influencing wood drying experiment. This explains why temperature is considered as a major parameter selected in explaining drying models in relation to diffusion analysis. At moisture content below fibre saturation point, wood drying rate increases at higher environmental temperature. This is because moisture molecules bound to the wood cell wall gain more kinetic energy which facilitates migration of water molecules (through diffusion) to the wood surface or atmosphere (Wan Nadhari et al., 2014).

Relative humidity describes the measure of moisture in the atmosphere. It is expressed as the ratio of the amount of moisture in the ambient environment at a given temperature to moisture that the air can hold when it is completely saturated at the same temperature. RH can also be termed as the partial pressure of water vapour divided by the saturated vapour pressure at the same temperature and total pressure (FWPRDC, 2004). According to Wengert (2006) at constant temperature, lower relative humidity results in higher rate of drying. This is because reduction in RH causes moisture content in the surface layers to reduce. Hence, moisture gradient in wood becomes increased. RH is a very vital factor as the amount of water in an environment influences the moisture content to which a timber will dry. Keey, et al. (2000) disclosed that relative humidity is among the important factors that determine drying rate and quality of lumber under specified drying environment.

According to Adeola et al. (2017) solar radiation is a renewable form of energy from earth’s surface. Its relevance to air- and solar kiln drying of timber cannot be overemphasized. In solar kiln technology, solar energy can be incorporated into designs involving solar collectors, solar heating systems and other photovoltaic equipment. Depending on attenuation properties of the atmosphere and the diverse geographical characteristics of the earth surface, the amount of insolation reaching the earth surface differs from one place to another. One of the basic characteristics of air- and solar kiln drying of timber is its dependence on solar radiation. Consequently, daily variation in intensities of solar radiation plays a major role in affecting solar kiln drying processes. Under normal environmental conditions, at higher solar radiation intensity, solar kiln systems receive higher solar energy which transforms into heat (temperature) within the kiln chamber. Consequently, there is a direct relationship between solar radiation intensity and internal temperature of the solar kiln. According to Pedro et al. (2015) daily changes in solar radiation intensity plays a vital role in influencing supply of heat energy required for drying in air and solar kiln drying systems. Consequently, wood drying outcomes under these aforementioned environments vary relatively.

Initial moisture content (IMC) is the moisture content at which wood cell lumen and cell walls are saturated with moisture. At this point, wood is referred to as green or fresh. According to FPL (1999) the IMC of timber ranges from 50% to about 267% of the dry weight of the wood. The higher the IMC of wood, the more moisture that requires drying out. Under any specified drying environment, wood moisture is given off until equilibrium moisture content-EMC (12-15% moisture content) with the prevailing environment is reached. It should be noted that wood moisture from the cell lumen is first given off until fibre saturation point (FSP) is reached. This is a point at which no water is left in the cell lumen but the cell wall is filled with bound water. On reaching FSP, bound water from wood cell wall is dried out under certain temperature and relative humidity. This situation continues until an EMC with the prevailing environment is attained. At this point, wood drying is complete. This represents final moisture content (FMC) in wood. According to Mahadi and Tsegaye (2019) final moisture content is the moisture content at which wood drying experiment is often terminated since no further moisture loss occurs in wood. This is because wood as reached a balanced equilibrium point with the condition under which it is dried.

MATERIALS AND METHODS OF RESEARCH

The experimental air drying shed and solar-powered kiln used for drying were sited at the Forestry Research Institute of Nigeria (FRIN) Ibadan, located on latitude 7°23'15" to 7°24'00" N and longitude 3°51'00" to 3°52'15"E. Annually, the average temperature of FRIN ranges between 18.07°C and 34.4˚C (for minimum and maximum value respectively). The study area is characterized by two seasons which are distinctly different: The rainy season (which begins in April and end in October) and the dry season (which starts in November and ends in March). A distinct harmattan often characterizes the dry season in December (Ariwaodo et al., 2012).

Similar to Helwa et al. (2006) and Bekkioui et al. (2017) the kiln design was a greenhouse type. It was constructed using frames of solid wood. Loading, offloading and assessment of kiln samples were easily carried out through the two doors provided at the rear of the structure. The first step was construction of the floor with solid lumber frames. Treated solid lumber were used for flooring in order to make the structure resistant to biodeterioration. Materials, machines, instruments, tools and devices used for this study include: *Gmelina arborea* wood samples, wax, record book, permanent marker, paint, brush, container, stickers, biro, stickers, ziplock polythene bags, sensitive weighing balance, oven, digital moisture meter, chainsaw, girth tape, wood mizer machine, circular saw machine, digital thermo-hygrometer, solar radiation meter, watch, tape rule, panel saw.

Harvesting of plantation-grown *Gmelina arborea* trees was done and conversion of samples to desired dimension performed at the Department of Forest Products Development and Utilization, Forestry Research Institute of Nigeria, Ibadan. Initial moisture content of boards was calculated using the ovendry method (Eq. 1) in conformity with ASTM (2003).

$$IMC\% = \frac{W_1 - W_2}{W_2} \times 100 \qquad (1)$$

Where:

$IMC\%$ represents the initial moisture content of samples;
W_1 represents weight of wet samples;
W_2 represents weight of ovendry samples.

Weight of wet boards (WWB) was measured on the weighing scale. Subsequently, boards were stacked under the ADS and SK. Stickers (19 mm thick) were used for separating alternate boards in order to air circulation. On a daily basis, periodic moisture content (PMC) of boards was calculated as a percentage of *DWB* (Eq. 2) in accordance to FPRL (1949) and Bond et al. (2011):

$$\%PMC = \frac{CWB - DWB}{DWB} \times 100 \qquad (2)$$

Where:

CWB represents current weight of the board;
DWB represents dry weight of the board.

Dry weight of boards (DWB) was estimated (Eq. 3) based on the average moisture content of the oven dried samples (Bond et al. 2011 and FPRL 1949).

$$DWB\ (Kg) = \frac{WWB}{\left(\frac{MCi}{100} + 1\right)} \qquad (3)$$

Where:

DWB is weight of dry board;
WWB is weight of wet board;
MCi is moisture content of the test specimen.

Daily drying rate (DR%/day) of plank was expressed according to Ogunsanwo and Amoo-Onidundu (2011). It was expressed as a percentage moisture content loss per unit time (days) following Eq. 4.

$$DR = \frac{PMC_{PRV} - PMC_{PRS}}{day} \qquad (4)$$

Where:

DR represents drying rate;
PMC_{PRV} represents periodic moisture content for previous reading;
PMC_{PRS} represents Periodic moisture content for present reading.

Temperature and relative humidity under SK and ADS environments were measured using sets of indoor digital thermo-hygrometers. The devices were placed directly on top of boards at the centre of the stack. Readings were taken 10 times daily (between 8:00 am to 5:00 pm) at interval of 1 hour as modification for climatic data capturing system in accordance to KNMI (2000) and GLOBE (2005). Ambient T, RH and solar radiation intensity of the ambient weather were measured to represent climatic data of the study Mean values of the hourly readings was computed for analysis.

RESULTS AND DISCUSSION

Daily changes in average moisture content of *G. arborea* were presented in Figure 1. From initial moisture content (IMC) of 243.99, final moisture content (FMC) were 19.42 and 10.40 for air drying and solar kiln drying, respectively. This indicated that SK-dried samples attained lower FMC compared to ADS-dried samples. At moisture content (MC) of 19.42, ADS-dried planks have not dried to equilibrium moisture content, EMC (12-15% MC); hence, its utilization potentials may be limited to external applications or end uses. However, it may be unsuitable for internal joinery applications or related end uses (TRADA, 2011).

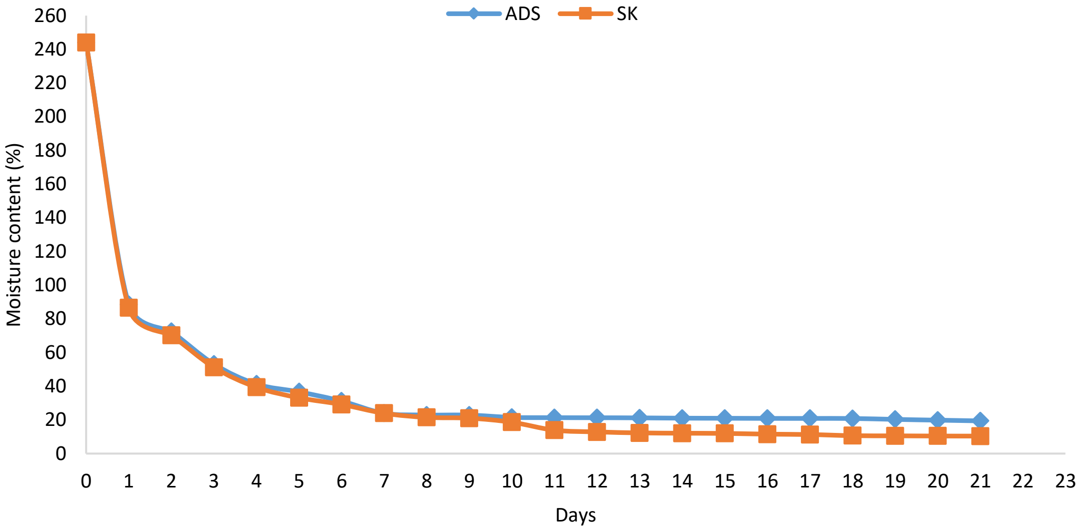

Figure 1 – Daily changes in moisture content level: from IMC to FMC

Based on the Graph (Fig. 1) above, the average DR average of *G. arborea* were 11.12 and 10.69 for SK and ADS, respectively. That indicated that higher drying rate was enhanced in SK compared to ADS. This may mean that the environmental condition (T and RH) in SK facilitated drying rate of *G. arborea* more than in ADS. The findings corroborate submissions (Plumptre, 1979; Simpson, 1993 and Wengert, 2006) that drying rate in solar kiln dryer is faster than in air drying shed.

Model 1 (Eq. 5) reveals that a unit increase in T will result to about 2.71 times increase in DR and a unit increase in RH will lead to -1.96 times increase in DR. In addition, just about 1% of the variation in DR can be predicted by T and RH. Considering the fit statistics (R^2 = 0.01 or 1%, SEE= 90.79, $p<0.05$) for Model 1, it was observed that the data did not fit well to the model as coefficient of determination (R^2) was relatively low and the value of standard error of estimate (SEE) was high. More so, result on ANOVA revealed that the model was not significant ($p<0.05$). This could be due to the fact that, above FSP, wood drying is not directly dependent on T and RH of the prevailing environment.

Table 1a – Model summary on Regression between DR and internal T and RH of SK

Model	R	R Square	Adjusted R Square	Std. Error of Estimate	Stage of drying
1	0.12[a]	0.01	-0.97	90.79	Above FSP
2	0.70[a]	0.49	0.41	1.37	≤ FSP

a. Predictors: (Constant), temperature, relative humidity.

Table 1b – ANOVA for T, RH and DR below and above FSP (solar kiln)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	221.07	2	110.54	0.01	0.99[ns]
	Residual	16486.98	2	8243.49		
	Total	16708.05	4			
2	Regression	23.15	2	11.58	6.22	0.01*
	Residual	24.21	13	1.86		
	Total	47.36	15			

*a. Dependent variable: DR b. Predictors: (Constant), RH, TEMP, ns means value is not significant, while * means value is not significant.*

Table 1c – Coefficients for T, RH and DR below and above FSP (solar kiln)

Model		Unstandardized coeff.		Standardized coeff.	T	Sig.
		B	Standard Error			
1	(Constant)	235.70	1403.88		0.17	0.88
	Temperature	-2.71	29.07	-0.07	-0.09	0.93
	Relative Humidity	-1.96	12.51	-0.12	-0.16	0.89
2	(Constant)	-17.72	6.44		-2.75	0.02
	Temperature	0.39	0.17	0.45	2.25	0.04
	Relative Humidity	0.11	0.05	0.47	2.36	0.04

a. Dependent variable: drying rate.

Model 1 (Above FSP):

$$DR = 235.70 - 2.71T - 1.96RH \ (R^2 = 0.01 \text{or } 1\%, SEE = 90.79, p<0.05) \qquad (5)$$

Model 2 (Below FSP):

$$DR = 17.72 + 0.39T + 0.11RH \ (R^2 = 0.49 \text{ or } 49\%, SEE = 1.37, p<0.05) \qquad (6)$$

Hence, at MC above FSP, free water from wood moves out through capillary forces without the influence of prevailing T or RH. This corroborates submission of Amoo-Onidundu, (2021) that at moisture content above FSP, increase or decrease in T or RH of a prevailing environment does not considerably determine wood DR.

For Model 2, result was summarized (Eq. 6) as DR = 17.72+0.39T+0.11RH (R^2 = 0.49 or 49%, SEE= 1.37, $p<0.05$). This implied that a unit increase in T will lead to about 0.39 times increase in DR and a unit increase in RH will result to 0.11 times increase in DR. In addition, the fit of statistics revealed that approximately 49% of the variation in DR can be predicted by T and RH. The SEE was lower compared to Model 1. The ANOVA indicated that Model 2 was significant at $p \leq 0.05$. Consequently, the data relatively fitted better compared to Model 1. The implication was that, the independent variables correlated more with the dependent variable in Model 2. Conclusively, the DR below FSP could be better explained based on influence of T and RH. This is in line with the submission of Wan Nadhari (2014) that higher T and lower RH facilitate DR of wood at MC below FSP.

Table 2a – Model summary on Regression between DR and internal T and RH of ADS

Model	R	R Square	Adjusted R Square	Std. Error of Estimate	Stage of drying
1	0.48[a]	0.23	-0.55	79.56	Above FSP
2	0.34[a]	0.12	-0.02	2.15	≤ FSP

a. Predictors: (Constant), temperature, relative humidity.

Table 2b – ANOVA for T, RH and DR below and above FSP (in ADS)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3705.95	2	1852.97	0.29	0.77^{ns}
	Residual	12658.65	2	6329.32		
	Total	16364.59	4			
2	Regression	7.80	2	3.90	0.84	0.45^{ns}
	Residual	60.09	13	4.62		
	Total	67.89	15			

a. Dependent variable: drying rate. Predictors: (Constant), RH, TEMP.

Table 2c – Coefficients for T, RH and DR below and above FSP (in ADS)

Model		Unstandardized coeff.		Standardized coeff.	T	Sig.
		B	Standard Error			
1	(Constant)	3084.39	4138.21		0.745	0.53
	Temperature	-63.91	92.63	-0.81	-0.690	0.56
	Relative Humidity	-15.35	20.19	-0.89	-0.760	0.53
2	(Constant)	14.23	18.11		0.79	0.45
	Temperature	-0.40	0.39	-0.31	-1.03	0.32
	Relative Humidity	0.02	0.12	0.05	0.17	0.87

a. Dependent variable: drying rate.

Model 1 (Above FSP):

$$DR = 3084.39 - 63.91T - 15.35RH \ (R^2 = 0.23 \text{ or } 23\%, SEE = 79.56, p<0.05) \qquad (7)$$

Model 2 (Below FSP):

$$DR = 14.23 - 0.40T + 0.02RH \ (R^2 = 0.12 \text{ or } 12\%, SEE = 2.15, p<0.05) \qquad (8)$$

The fit statistics (Eq. 7) for Model 1 (DR = 3084.39 -63.91T- 15.35RH; R^2 = 0.23 or 23%, SEE= 79.56, $p<0.05$), indicated that a unit increase in T resulted to about 63.91 times increase in DR and a unit increase in RH resulted to 15.35 times increase in DR. In addition, just about 23% of the variation in DR can be predicted by T and RH. Considering the fit statistics, it was observed that the data did not fit well to the model. This was because coefficient of determination (R^2) was relatively low and the value of standard error of estimate (SEE) was high. More so, result revealed that the model was not significant ($p<0.05$). This implied that no significant variation in T and RH can be attributed to changes in DR at MC above FSP. This corroborates the submission of Korkut (2018) that, at MC above FSP, environmental factors are not major indices that determine DR. In Eq. 8, a unit increase in RH resulted to 0.02 times increase in DR for ADS. In addition, approximately 12% of the variation in DR can be predicted by T and RH with SEE of 2.15. ANOVA indicated that the Model was not significant at $p<0.05$. Consequently, a comparative study revealed that the data in ADS did not fit into the Model 2 as much as for solar kiln drying (Eq. 6). Hence, it implied that variation in T and RH had significant on effect on DR of *Gmelina arborea* wood under SK environment.

Table 3a – Model summary for regression between internal and ambient T/RH in SK

Model	R	R Square	Adjusted R Square	Std. Error of Estimate
1: T	0.49[a]	0.24	0.20	1.84
2: RH	0.08[a]	0.01	-0.05	7.00

a. Predictors: (Constant), Ambient T (Model 1); (Constant), AMB. RH (Model 2).

Table 3b – ANOVA for solar and ambient drying conditions (T and RH)

	Model	Sum of Squares	df	Mean Square	F	Sig.
Temperature	Regression	19.88	1	19.88	5.84	0.03[*]
	Residual	64.67	19	3.40		
	Total	84.55	20			
Relative humidity	Regression	5.68	1	5.68	0.12	0.74[ns]
	Residual	931.46	19	49.02		
	Total	937.15	20			

*Model 1: a. Dependent variable: solar temp. b. predictor: ambient T. *mean value is significant (p≤0.05).*
*Model 2: a. Dependent variable: solar RH. b. predictor: ambient RH. *mean value is not significant (p≤0.05).*

Table 3c – Coefficient for solar and ambient drying condition (T and RH)

Model		Unstandardized coeff.		Standardized coeff.	T	Sig
		B	Standard Error	Beta		
1	(Constant)	22.06	6.34		3.48	0.00
	Amb. T	0.56	0.23	0.49	2.42	0.03
2	(Constant)	50.28	23.46		2.14	0.05
	Amb. RH	-0.12	0.35	-0.08	-0.34	0.74

a. Dependent Variable: Solar T: Dependent Variable: Solar RH.

Model 1:

$$\text{Tsolar}=22.06+0.56\text{amb. T}\ (R^2=0.24 \text{ or } 24\%,\ \text{SEE}=1.84,\ p<0.05) \qquad (9)$$

Model 2:

$$\text{RHsolar}=50.28-0.12\text{amb. RH}\ (R^2=0.01\text{or } 1\%,\ \text{SEE}=7.00,\ p<0.05 \qquad (10)$$

Table 4a – Model summary for regression between internal and ambient T/RH in ADS

Model	R	R Square	Adjusted R Square	Std. Error of Estimate
1: T	0.20[a]	0.04	-0.01	2.07
2: RH	0.08[a]	0.01	-0.05	7.00

a. Predictors: (Constant), Ambient T (Model 1); (Constant), Ambient. RH (Model 2).

Table 4b – ANOVA for ADS and ambient drying conditions (T and RH)

	Model	Sum of Squares	df	Mean Square	F	Sig.
Temperature	Regression	3.49	1	3.49	0.82	0.38[b]
	Residual	81.06	19	4.27		
	Total	84.55	20			
Relative humidity	Regression	5.68	1	5.68	0.12	0.74[b]
	Residual	931.46	19	49.02		
	Total	937.15	20			

*Model 1: a. Dependent variable: solar temp. b. predictor: ambient T. *mean value is significant (p≤0.05).*
*Model 2: a. Dependent variable: solar RH. b. predictor: ambient RH. *mean value is not significant (p≤0.05).*

In Eq. 9, the fit statistics for T_{solar} versus $T_{ambient}$ (R^2 = 0.24 or 24%, SEE = 1.84) implied that about 24% of the variation in T_{solar} can be explained by $T_{ambient}$ with relatively low error of estimate. However, in Equation 10, the fit statistics 0.01 or 1%, SEE = 7.00) for RH_{solar} versus $RH_{ambient}$ implied that only 1% of the variation in RH_{solar} can be explained by $RH_{ambient}$. Results on ANOVA showed that T (0.03) was significant while RH (0.74) was not significant. This indicated that data fitted more into the Temperature-model than RH-model. The implication is that drying process within the SK chamber is more influenced by changes in ambient temperature of the study area. This conforms to submissions (Pedro et al., 2015, Bauer, 2003) that temperature is a major and crucial factor influencing wood drying experiment and explains why temperature was considered as a major parameter in the selected drying models in relation to diffusion analysis.

Table 4c – Coefficient for ADS and ambient drying condition (T and RH)

Model		Unstandardized coeff.		Standardized coeff.	T	Sig
		B	Standard Error	Beta		
1	(Constant)	48.71	12.58		3.87	0.00
	Amb. T	-0.41	0.45	-0.20	-0.91	0.38
2	(Constant)	50.28	23.46		2.14	0.05
	Amb. RH	-0.12	0.35	-0.08	-0.34	0.74

a. Dependent Variable: Solar T: Dependent Variable: Solar RH.

Model 1:

$$T_{ADS}=48.71-0.41\text{ambient } T\ (R^2=0.04 \text{ or } 4\%,\ SEE=2.07,\ p<0.05) \quad (11)$$

Model 2:

$$RH_{ADS}=50.28-0.12\text{ambient } RH\ (R^2=0.01 \text{or } 1\%,\ SEE=7.00,\ p<0.05 \quad (12)$$

In Eq. 11, the fit statistics for T_{ADS} versus $T_{ambient}$ ($R^2 = 0.04$ or 4%, SEE = 2.07) revealed that about 4% of the variation in T_{ADS} can be explained by $T_{ambient}$. However, Eq. 12 revealed that the fit statistics was $R^2 = 0.01$ or 1%, SEE = 7.00 for RH_{ADS}versus $RH_{ambient.}$ This indicated that only 1% of the variation in RH_{ADS} can be explained by $RH_{ambient}$. Based on the results, Models 1 and 2 did not fit well. These implied that statistically, changes in ambient T and RH had no significant influence on ADS' internal condition. This may imply that under ADS environment, variation between highest and least temperature/ relative humidity, did not result into statistically differences response *G. arborea* to rate of drying.

CONCLUSION

This study has provided relevant information on influence of weather variability on selected drying characteristics of air-and solar kiln dried *Gmelina arborea* wood. Considering the average final moisture content (FMC) of the samples, it was evident that solar kiln-dried boards dried to a lower (more desirable) FMC when compared to air-dried samples. More so, DR of *Gmelina arborea* wood was higher in SK- signifying that drying condition in the SK was more favourable. Relationship between ambient condition and internal condition in SK and ADS revealed that variation in ambient temperature influenced internal condition of SK more that in ADS. More so, daily variation in internal condition of SK had significant influence on moisture ratio. This implied that variability in ambient weather is a key factor that influences the selected drying characteristics of *Gmelina arborea* wood.

In order to avoid conservatism of result and for validation of findings, it is pertinent that similar experiment on air and solar kiln drying of *Gmelina arborea* be subsequently conducted under different design of drying facility, altitude and geographical location. This will give a wider horizon to the study and provide additional information on influence of environmental factors on drying characteristics of *G. arborea* under nonisothermal conditions.

EDITORIAL NOTE

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