Thin Layer Drying Characteristics of Stinging Nettle (Urticadioica L.) in a Solar Tunnel Dryer

Michael M. Kamwere*,
Agricultural Technology Development Centre,
Box 1177-00232,
Ruiru, Kenya

Christopher L. Kanali
Department of Agricultural and Bio systems
Engineering, JKUAT University,
Box 62000-00200,
Nairobi, Kenya

Urbanus N. Mutwiwa
Department of Agricultural and Bio systems Engineering,
JKUAT University,
Box 62000-00200,
Nairobi, Kenya

Gareth M. Kituu
Department of Agricultural and Bio systems Engineering,
JKUAT University,
Box 62000-00200,
Nairobi, Kenya,

***Abstract*: High moisture content vegetables form the bulk of most of the postharvest losses, estimated to be 30-40% in developing countries in the tropics and subtropics, due to poor post-harvest handling, transportation, processing and storage facilities. Various technologies have been used to minimise the losses and include cooling, traditional open sun drying, chilling and solar drying among others. In this study, thin layer solar drying characteristics of stinging nettle (*Urticadioica L.*) vegetables in a solar tunnel dryer were modelled against open sun drying. Fresh stinging nettle vegetables with average moisture content of 566.7% (dry basis) were dried for eight hours to final moisture content of 7.3 and 13.9 % (dry basis) for solar dryer and open sun, respectively. The colour of the samples was recorded at the start and end of the drying process. The data obtained from the drying tests was applied to nine (9) mathematical models namely Verma et al, Newton, Page, Modified Page, Henderson & Pabis, Logarithmic, Diffusion approximation, Two term and Two Term exponential. All the nine models investigated were found to be suitable for describing the drying characteristics of stinging nettle vegetables with R^2 values greater than 0.96. However, Verma et al model satisfactorily predicted thin layer drying of stinging nettle vegetables better than the other models with the highest R^2 of 0.994 and lowest χ^2 of 0.00112 and $RMSE$ of 0.02899 for the solar dryer. Hue angle, h^*, values obtained for the solar drying and open sun were 108.17 ± 4.32^0 and 103.37 ± 5.90^0, respectively, which were lower than the values for fresh stinging nettle of 125.60 ± 1.31^0. Although the hue angle of dried vegetables is lower than the fresh ones, solar dried vegetables have high hue angle as compared to sun dried hence better quality.**

Keywords: Thin layer drying models, moisture content, moisture ratio, solar tunnel dryer

I. INTRODUCTION

Stinging nettle (*Urticadioica L.*) is one of the numerous traditional leafy vegetables that are commonly used in Kenya to spice up food. It is mainly found growing wildly especially in forested areas like the Mt. Kenya and Aberdare ranges [1]. Few farmers cultivate stinging nettle as a crop in the farms where they harvest, dry it and mill before packaging and selling [1].

However the plant is popularly used both a vegetable and as a herb. Specific studies have demonstrated that stinging nettle has antifungal properties [2]. In Europe, nettle leaves and roots have been used in hair products to promote hair growth, treat eczema and control dandruff [3]. It is therefore among plants foraged from the wild and eaten as a vegetable [4]. It is a popular crop both as food and as herbal medicine even in countries like Nepal [5] and Poland [6]. The fresh vegetables start to lose their quality immediately after harvest, becoming damaged, wilted and eventually rotten if no preservation is done. Good quality vegetables are abundantly available during the rainy season but scarce thereafter. It’s therefore necessary to reserve them for use during the off-peak period.

Drying is one of the traditional methods of preservation, which converts the vegetables into lightweight, easily transportable, and storable product. One of the advantage of this method is that the vegetable can easily be converted into fresh like form by rehydration, which makes the vegetable available in times of lean supply periods. In addition, drying reduces post-harvest losses, labour and storage space and makes dehydrated vegetables easy to use while increasing their shelf-life [7]. In order to assure preservation for long-term storage, it is necessary to process the vegetables by drying [8]. The drying process effects changes in the product both biochemically (viz., Maillard reactions, vitamin degradation, fat oxidation, denaturation of thermally unstable proteins, enzyme, etc.) and physically [9]. The quality of dried vegetables depends partly on changes occurring during the drying process and storage. A number of traditional and modern advanced techniques are used to accomplish drying. These methods are conventional sun drying, microwave drying, oven drying, freeze drying and solar drying. Open sun drying has traditionally been used to dry agricultural produce for decades [10]. However, open sun drying has limitations like inability to have control of the drying process, unpredictability of weather during drying process, high labour costs, large area requirements, insect infestation and contamination with dust, animal droppings and other foreign materials.

Solar drying, on the other hand, has become an important alternative for farmers and entrepreneurs for adding value to agricultural produce in Kenya [11]. Enclosed drying methods provide protection against rain and contamination and usually reduce drying time. Solar cabinet, tunnel dryers and green house dryers have lower operating costs and can be completely passive (natural convection) [12], or rely on forced convection (use mechanical fans). Mechanized drying is usually the fastest with optimized conditions, but requires fuel or electricity to operate.

Solar powered dryers generate relatively high air temperatures and low relative humidity, both of which are conducive to improved drying rates [13]. The abundance of solar power, its cleanliness to environment and renewable energy source makes it more preferable in Kenya as well as other tropical countries for use in solar drying systems and as a source of power for domestic use like lighting. The technologies that are employed to tap the solar energy for drying are also relatively cheap and can be made with locally available materials, hence, making it quite appealing and easily adoptable compared to other sources like oil, gas, wood or electricity.

Mathematical modelling of thin layer drying is important for optimum management of operating parameters and prediction of performance of the drying system [14], and understanding of the drying process [15]. It is essential to set out accurate models to simulate the drying curves under different drying conditions [16]. The theoretical drying models suggest that the moisture transport is controlled mainly by internal resistance mechanisms of the product, while the others (semi-theoretical and empirical models) consider only external resistance [17]. These models are Newton, Page, Modified Page, Verma et al Henderson & Pabis, Logarithmic, Diffusion approximation, Two term and Two Term exponential. Validation of the established drying models, can be made by comparing the computed and measured moisture contents [18], [19], [16] and/or plotting of the residuals versus the predicted values by the model [20]-[23]. Using these models the drying characteristics of vegetable will be established.

II. MATERIALS AND METHODS

Experimental site

The study was conducted at the School of Bio-systems and Environmental Engineering of Jomo Kenyatta University of Agriculture and Technology (JKUAT), Kenya, during the month of March 2015. JKUAT is located in Juja which is situated at latitude of 37.01^0E and longitude of, 1.09^0S, and at an altitude of 1537 m above sea level.

Solar tunnel dryer description

The solar tunnel dryer used for the thin layer drying of the stinging nettle vegetables was earlier used for fish by Kituu et al [24], (Figure 1). The dryer comprised of three sections namely the rectangular collector surface and the air heating chamber beneath the collector both measuring 2.44m by 1.22m and the drying compartment. The collector plate is 19mm thick and is made of galvanized iron (GI). To enhance absorption and emission of solar energy, the collector plate is painted black and is covered by a dome shaped vinyl cover to protect collector plate from dust and rain as well as retarding heat from escaping. The base of the heating chamber is made of aluminium painted galvanized sheet in order to reflect incident energy to enhance heating. A soft board, sandwiched between G.I sheets was used for insulating the side walls and the doors of the dryer in order to reduce energy losses [24]. To further minimise temperature fluctuation, heat chamber unit was packed with riverbed stones (1.9-2.54cm in diameter) occupying a volume of 0.26 m^3, which is the average limit volume of between 0.15 to 0.35 m^3 [25]. Riverbed were preferred due to their cleanliness and high thermal conductivity (0.7 W/ (m.K) compared to sand (0.15 - 0.25W/ (m.K). A direct current solar driven exhaust fan of capacity 1.2m/s was fitted to the dryer at the base of the chimney to enhance air flow when needed. Temperature and relative humidity both inside and outside the dryer were recorded using digital data loggers (HOBO mini weather station U30 Onset, MA, USA). Two thermocouples recorded drying air temperature and relative humidity at entrance and exit of the drying chamber while a third one recorded ambient air condition. Solar radiation was recorded using a solar radiation sensor (Silicon Pyranometer smart sensor, model S-LIB-M003) which was mounted on the HOBO mini weather station data logger

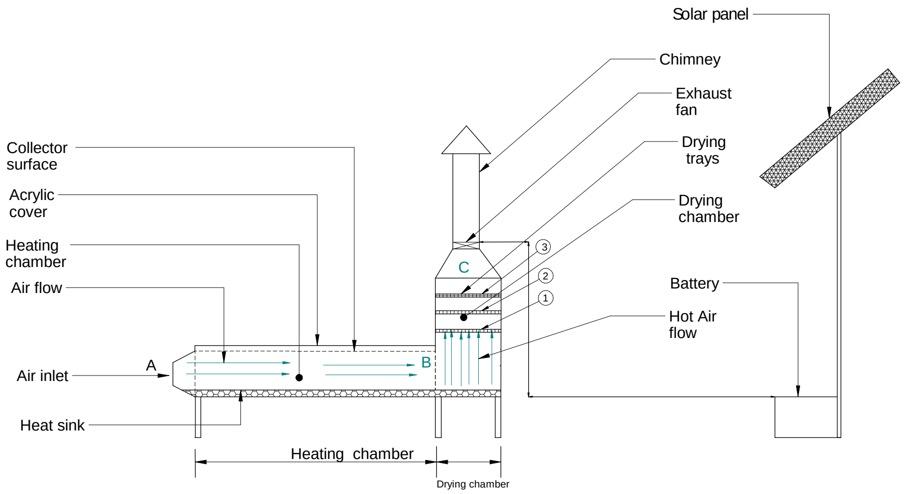

Figure 1: A schematic diagram of the solar tunnel dryer

Data collection procedure and analysis

Drying tests

Fresh stinging nettle vegetables were bought from local market (Juja market) early in the morning and transported to the site in a sealed plastic bucket in order to minimise moisture loss. The samples were prepared for drying by removing stalks, dry leaves, damaged leaves and foreign materials like pests and other objects. No size reduction was done on the leaves. The weight of the samples before and after drying, and that of the plastic trays on which the samples were placed were measured using a digital scale Mittler Toledo (Model PB3002, Mittler Toledo, Switzerland, sensitivity 0.1mg). Nine samples were placed in the three dryer levels (1,2,3) inside the solar dryer, three at each level whereas control sample were placed in the open sun.The drying preparation and process was carried out between 9am and 6pm on 12th March 2015.The weights of the samples were recorded as the drying progressed. The relative humidity and temperature inside the dryer and ambient air were recorded at 30 minutes interval using HOBO-mini weather station logger

A fresh vegetable sample was placed in a electirc convective oven for 24 hours to determine the initial moisture content at 105^{0}C [26]. The amount of moisture content (M.C) in a product is designated on the basis of the weight of water (i.e. dry or wet basis). On dry basis (%), it can be calculated as in equation 1[27]. In this equation, *M.C* is moisture content, W_w is weight of fresh sample and W_d weight of dry sample.

$$\%M.C_{db} = \frac{W_w}{W_d} * 100 \tag{1}$$

Moisture ratio, *MR*, is the ratio of the residual moisture content at any given time to the absolute residual moisture content and is represeted by equation 2, [28], in which M_o is the initial moisture content and M_e the equilibrium moisture content

$$MR = \frac{M - M_e}{M_o - M_e} \tag{2}$$

Since the values of *Me* are relatively small compared to *M* and M_o during solar drying and the continuous fluctuation of relative humidity, equation 2 can be simplified to equation 3 [29].

$$MR = \frac{M}{M_0} = e^{-kt} \tag{3}$$

The effective moisture diffusivity coefficients (D_{eff}) was determined by plotting experimental drying data in terms of ln(*MR*) versus time (*t*) [30].The plot gives a straight line with a slope *S* given by equation 4, where, D_{eff} is the effective moisture diffusivity (m^{2}s^{-1}) and *L* is the half thickness of vegetable (m).

$$S = \frac{\pi^2 D_{eff}}{4L^2} \tag{4}$$

Quality evaluation

Quality was evaluated based on colour and the parameters of colour (lightness (*L**), redness (*a**), yellowness (*b**) for the vegetables) were measured at the start and the end of the drying period, using Minolta colour difference meter (Model CR-200, Osaka, Japan) [31]. According to the colour meter model, the *L** measures the whiteness, ranges from (black at 0 to white at 100). The *a** measures green when negative and red when positive and the *b** measures blue when negative and yellow when positive.

Hue angle, h^* is the attribute of colour that is related to the perceived colours: red, yellow, green and blue or a combination of two of them, and measures the color the eye is able to perceive and is given by equation (5) [32].

$$\begin{aligned} H^* &= \tan^{-1}\left\{\frac{b^*}{a*}\right\} for \;\; a > 0, \;\; b > 0 \\ &= \left(180 + \tan^{-1}\left\{\frac{b^*}{a^*}\right\}\right), \; for \;\; a < 0, \;\; b > 0; \\ & \quad and \;\; for \;\; a < 0, \;\; b < 0, \\ &= \left(360 + \tan^{-1}\left\{\frac{b^*}{a^*}\right\}\right), \; for \;\; a > 0, b < 0 \end{aligned} \tag{5}$$

The colour parameters are related to the browning reaction where a decrease in *L** values, and increase in *a** values and a decrease in *h** values indicate more browning [33-34].

Modelling the drying process

The data obtained was fitted to nine (9) thin-layer drying models given in Table 1 using the nonlinear least squares regression analysis. Statistical analyses of the test data was performed using Excel spreadsheet (MS Excel, 2013^{TM}). The statistical validity of the models was evaluated and compared using the coefficient of determination (R^2), root mean square error (*RMSE)*, and reduced chi-square (χ^2), (equations 6,7,8). Best model was based on $R^2 \cong 1$, and low values of χ^2 and *RMSE*, respectively. The consonants a, b, c and n are drying coefficients, t is drying time (hours) and k is drying constant (h^{-1}) (35, 36, 37)

Table 1: Mathematical models given by various authors for drying curves

Model Equation	Model name
$MR = \exp(-kt)$	Newton
$MR = \exp\,(-kt^n)$	Page
$MR = a\ \exp\,(-kt)$	Henderson and Pabis
$MR = a\exp\,(-kt) + c$	Logarithmic
$MR = a\ \exp\,(-k_1 t) + b\exp\,(-k_2 t)$	Two-Term
$MR = a\ \ \exp(-kt) + (1-a)\ \exp(-kat)$	Two-Term Exponential
$MR = \exp\,(-(kt)^n$	Modified Page
$MR = a\ \ \exp(-kt)\ +\ (1-a)\ \exp(-gt)$	Verma et al.
$MR = a\ \exp(-kt) + (1-a)\ \exp(-kbt\ )$	Diffusion approximation

The acceptability of the best model was based on how close to one (1) the values of R^2 were, and how low values for the reduced χ^2 and root *RMSE* were [35]. This evaluates how well the best model fits the data describing the drying of the vegetables. The absolute residual error ($\mathcal{E}$) was defined by equation 9, where lower values further confirms the suitability of the model, [38].

$$R^2 = 1 - \left(\frac{\sum_{i=1}^{N} \left(MR_{pred,i} - MR_{\exp,i} \right)^{2}}{\sum_{i=1}^{N} \left(\overline{MR_{pred}} - MR_{pred,i} \right)^2} \right) \qquad (6)$$

$$RMSE = \left(\frac{1}{N} * \sum_{i=1}^{N} \left(MR_{pred,i} - MR_{\exp,i} \right)^2 \right)^{1/2} \qquad (7)$$

$$X^2 = \left(\frac{\sum_{i=1}^{N} \left(MR_{pred,i} - MR_{\exp,i} \right)^2}{N-n} \right)^{1/2} \qquad (8)$$

In the equations, $MR_{\exp,I}$ is actual moisture ratio*;* $MR_{pre,I}$ is predicted moisture ratio; *N* is number of observations; *n* is number of constants.

$$\varepsilon(\%) = \left| \frac{(MR_{pred,i} - MR_{act,i})}{MR_{act,i}}\ x\ 100 \right| \qquad (9)$$

III. RESULTS AND DISCUSSION

Weather data

The results on the solar tunnel dryer during the drying on 12th March 2015 revealed that the maximum drying chamber temperatures were 52.9°C recorded at 15.30hrs while the maximum ambient temperature was 34.8°C at 14.45hrs. The highest solar radiation intensity recorded during the period of drying was 1081.9 W/m^2 at 13.01hrs (Figure 1 and 2). The test results further show that the temperature and relative humidity in the drying chamber experienced minimal fluctuations as solar radiation fluctuated. This was associated to heat storage provision in the heating chamber that released stored heat.

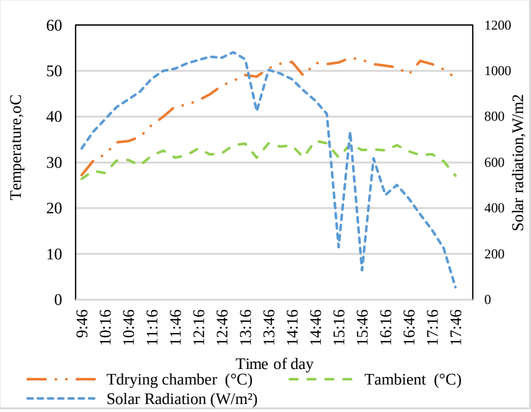

Figure 1: Temperature and solar radiation during the drying period

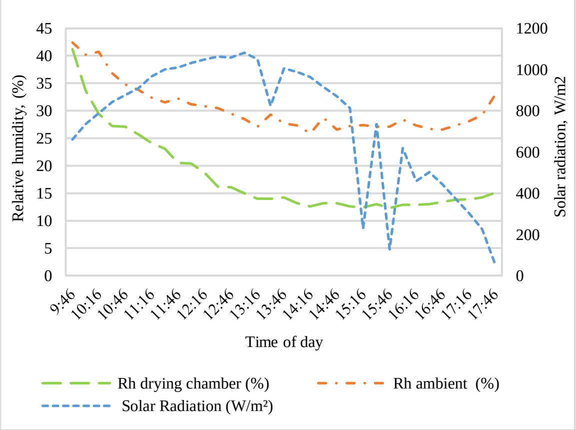

Figure 2: Relative humidity and solar radiation during the drying period

Drying curves

Drying test results show that the moisture content of the vegetables was reduced from 566.7 to 7.3 and 13.9% db. for solar dryer and open sun, respectively, within 8 hours of drying (Figure 3 and 4). The results further indicate that drying took place mainly in the falling rate period as there was no evidence of constant rate period, implying that diffusion was the dominant physical mechanism governing moisture movement in the material [39], which is dependent on the moisture content of the samples [40].

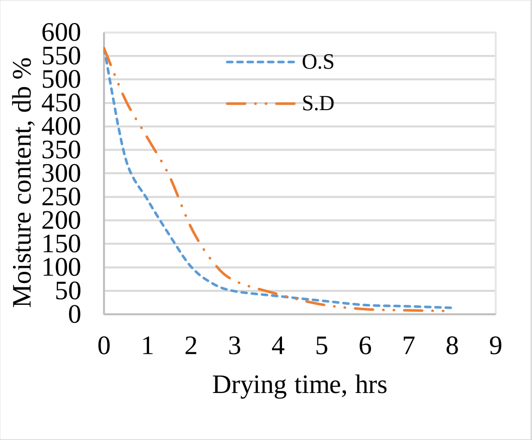

Figure 3: Moisture content curves for vegetable drying in solar dryer and open sun

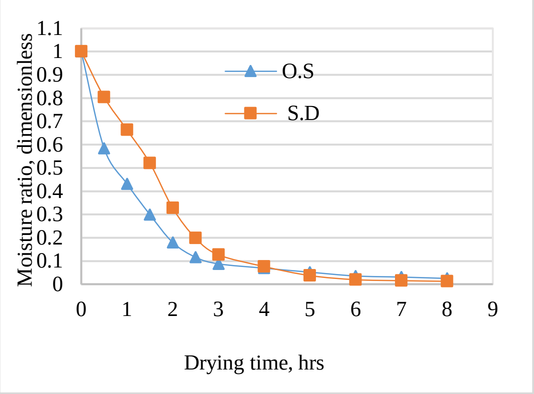

Figure 4: Moisture ratio curves for the vegetables dried in the solar dryer and open sun

Effective diffusivity

The mean effective moisture diffusivity (D_{eff}) values of the vegetables dried in the solar drier and open sun were 1.41 x 10^{-9} and 8.81 x 10^{-10}m^{2}s^{-1}, respectively. The higher values obtained for the solar dryer are related to the higher temperature in the solar dryer as compared to open sun as confirmed by earlier studies indicating that an increase in temperature leads to increase in moisture removal rate from the product [41]. The values obtained for the vegetables were consistent with the general range of 10^{-9} to 10^{-11} m^2/s, which is typical of food materials and agricultural crops as reported in earlier studies for kale leaves [42] and mint leaves [43].

Quality evaluation

Colour plays a key role in food choice, food preference and acceptability, and may influence taste thresholds, sweetness perception, and pleasantness [34]. Hence, it is a very important quality factor in processed vegetable products to influence consumer acceptability. Many reactions take place during thermal processing which affect colour. The most common are pigment degradation, chlorophyll, and browning reactions such as Maillard reaction and oxidation of ascorbic acid [9].

Colour measurement was done at the start and finish of the drying process for both the solar and open sun drying. As shown in Table 2, the values of *L**, *a**, and *b** for fresh, solar dried and open sun dried vegetables ranged from 44.22 to 27.36, -15.23 to -2.03 and 21.31 to 8.57 respectively. The colour parameters are related to the browning reaction where a decrease in *L** values, an increase in *a** values and a decrease in *h** values indicate more browning [33, 34].The computed average hue angle, *h**, values obtained for the fresh vegetables was (125.60±1.31^{0}), higher than for solar dried (108.17±4.32^{0}) and open sun drying (103.37±5.90^{0}), respectively. From the results, therefore, solar drying showed less browning effect on vegetables compared to open sun drying.

At 95% level of confidence, t test results showed significant difference ($t_{calculated}$, 13.778; $t_{critical}$, 2.262) between *h** of the fresh and solar dried vegetables. Similar results were observed for open sun drying ($t_{calculated}$, 12.815; $t_{critical}$, 2.262) showing significant difference between the fresh and the dried vegetables. However, there was no significant difference between the solar tunnel and open sun dried vegetables ($t_{calculated}$, 1.740; $t_{critical}$, 2.262)

Table 2: Colour parameters for fresh, solar dried and open sun dried vegetables

Vegetable state	Colour parameters			
	*L**	*a**	*b**	*h**
Fresh	44.22± 1.95	-15.23±0.75	21.31±1.52	125.60±1.31
Solar dried	28.37±2.66	-3.03±1.23	8.91±1.45	108.17±4.32
Open sun dried	27.36±3.13	-2.03±1.10	8.57±1.86	103.37±5.90

Modelling

Regression analysis was conducted to fit the experimental data to the nine drying models (Table 1). This analysis related the drying time and moisture ratio to select the model that best describes thin layer drying of the vegetable. The results show that all the nine models considered satisfactorily described the drying process of the vegetable, with all attaining $R^2 > 0.96$. However, Verma et al model was the best with R^2 (0.994) and the lowest *RMSE* and χ^2 (0.0289, 0.0011) values, respectively, for the solar tunnel dryer thus satisfactorily predicting the thin layer drying of vegetable better than the other models. Similarly, for open sun drying, all the nine models satisfactorily predicted the drying process, with $R^2 > 0.99$. However, Logarithmic model best predicted the thin layer drying characteristic of the vegetable with the values of R^2, RMSE and χ^2 of 0.998, 0.0115 and 0.0002, respectively.

The mean values of absolute residual errors and the corresponding standard deviations achieved by the nine drying models indicate that the Verma *et al* and Logarithmic models attained the lowest mean residual errors of 11.9±19.1 and 6.8±3.7 for solar dryer and open sun drying, respectively, further confirming the superiority of the two models. The low corresponding standard deviations illustrate uniformity in prediction level of these models [38]. Comparison of the predicted and experimental moisture ratios values by the two models show that the data is bundled along a straight line with R^2 of 0.994 and 0.998 for solar dryer and open sun, respectively thus confirming the superiority of the two models, Figure 5 and 6.

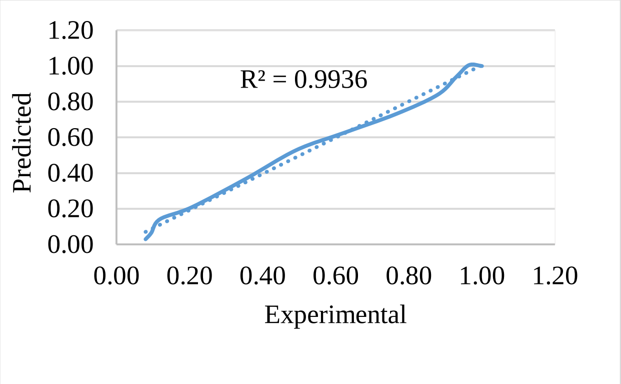

Figure 5: Comparison between the predicted moisture ratios using Verma model and the experimental values for the solar tunnel dryer

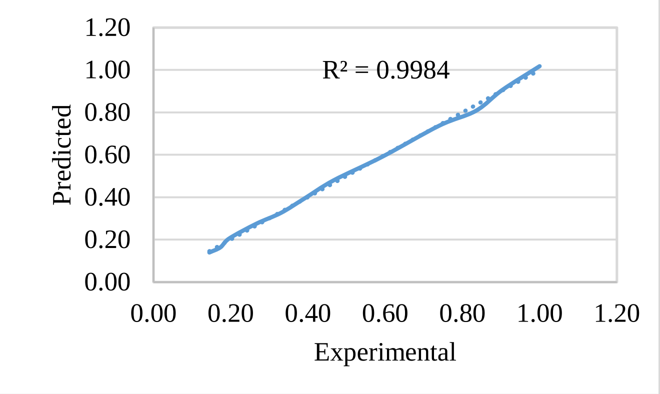

Figure 6: Comparison between the predicted moisture ratios using logarithmic model and the experimental values for the open sun

IV. CONCLUSIONS

Although all the nine models show good predictive results of R^2 >0.961, Verma *et al* model was the best model predicting the drying of stinging nettle in the solar dryer, with the highest R^2 0.993 and the lowest χ^2 0.00112 and RMSE 0.02899, respectively. Further, the results of the mean absolute residual errors and the corresponding standard deviations 11.9±19, confirms that Verma *et al* model was the best for predicting the drying of stinging nettle the tunnel solar dryer in comparison to the other models. The mean effective moisture diffusivity (D_{eff}) values of the vegetables dried in the solar drier and open sun were 1.41 x 10^{-9} and 8.81 x $10^{-10}m^2s^{-1}$, respectively, which is within the general range of 10^{-9} to 10^{-11} m^2/s, typical of food materials and agricultural crops. The computed average hue angle, *h**, values obtained for the fresh vegetables was 125.60±1.31, higher than for solar dried 108.17±4.32 and open sun drying 103.37±5.90, respectively.

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