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Mathematical Modeling of Thin layer Solar Drying of Gum Arabic from *Acacia senegal* and *Acacia seyal*

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Abstract: Determination of the solar drying characteristics of a thin layer of gum Arabic nodules from *A.senegal* and *A.seyal* and simulation of a thin-layer solar drying of gum Arabic nodules from the two species were investigated. A previously manufactured flat plate type natural convective solar dryer was used for conducting thin layer drying of gum Arabic nodules from *A.senegal* (hashab) and *A.seyal* (talha). The drying process of gum Arabic nodules from the two species was carried out during seven successive days interrupted by six night periods. The moisture contents of gum Arabic nodules from the two species at any time were compared by three drying models namely; Newton (Lewis), Page and Henderson and Pabis models. The drying process of gum Arabic nodules from the two species occurred effectively during the first day and took place in the falling rate period i.e. the moisture contents of gum Arabic nodules from the two species were less than their critical moisture content values. An equilibrium state was attained during the seventh day of the drying process. The three tested drying models predicted the drying process of gum Arabic nodules from the two species adequately but Henderson and pabis model was more accurate. Mathematical modelling on thin layer drying of gum Arabic nodules could save money, time and labour.

Keywords: Gum Arabic; Mathematical modeling; Thin layer, Solar drying

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INTRODUCTION

Gum Arabic is defined by FAO/WHO Joint Expert Committee for Food Additives (JECFA) as: "dried exudates obtained from the stems and branches of *Acacia senegal* (L.) Willdenow or *Acacia seyal* (Fam. Leguminosae)" (Verbeken *et al*. 2003).

In Sudan, the term gum Arabic is used in a wider context to include two types of gum which are produced and marketed, but which are, nevertheless, clearly separated in both national statistics and trade: "hasab" from *A. senegal* and "talha" from *A. seyal*. Gum Arabic from *A. senegal* is a pale to orange-brown coloured solid, which breaks with a glassy fracture. The best grades are in the form of whole, round tears, orange-brown in colour and with a matt surface texture; in the broken, kibbled state the pieces are much paler and have a glassy appearance. Gum Arabic from *A. seyal* is more friable than the hard tears produced by *A. senegal* and is rarely found as whole lumps in export consignments (Cozic *et al*. 2009).

Moisture content is one of the most important factors affecting the quality of gum Arabic during storage and it is at a high level at the time of the harvest and must be reduced to nearly 15% (d.b.) with an appropriate drying process. Drying is one of the oldest methods of food preservation and it represents a very important aspect of food processing. The main aim of drying products is to allow longer shelf life, minimize packaging requirements and reduce shipping weights. Sun drying is the most common method used to preserve agricultural products in many parts of the world. However, it has some problems related to the contamination with dust, soil, sand particles and insects and being weather dependent. Also, the required drying time can be quite long. Therefore, the drying process should be undertaken in environment to improve the quality of the final product (Domyaz, 2006). Solar drying refers to the methods of use of sun energy for drying but excludes open-air sun drying. The justification for the use of solar dryers is that: they may be more effective than sun drying and have lower operating costs than mechanized dryers. Solar dryers can be constructed from locally available materials at a relatively low capital cost and there are no fuel costs. Thus, they can be useful in areas where fuel or electricity are expensive, land for sun drying is in short supply or expensive, sun shine is plentiful but the air humidity is high. Moreover, they may be useful as mean of heating air for artificial dryers to reduce fuel costs. Sudan lies within the tropics between latitudes 3^o to 22^o N and like many other countries of the tropics, Sudan is blessed with plentiful sun shine all the year round, where the duration of the sun shine ranges from 10-12 hours daily with average solar radiation of more than 20 MJ/m^2/day (Akoy 2000). Solar dryers must be properly designed in order to meet particular drying requirements of agricultural products and give satisfactory performance concerning energy requirements. The prediction of drying rate of the specific crops under various conditions is of importance for the design of the drying systems. Full-scale experimentation for different products and systems configurations is sometimes costly and not possible.

The use of a simulation model is a valuable tool for prediction of performance of solar drying systems (Sacilik *et al*. 2006). Many investigators have successfully used thin layer equations to explain drying of several agricultural products. For example, potato slices (Aghbashlo *et al*. 2009), onion slices (Arslan and Özcan 2010), coroba slices (Corzo *et al*. 2008), okra (Doymaz 2005), sweet cherry (Doymaz and Ismail 2011), mango slices (Goyal *et al*. 2006), pistachios (Kouchakzadeh and Shafeei 2010) and carrots (Zielinska and Markowski 2010). However, no published work seems to have been done on the solar drying process of gum Arabic nodules. Therefore, the objectives of this study were: (i) determination of the solar drying characteristics of a thin layer of gum Arabic nodules from *A. senegal* and *A. seyal* and (ii) simulation of a thin-layer solar drying of gum Arabic nodules from the two species by testing three drying models.

MATERIAL AND METHODS

Experimental solar dryer

A flat plate type natural convective solar dryer, which was previously manufactured from local materials at the Workshop of the Department of

Agricultural, Engineering, Faculty of Agriculture, University of Khartoum, Sudan, was used in conducting the thin layer drying experiments of gum Arabic nodules from the two species. The dryer mainly consists of a flat plate type solar collector and drying chamber combined into one unit. The solar collector was titled 15^{o} upwards from the ground surface and directed southwards in order to get maximum performance. The drying chamber consists of two cylinders fitted coaxially and the inner cylinder is removable with a perforated base and was used for holding samples during the drying process. A schematic diagram of the experimental solar dryer is shown in Figure1.

Experimental procedure

Samples of gum Arabic nodules from healthy trees of *A. senegal* and *A.seyal* were collected from Kordofan State and Gadarif State, Sudan during the production season of 2006/2007. The gum Arabic samples were firstly cleaned manually to remove soil particles and foreign materials. After that the samples were sealed in polyethylene bags and stored in a refrigerator maintained at 4°C until needed. The moisture contents of samples of gum Arabic nodules were determined by using the trial and error method. In this method triplicate representative samples of gum Arabic nodules each with a weight of 5 g from each of the two

species were put into three empty metal moisture cans of known weights. The moisture cans were then put inside an air-oven which was set at a temperature of 103°C and the drying of samples of gum Arabic nodules was continued for 48 h until constant weights were reached. After the drying time the moisture cans were removed from the oven and placed in a desiccator until they got cold. The losses in weights of samples of gum Arabic from the two species were recorded using a digital balance (Model ACB 3000) of ± 0.01 g accuracy and expressed as their initial average moisture content values on wet basis and dry basis as calculated by equations 1 and 2, respectively.

$$M_{0\text{wb}} = \frac{W_1 - W_2}{W_0} \qquad (1)$$

$$M_{0\text{db}} = \frac{W_1 - W_2}{W_3} \qquad (2)$$

where,

M_{0wb} = initial moisture content of gum Arabic nodules sample on wet basis, decimal

W_1 = weight of undried gum Arabic nodules sample + weight of metal moisture can, g

W_2 = weight of dried gum Arabic nodules sample + weight of metal moisture can, g

W_0 = initial weight of undried gum Arabic nodules sample, g

M_{0db} = initial moisture content of gum Arabic nodules sample on dry basis, decimal

W_3 = final weight of dried gum Arabic nodules sample, g

The initial average moisture content of gum Arabic from *A. senegal* and *A. seyal* were found to be 26.3% and 20.9% (w.b.), respectively. Samples of gum Arabic nodules with initial weights of 20.13 g and 29.16 g from *A. senegal* and *A. seyal*, respectively were uniformly spread in a thin layer on the perforated base of the inner cylinder of the drying chamber. Daily the thin layer solar drying experiments were commenced at 9:00 and terminated at 18:00. The thin layer solar drying experiments were run continuously till constant weights of the dried gum Arabic nodules samples from the two species were attained. The losses in drying weights of the gum Arabic nodules samples from the two species were recorded at intervals of one hour by using the digital balance. It was found that drying process of gum Arabic nodules from the two species was accomplished in seven consecutive days interrupted by six night periods (March 2007). The recorded losses in drying weights of the gum Arabic nodules samples from the two species were then converted into corresponding moisture contents on wet basis and dry basis by using equations 3 and 4, respectively as reported by (Ekechukwu 1999).

$$M_{\mathrm{twb}} = 1 - \left[\frac{\left(1\text{-}M_{0\mathrm{wb}}\right) * W_0}{W_{\mathrm{t}}} \right] \qquad (3)$$

$$M_{\mathrm{tdb}} = \left[\frac{\left(M_{0\mathrm{db}} + 1\right) * \; W_{\mathrm{t}}}{W_0} \right] - 1 \qquad (4)$$

Where,

M_{twb} = moisture content of gum Arabic nodules sample on wet basis at time t, decimal

W_t = weight gum Arabic nodules sample undergoing drying at time t, g

M_{tdb} = moisture content of gum Arabic nodules sample on dry basis at time t, decimal

At the end of each drying day the gum Arabic nodules samples from the two species were wrapped by aluminum foil in order to prevent moisture exchange between the samples and the surrounding atmosphere. During the thin layer drying experiments air temperatures measurements were made by using copper-constantan thermocouples of ±0.2°C accuracy connected to a data logger (2e Delta T-logger, Delta-T Device Ltd, Cambridge, UK) which was configured to record at intervals of one hour.

The measurements were taken at the: (i) inlet of the solar collector, (ii) outlet of the drying chamber and (iii) outside air.
The drying rate of gum Arabic nodules from the two species was calculated by equation 5 as follows:

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t} \qquad (5)$$

Where,

DR = drying rate, kg H_2O/100 kg DM

$M_{t+\Delta t}$ = moisture content of gum Arabic nodules sample on dry basis at time ($t + \Delta t$), decimal

M_t = moisture content of gum Arabic nodules sample on dry basis at time (t), decimal

Δt = drying time interval, min

Modeling of thin layer solar drying of gum Arabic nodules
The experimental drying curves of gum Arabic nodules from the two species were fitted using three drying models (moisture ratio equations) namely; Newton (Lewis), Page and Henderson and Pabis models as reported by previous works (Arslan *et al*. 2010; Arslan and Özcan 2010; Dissa *et al*. 2011; Doymaz 2010; Jazini and Hatamipour 2010; Kaleta and Górnicki 2010; Meziane 2011; Xanthopoulos *et al.* 2010). Newton (Lewis), Page and Henderson and Pabis models are expressed by equations 6, 7 and 8, respectively.

$$MR = \exp(-kt) \qquad (6)$$

$$MR = \exp(-kt^n) \qquad (7)$$

$$MR = a\exp(-kt) \qquad (8)$$

Where,

MR = moisture ratio, dimensionless

k = drying rate constant, h^{-1}

t = drying time, h

n and *a* = model-dependent constants

The moisture ratio (MR) in equations 6, 7 and 8 is calculated using equation 9 as follows:

$$MR = \frac{(M_{\text{tdb}} - M_{\text{edb}})}{(M_{\text{0db}} - M_{\text{edb}})} \qquad (9)$$

Where,

M_{edb} = equilibrium moisture content of gum samplse on dry basis, decimal

MR has been simplified to M_t/M_0 by some investigators (Wang *et al*. 2007; Akpinar and Bicer, 2008; Madhiyanon *et al*. 2009; Meziane 2011) because of the continuous fluctuation of the relative humidity of the drying air during the thin layer solar drying. The constant(s) of the three tested drying model were calculated experimentally by normalization (linearization) the equation form for each model by employing the linear regression technique using Microsoft® Office Excel 2003 software. The normalized forms of Newton (Lewis), Page and Henderson and Pabis models are given by equations 10, 11 and 12, respectively.

$$\ln(MR) = -kt \qquad (10)$$

$$\ln[-\ln(MR)] = -\ln(k) + n\ln(t) \qquad (11)$$

$$\ln(MR) = \ln a - kt \qquad (12)$$

The fitting of the three tested drying models to the measured data was evaluated graphically based on the comparison between measured and predicted moisture content values as well as the comparison among the three tested drying models with regard to the obtained linear regression line equation, intercept, slope and coefficient of determination (R^2) by linear regression plotting of the corresponding model predicted moisture content values versus measured values. The linear regression line equation is given by the following form

$$Y = a + bX \qquad (13)$$

Where,

Y = the dependent variable

a = the intercept of the linear regression line (the value of *Y* when *X* = 0).

b = the slope of the linear regression line

X = the explanatory (independent) variable

Also the fitting of the three tested drying models was evaluated statistically based on criteria such as: four statistical parameters namely; average model error (*AME*), average absolute difference (*AAD*), and standard error of estimate (*SEE*) or sometimes is known as root mean square of error (RMSE) and reduced chi-square. *AME*, *AAD* and *SEE* are calculated by equations 14, 15 and 16 respectively.

$$AME = \frac{\sum_{i=1}^{n}(MR_{\exp,i}\ MR\text{-}_{pred_i})}{N} \qquad (14)$$

$$AAD = \frac{\sum_{i=1}^{n}(abs(MR_{\exp,i}\ \text{-}MR_{pred_i})}{N} \qquad (15)$$

$$SEE = \sqrt{\frac{\sum_{i=1}^{n} MR_{pred.i_i}\ \text{-}MR_{\exp.i})^2}{N}} \qquad (16)$$

Where,

AME = average model error expressed as moisture content on dry basis, decimal

$exp._i$ = ith observation for the experimental moisture content of gum on dry basis, decimal

$pred._i$ = ith observation for the predicted moisture content of gum on dry basis, decimal

N = number of observations

AAD = average absolute difference expressed as moisture content on dry basis, decimal

SEE = standard error of estimate expressed as moisture content on dry basis, decimal

By regressing the corresponding model predicted moisture content values (Y) versus measured values (X) and if the Y values equal X values then the form of linear regression line equation (equation 13) will reduce to equation 17 as follows:

$$Y = X \qquad (17)$$

Equation 17 means that the intercept of the linear regression line (a) equals zero, the slope of the linear regression line (b) equals one and the coefficient of determination (R^2) equals one. Microsoft® Office Excel 2003 software was also used in linear regression plotting of the corresponding model predicted moisture content values versus measured values. Abbouda (1984) stated that an accurate model should have an average model error (*AMA*) and an average absolute difference (*AAD*) close to zero and a small standard error of estimate (*SEE*). MINITAB statistical, Release 13.30 software was used for carrying out the statistical analysis to compare among the three tested drying models. A computer programme using Turbo Pascal for Windows, Version 1.5 was then written for each of the three tested drying models for simulating the thin layer drying process of gum Arabic nodules from the two species during the seven days of drying period.

RESULTS AND DISCUSSION

Determination of the solar drying characteristics of a thin layer of gum Arabic nodules from *Acacia senegal* and *Acacia seyal*

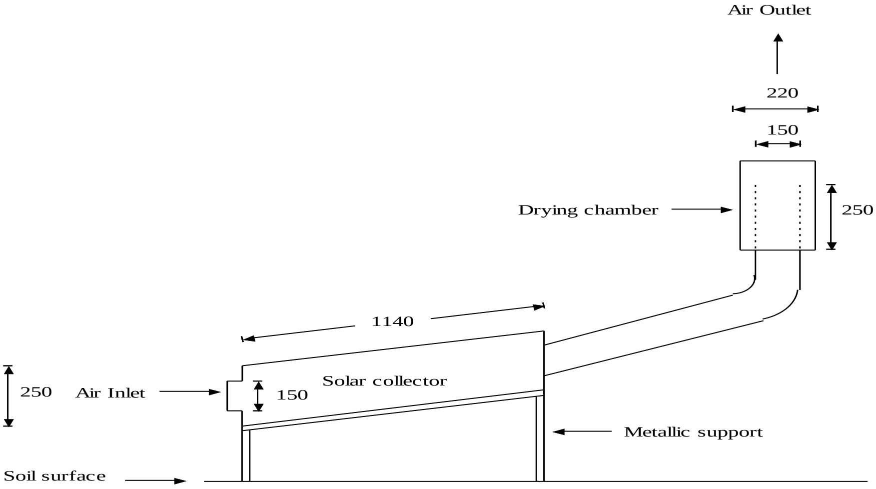
Figures 2 and 3 show the drying curves of gum Arabic nodules by plotting moisture content versus drying time of gum Arabic from *A. senegal* and *A. seyal*, respectively. Figures 4 and 5 show the drying curves of gum Arabic nodules by plotting moisture ratio (MR) versus drying time of gum Arabic from *A. senegal* and *A. seyal*, respectively. While, Figures 6 and 7 show the drying curves of gum Arabic nodules by plotting drying rate versus drying time interval of gum Arabic from *A. senegal* and *A. seyal*, respectively. From these six figures it is clear that the whole drying process of gum Arabic nodules from the two species occurs effectively during the first day and takes place in the falling rate-drying period i.e. there is no constant rate-drying period. Similar results were obtained by Akpinar and Bicer (2008) for long green pepper, Doymaz (2005) for okra, Doymaz (2006) for mint leaves, Doymaz (2007) for tomatoes, Doymaz (2010) for Amasya red apples, Madhiyanon *et a*l. (2009) for chopped coconut and Meziane (2011) for olive pomace. Also it is clear that during the seventh (last) day of the drying process an equilibrium state is attained.

Simulation of thin layer solar drying of gum Arabic nodules from *Acacia senegal* and *Acacia seyal*

Figures 8 and 9 show the measured and predicted moisture contents by Newton (Lewis), Page and Henderson and Pabis models of gum Arabic nodules from *A. senegal* and *A. seyal*, respectively. It is clear that the three tested drying models predict drying moisture contents of gum Arabic nodules from the two species adequately, but Henderson and Pabis model gives a close agreement between measured and predicted data. Table 1 show linear regression line equation, intercept, slope and coefficient of determination (R^2) by plotting the corresponding predicted moisture contents of Lewis, Page and Henderson and Pabis models versus measured values of gum Arabic nodules from *Acacia senegal*. Whereas, Table 2 shows linear regression line equation, intercept, slope and coefficient of determination (R^2) by plotting the corresponding predicted moisture contents of Lewis, Page and Henderson and Pabis models versus measured values of gum Arabic nodules from *A. seyal*. With respect to values of intercept, slope and R^2 it is clear from these two tables that predicted moisture contents of Henderson and Pabis model in a close agreement with measured data for the two species of gum Arabic nodules. Table 3 shows the three statistical parameters *AME*, *AAD* and *SEE* expressed as decimal moisture content on dry basis for Newton (Lewis), Page and Henderson and Pabis models of gum Arabic nodules from *A. senegal*. Whereas, Table 4 shows the three statistical parameters *AME*, *AAD* and *SEE* expressed as decimal moisture content on dry basis for Newton (Lewis), Page and Henderson and Pabis models of gum Arabic nodules from *A. seyal*. Also these two tables show that the three tested drying models predicted the drying process of gum Arabic nodules from the two species adequately but Henderson and Pabis model predictions are close to measured data.

CONCLUSIONS

The initial moisture contents of gum Arabic nodules from the two species were less than their critical moisture content values because no constant rate-drying was observed. The drying process of gum Arabic nodules from the two species occurred effectively during the first day and the whole drying process could be accomplished safely during seven days interrupted by six overnights. The three tested drying models predicted the drying process of gum Arabic nodules from the two species adequately but Henderson and Pabis model predictions are close to measured data. Mathematical modelling on thin layer drying of gum Arabic nodules could save money, time and labour.



Figuer.1.Schematic diagram of the experimental solar dryer (all dimensions in mm)

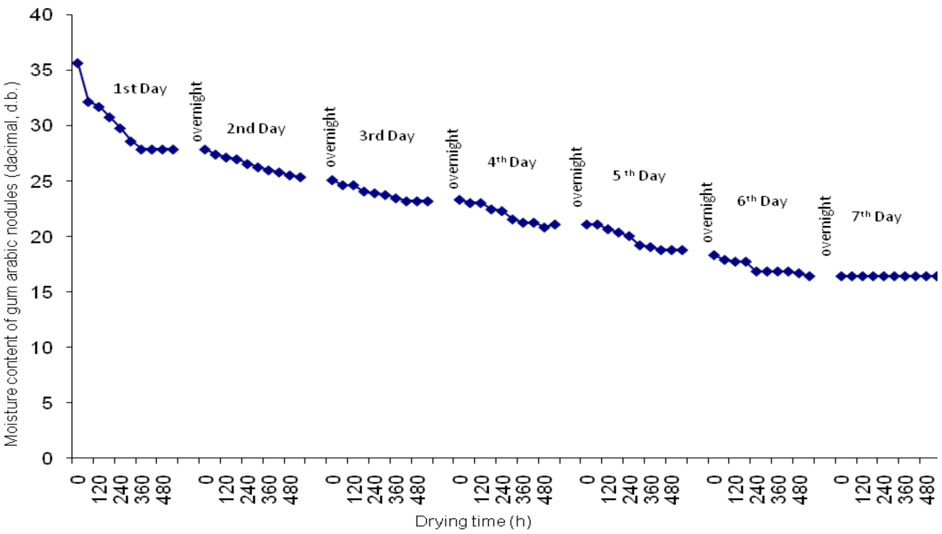


Figure 2.Changes in moisture content withe drying time for Hashab

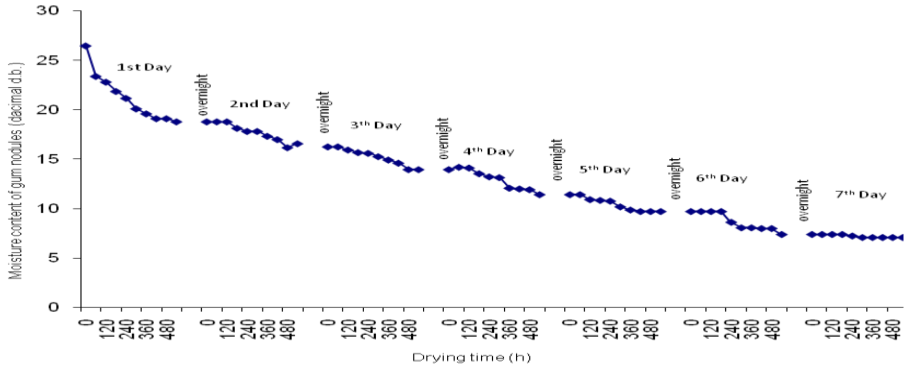


Figure 3. Changes in moisture content with drying time for Talh.

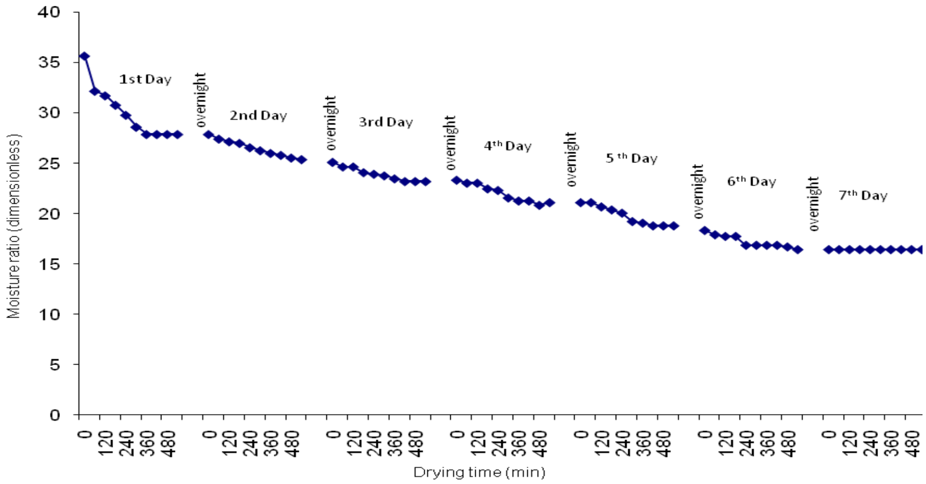


Figure 4. Changes in Moisture ratio with drying time for Hashab

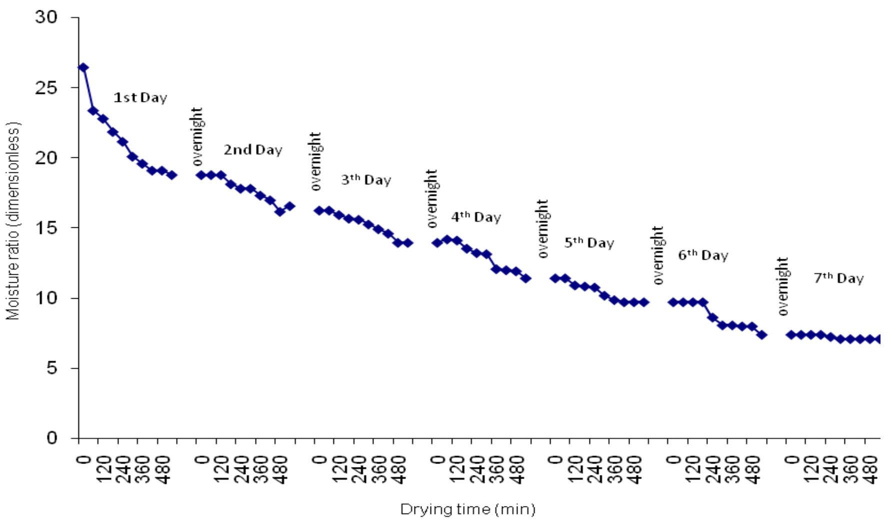


Figure 5. Changes in moisture ratio with drying time for Talh

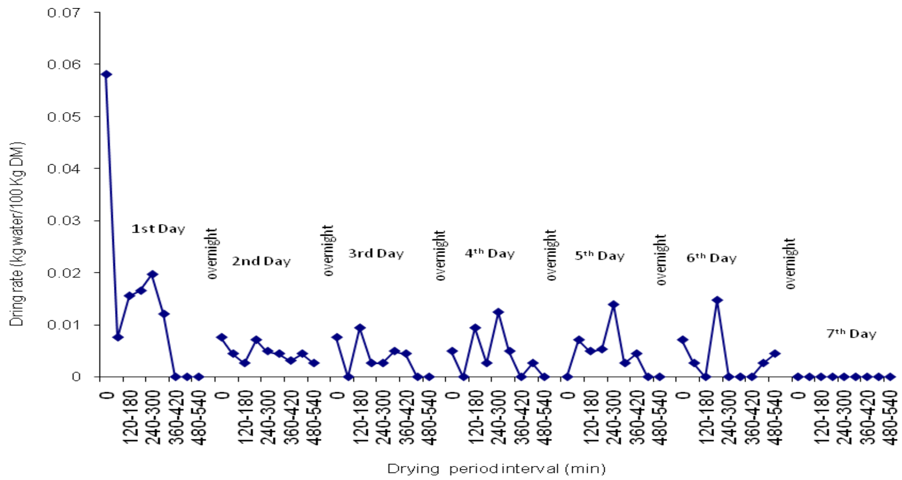


Figure 6. Changes of tdrying rate with drying time for *Acacia senegal*

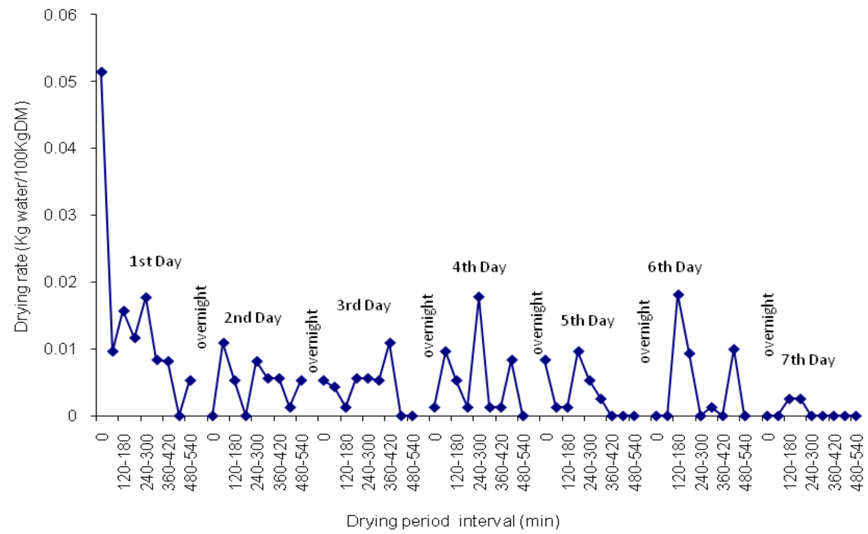


Figure 7. Changes of drying rate with drying time for *Acacia seyal*

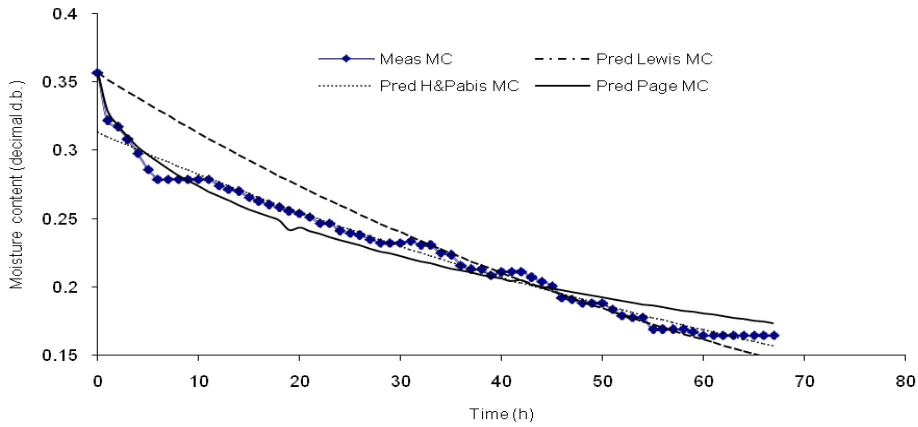


Figure 8. Plotting measured and predicted MC values for tested models versus drying time for Hashab

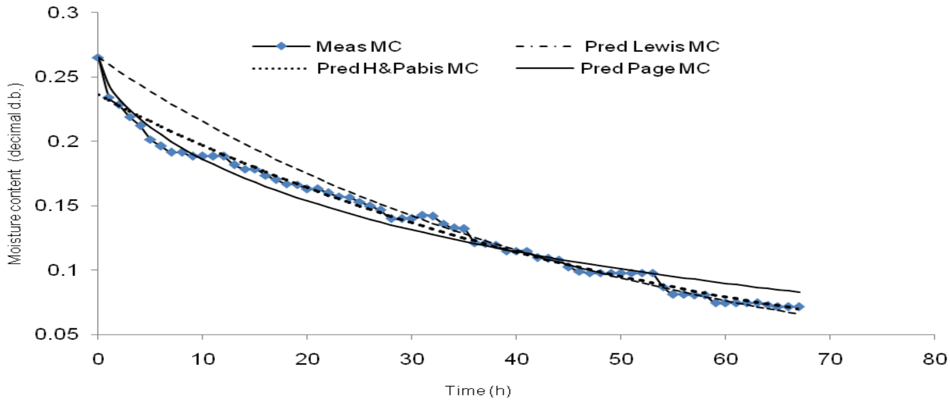


Figure 9. Plotting measured and predicted MC values for tested models versus drying time for talh

Table. 1. Linear regression line equation, slope (b), intercept (a) and coefficient of determination (R2) by plotting the corresponding predicted moisture content of Lewis, Page and Henderson and Pabis models versus measured values of gum Arabic from Acacia senegal

Model Name	Linear regression line equation	Slope (b)	Intercept (a)	Coefficient of determination (R^2)
Lewis (Newton)	Y = 1.2957X - 0.0563	1.2957	-0.0563	0.9758
Page	Y = 0.8991X + 0.0230	0.8991	0.0230	0.9641
Henderson and Pabis	Y = 0.9677X + 0.0073	0.9677	0.0073	0.9750

Table. 2. Linear regression line equation, slope (b) intercept (a) and coefficient of determination (R^2) by plotting the corresponding predicted moisture contents of Lewis, Page and Henderson and Pabis models versus measured values of gum Arabic from *Acacia seyal*

Model Name	Linear regression line equation	Slope (b)	Intercept (a)	Coefficient of determination (R^2)
Lewis (Newton)	Y = 1.2003X - 0.0199	1.2003	- 0.0199	0.9815
Page	Y = 0.9138X + 0.0121	0.9138	0.0121	0.9679
Henderson and Pabis	Y = 1.0055X - 0.0001	1.0055	- 0.0001	0.9828

Table 3 Average model error (AMA), average absolute difference (AAD) and standard error of estimate (SEE) between experimental and predicted moisture contents of gum from *Acacia senegal* by the three tested drying models expressed as moisture content on dry basis, decimal

Model name	*AME*	*AAD*	*SEE*
Newton (Lewis)	-0.0106	0.01429	0.01981
Page	-0.0001	0.00840	0.00934
Henderson and Pabis	0.00005	0.00459	0.00736

Table 4 Average model error (AMA), average absolute difference (AAD) and standard error of estimate (SEE) between experimental and predicted moisture contents of gum from *Acacia seyal* by the three tested drying models expressed as moisture content on dry basis, decimal

Model name	*AME*	*AAD*	*SEE*
Newton (Lewis)	-0.0073	0.0094	0.01433
Page	-0.0004	0.0077	0.0089
Henderson and Pabis	0.0006	0.0042	0.00634

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نمذجة رياضية لتجفيف شمسي لطبقة رفيعة لنوعين من الصمغ صمغ الهشاب و صمغ الطلح

زينب أحمد عبد الحميد أحمد[1] و محمد أيوب إسماعيل[2]
و عبد العظيم يس عبد القادر[1]

المُستخلص: تم البحث عن خصائص التجفيف الشمسي لطبقة رفيعة من الصمغ العربي (صمغ الهشاب وصمغ الطلح) ومحاكاة التجفيف الشمسي لطبقة رفيعة لنوعي الأصماغ. تم استخدام مجففة شمسية ذات حمل طبيعي تم تركيبها مسبقاً لعمل بحثي سابق لإجراء تجربة التجفيف الشمسي لطبقة رفيعة لنوعين من الأصماغ هما، صمغ الهشاب وصمغ الطلح في شكل كعاكيل وقد أجريت عملية التجفيف لكعاكيل نوعي الصمغ العربي خلال سبع أيام متعاقبه تتخللها سته ليالي. وتمت مقارنة المحتوي الرطوبي المتزن باستخدام ثلاثة نماذج تجفيف تُسمى: أنموذج لويس، أنموذج هندرسون و بابيس و أنموذج بيچ لمحاكاة التجفيف الشمسي لطبقة رفيعة لنوعي الأصماغ. حدثت عملية التجفيف الشمسي للطبقة الرفيعة لنوعي الأصماغ بصورة فعالة خلال اليوم الأول وأيضاً خلال فترة معدل التجفيف الساقط ، أي أن المحتوي الرطوبي المتزن لعينات نوعي الأصماغ اقل من النقطه الحرجه لهم. نماذج التجفيف الثلاثة المُختبرة عملت على التنبؤ بالمحتويات الرطوبية بدقة لنوعي الأصماغ المجففة شمسياُ في شكل طبقة رفيعة ولكن أنموذج هندرسون و بابيس كان اكثر دقه. النمذجه الرياضيه للتجفيف الشمسي لطبقة رفيعة من كعاكيل الصمغ العربي تساعد في توفير المال والوقت والعمال.