Univerzitet u Beogradu
Poljoprivredni fakultet
Institut za poljoprivrednu tehniku
Naučni časopis
POLJOPRIVREDNA TEHNIKA
Godina XXXVIII
Broj 3, 2013.
Strane: 85 – 100

University of Belgrade
Faculty of Agriculture
Institute of Agricultural Engineering
Scientific Journal
AGRICULTURAL ENGINEERING
Year XXXVIII
No. 3, 2013.
pp: 85 – 100

UDK: 582.872

Originalni naučni rad
Original scientific paper

THIN LAYER DRYING KINETICS OF HENNA LEAVES

Dattatreya M. Kadam[1], Manoj Kumar Gupta[2*], Vaijayanta M. Kadam[3]

[1]Central Institute of Post-Harvest Engineering and Technology (CIPHET), PO: PAU campus, Ludhiana-141004 (Punjab), India
[2]Infosys Limited, Electronic City, Phase I, Bangalore, Karnataka, India
[3]Karnataka State Department of Horticulture, India

Abstract: Henna leaves are well known for their cosmetic agent with anti-carcinogenic, anti-inflammatory, analgesic and antipyretic properties. To investigate the effect of different drying conditions on kinetics of henna leaves, the laboratory models of tunnel dryer was employed and the leaves were dried at 40, 45, 50, 55, 60 and 65°C. Drying of henna leaves prominently occurred in falling rate period and drying was faster at higher temperature. Twelve thin layer-drying models were fitted to the experimental moisture ratio data. Among the mathematical models investigated, the Midilli-Kucuk model satisfactorily described the drying behavior with highest r^2 values. The effective moisture diffusivity (D_{eff}) of basil leaves increased with the increase in drying air temperature. Effective moisture diffusivity of henna leaves ranged from $2.24 \cdot 10^{-10}$ to $4.31 \cdot 10^{-10}$ $m^2 \cdot s^{-1}$ and activation energy was 27.03 $kJ \cdot mol^{-1}$. The dried leaves were ground to make the powder and the powder had average particle size of 0.2069 mm with a fineness modulus of 1.3685.

Key words*: henna, mathematical modeling, drying, moisture diffusivity, activation energy*

INTRODUCTION

Henna (*Lawsonia inermis*, syn. *L. alba*) is native to tropical and subtropical regions of Africa, southern Asia, and northern Australia in semi-arid zones. The plant is found all over the world including Australia, the Mediterranean, Africa, and in Southern United States. The variety of henna plant varies from region to region and different plants have

* Corresponding author. E-mail: mnjoff@gmail.com

different coloring properties and the color of the powder also varies. Henna is a tall shrub or small tree 2 to 6 m high. It is glabrous, multi-branched with spine tipped branch lets. Henna is commercially cultivated in western India, Pakistan, Iran, Yemen, Morocco and Sudan.

Herbal medicines are in great demand in the developed as well as developing countries for primary healthcare because of their wide biological and medicinal activities, higher safety margins and less cost. Henna has been used for thousands of years for its medicinal properties and cosmetic properties. Henna is worldwide known as cosmetic agent with anti-carcinogenic, anti-inflammatory, analgesic and antipyretic properties [1]. Alcoholic extracts of henna, leaves showed mild antibacterial activity against, *Micrococcus pyrogenes var Aureus* and *Eschericia coli* [2]. The tannin and the gallic acid seem to have a complimentary beneficial effect. Several studies have been dedicated to explore the medicinal value of henna leaves. Henna leaves have been effective in management of burn wound infections [3], and henna leaves extract can be used as sources of natural antioxidants [1]. Researchers studied the stability of henna paste for skin decoration, tattooing and hair dyeing [4]. Researchers have also applied henna dye on wool fabric to impart antimicrobial characteristics and found the treated fabrics were antimicrobial [5, 6]. Henna produces a red-orange dye molecule called laws one. This molecule has an affinity for bonding with protein, and thus has been used to dye skin, hair, fingernails, leather, silk and wool. The color produced by pure natural henna ranges from orange to red, to black cherry and to near black color. The color of henna powder depends not only on the variety of the plant, storage conditions, pasting method but also on the drying method and dying process parameters. Most of the henna is traded in powder form after drying and grinding of dried leaves. So, drying of the leaves is an interesting area of the research to ascertain optimized drying conditions of the leaves. The presented study evaluates drying kinetics of henna leaves.

THEORETICAL CONSIDERATIONS

Mathematical formulation

The moisture contents of henna leaves during the experiments were expressed in dimensionless form as moisture ratios (*MR*) with the help of the following equation [7-12].

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

where:
M [%] - mean henna leaves moisture content,
M_o [%] - initial moisture content,
M_e [%] - equilibrium moisture content.

M_e value is very small compared to those of M_o and M. So, the M_e value can be neglected and the moisture ratio can be simplified and can be expressed as [10-15]:

$$MR = \frac{M}{M_0} \tag{2}$$

Table 1. Thin layer drying models considered for the study

S.No.	Name of the model	Model equation
1	Newton	MR = Exp(-k*t)
2	Page	MR = Exp(-k * t ** n)
3	Modified Page 1	MR = Exp(-(k * t) ** n)
4	Henderson and Pabis	MR = a * Exp(- k * t)
5	Logarithmic	MR = a * Exp(- k * t) + c
6	Two-term	MR = a * Exp(-k * t) + b * Exp(-n * t)
7	Two-term exponential	MR = a * Exp(-k * t) + (1-a) * Exp(-k *a* t)
8	Wang and singh	MR = 1 + (a * t) + (b * (t ** 2))
9	Diffusion approach	MR = a * Exp(-k * t) + (1-a) * Exp(-k *b* t)
10	Modified Henderson and Pabis	MR = a * Exp(-k * t) + b * Exp(-n * t) + c * Exp(-m * t)
11	Verma *et al.*	MR = a * Exp(-k * t) + (1-a) * Exp(-m* t)
12	Midilli-Kucuk	MR = a * Exp(-k *(t ** n)) + b * t

Data were fit to 12 thin layer drying models to ascertain the best model which can describe the drying behavior of the product (Table 1). To determine the best fit model, non-linear regression analysis was done using the STATISTICA. The coefficient of determination, r^2, was one of the primary and main criteria for selecting the best equation to account for variation in the drying curves of dried samples [8, 16, 17]. In addition to coefficient of determination, the goodness of fit was determined by the statistical parameters such as reduced chi-square (χ^2), mean bias error (*MBE*), and root mean square error (*RMSE*). The best fit was evaluated on the basis of highest r2 value, and lowest values of χ^2, *MBE* and *RMSE* [17-20]. The above parameters were calculated as per the following relationships:

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{\exp.i} - MR_{pre.i})^2}{N - z} \tag{3}$$

$$MBE = \frac{1}{N}\sum_{i=1}^{N}(MR_{pre.i} - MR_{\exp.i}) \tag{4}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{pre.i} - MR_{\exp.i})^2\right]^{1/2} \tag{5}$$

Effective moisture diffusivity (D_{eff})

Fick's diffusion equation for particles with slab geometry was used for calculation of effective moisture diffusivity. The samples were considered of slab geometry [21]. The diffusion equation can be expressed as [22]:

$$MR = \frac{8}{\pi^2} \exp\left(\frac{-\pi^2 D_{eff} t}{4\, L^2} \right) \tag{6}$$

Equation (6) can be rewritten as:

$$\ln MR = D_{eff} k_0 + \ln \frac{8}{\pi^2} \tag{7}$$

where:
k_o [-] - slope,
is calculated by plotting *ln(MR)* versus time according to equation (7) to determine the effective diffusivity for different temperatures.

$$k_o = \left(\frac{\pi^2 D_{eff}}{4\, L^2} \right) \tag{8}$$

Activation energy (E_a)

The effective diffusivity can be related with temperature by Arrhenius equation [23] as presented in the following equation:

$$D_{eff} = D_0 \exp\left[\frac{E_a}{R(T+273.15)} \right] \tag{9}$$

where:
D_0 [$m^2 \cdot s^{-1}$] - constant in Arrhenius equation,
E_a [$kJ \cdot mol^{-1}$] - activation energy,
T [°C] - temperature,
R [$kJ \cdot mol^{-1} \cdot K^{-1}$] - universal gas constant

Equation (9) can be rearranged in the form of :

$$\ln(D_{eff}) = \ln(D_0) - \frac{E_a}{R(T+273.15)} \tag{10}$$

The activation energy can be calculated by plotting a curve between $ln(D_{eff})$ versus $1 \cdot (T+273.15)^{-1}$.

MATERIAL AND METHODS

The experiments were conducted at CIPHET, Ludhiana. Henna leaves were dried in tunnel dryer to study the drying behavior of henna leave.

Sample Preparation

The henna leaves from CIPHET, Ludhiana farm were harvested in the morning for each experiment. Harvested leaves were cleaned and sorted for unwanted stems and waste materials before putting them in to drying operation. The known weights of samples (300 g) were weighed and spread uniformly in thin layers within the drying trays.

Drying Equipment and Procedure

Henna leaves were dried in a tunnel dryer at six drying temperatures viz.; 40, 45, 50, 55, 60 and 65°C. Tunnel dryer, laboratory model, was a cross flow type dryer (NSW-600, Narang Scientific Works, New Delhi). Tunnel dryer's overall dimensions were 3.06 x 1.10 x 2.15 m. A tunnel, an electrical heater, a fan and a temperature controller (30 to 110°C) were the main components of the dryer. The speed of the tunnel was fixed at 0.004 $m \cdot s^{-1}$ for the experiments. Samples were replicated thrice in each case of drying. The weight loss data were observed at an interval of 30 minutes during drying.

Physical Properties

Henna leaves thickness, length and breadth were measured using micrometer with a least count of 0.01 mm. Surface temperatures of henna leaves were measured by high performance Infrared thermometer (MaxiTemp, SIKA, Germany, Model: IR M x 4PTDG).

Henna Powder Preparation

Dried henna leave samples were ground to fine particles by using a home mixer and the powder was sieved before making paste. Henna powder was analyzed for particle size distribution with the help of sieve analysis (Sieve No: 100, 65, 35 and pan).

Statistical Analysis

The experimental data was analyzed as per the procedure of one way/ two way classified ANOVA using computer software package AgRes and mathematical modeling of convective thin layer drying of henna leaves was done by using STATISTICA 6.0.

RESULTS AND DISCUSSION

Physical Dimensions of Fresh Henna Leaves

The physical dimensions of henna leaves are presented in Table 2. The average thickness, length and central breadth of leaves were about 0.26 mm, 18.42 mm, and 7.82 mm, respectively. The surface area of the leaves was ranged from 63.90 to 205.00 mm^2 with an average of 149.42 mm^2.

Table 2. Physical dimension of henna leaves (mm)

Sample	Thickness (mm)	Length (mm)	Breadth (mm)	Surface area (mm^2)
1	0.27	19.63	7.46	146.40
2	0.26	17.42	7.95	138.49
3	0.26	22.60	7.36	166.33
4	0.27	16.80	12.13	203.70
5	0.27	21.75	7.31	188.99
6	0.26	14.20	5.14	73.02
7	0.25	19.20	8.28	158.97
8	0.26	14.20	4.50	63.90
9	0.25	20.00	10.25	205.00
Mean	0.26	18.42	7.82	149.42

Drying Behavior of Henna Leaves

Moisture content of fresh henna leaves was 66.954% (w.b). Table 3. presents the drying time at different drying temperature regime in tunnel dryer. Minimum time (270 min) was recorded at 65°C, whereas maximum time (540 min) was observed for henna leaves drying in tunnel dryer at 40°C.

Table 3. Drying time for henna leaves in tunnel dryer

S. No.	Drying air temperature (°C)	Henna leaves drying time (min)
1	65	270
2	60	300
3	55	360
4	50	420
5	45	510
6	40	540

Drying of the leaves mainly occurred in falling rate period. Figure 1. shows the plot between moisture losses with respect to time for the samples dried in tunnel dryer at different drying temperatures. The more was the temperature, the faster was the drying. The moisture depletion per hour was more in the initial drying period and subsequently it started to decrease. The similar pattern was observed for all samples dried at different temperatures in tunnel dryer. In some cases drying rate was initially low and then started to increase, this period is known as heating period. Heating period observed because sometimes a portion of energy is utilized to heat the material instead of completely contributing for moisture loss. A constant rate period was not observed because of higher time interval between (30 min) between two successive observations. A single falling rate period was observed for all samples for drying of henna leaves in tunnel dryer. Similar findings were observed by [10] for basil leaves and by [11] for mint leaves. Figure 1 shows moisture ratio variation with respect to time for henna drying in the tunnel dryer at different temperatures.

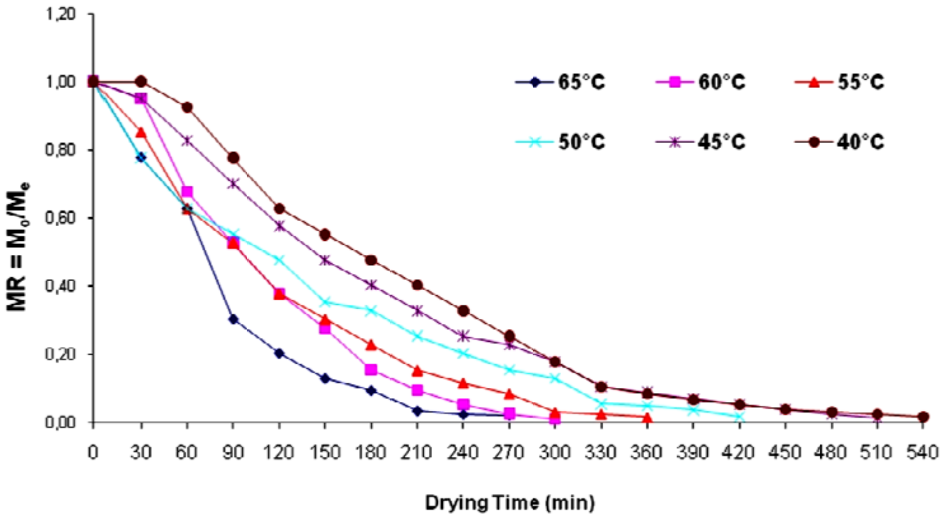


Figure 1. MR of tunnel dried henna leaves

Mathematical Models for Fitting Drying Curves

Moisture ratio and drying time data were fitted for 12 thin layer drying models (Table 1) and the models were evaluated on the basis of r^2, χ^2, *MBE* and *RMSE* values. Table 4. depicts on the mentioned parameters to ascertain the best fit of the observed data.

In all cases, the r^2 values were greater than 0.90 except for Page model at all temperatures, indicating a good fit of the data. The results (Table 4) show that highest values of r^2 and lowest values of χ^2, *MBE* and *RMSE* were obtained for Midilli-Kucuk model with highest r^2 value of 0.9987 followed Modified Page 1 (0.9985) and Diffusion approach (0.9984). Thus, Midilli-Kucuk model marginally better represented the thin layer drying behavior of henna leaves when dried in tunnel dryer. Similar findings were reported for hot air drying of apricots [15, 19], rosehip [8] and plum [20]. An examination of the r^2, χ^2, *MBE* and *RMSE* showed that the all models vary with temperatures (Table 4). The constants of the models are presented in Table 5(a-c).

Table 4. Mathematical models statistical analyses results of thin layer tunnel drying of Henna leaves

S.no.	Model name	Model equation	Drying temp.(°C)	R^2	*Chi sq*	*MBE*	*RMSE*
1	Newton						
		MR = Exp(-k t)	65	0.97042	0.00369	-0.00396	0.01824
			60	0.95016	0.00664	-0.00039	0.02343
			55	0.98806	0.00127	-0.00340	0.00950
			50	0.99000	0.00089	-0.00605	0.00742
			45	0.97141	0.00315	-0.00078	0.01285
			40	0.94089	0.00737	0.00146	0.01918
2	Page						
		MR = Exp(-k t^n)	65	0.45550	0.07650	0.00000	0.07823
			60	0.32056	0.10065	0.00000	0.08652
			55	0.37623	0.07245	0.00000	0.06867
			50	0.38350	0.05879	0.00000	0.05828
			45	0.23870	0.08901	0.00000	0.06630
			40	0.18953	0.10705	0.00000	0.07100
3	Modified Page 1						
		MR = Exp (-(k $t)^n$)	65	0.99157	0.00118	0.00248	0.00973
			60	0.99558	0.00066	0.00124	0.00698
			55	0.99736	0.00031	-0.00204	0.00447
			50	0.99010	0.00094	-0.00608	0.00739
			45	0.99855	0.00017	0.00040	0.00289
			40	0.99580	0.00055	0.00256	0.00511
4	Henderson and Pabis						
		MR = a Exp(- k t)	65	0.97440	0.00360	-0.01045	0.01696
			60	0.96452	0.00526	-0.01457	0.01977
			55	0.99081	0.00107	-0.00783	0.00834
			50	0.99017	0.00094	-0.00514	0.00736
			45	0.98280	0.00201	-0.01015	0.00997
			40	0.96479	0.00465	-0.01436	0.01480
5	Logarithmic						
		MR = a Exp(- k t) + c	65	0.98137	0.00299	0.00000	0.01447
			60	0.98520	0.00247	0.00000	0.01277
			55	0.99711	0.00037	0.00000	0.00467
			50	0.99462	0.00056	0.00000	0.00544
			45	0.99369	0.00079	0.00000	0.00604
			40	0.98359	0.00230	0.00000	0.01010
6	Two-term						
		MR = a Exp(-k t) +b Exp(-n t)	65	0.98737	0.00237	-0.00421	0.01191
			60	0.99308	0.00132	-0.00762	0.00873
			55	0.99563	0.00062	-0.00486	0.00575
			50	0.99039	0.00108	-0.00561	0.00728

			45	0.99388	0.00082	-0.00667	0.00594
			40	0.98529	0.00220	-0.01007	0.00956
7	Two-term exponential						
	MR = a Exp (-k t) +(1 - a) Exp(-k a t)		65	0.97017	0.00419	-0.00472	0.01831
			60	0.94983	0.00743	-0.00089	0.02351
			55	0.98784	0.00141	-0.00382	0.00959
			50	0.99039	0.00092	-0.00561	0.00728
			45	0.97107	0.00338	-0.00166	0.01292
			40	0.94048	0.00786	0.00038	0.01924
8	Wang and Singh						
	$MR = 1 + a\,t + b\,t^2$		65	0.98693	0.00184	0.00187	0.01212
			60	0.98570	0.00212	0.00966	0.01255
			55	0.99518	0.00056	0.00961	0.00604
			50	0.97962	0.00194	-0.01054	0.01060
			45	0.99476	0.00061	0.00509	0.00550
			40	0.98129	0.00247	0.01265	0.01079
9	Diffusion approach						
	MR = a Exp(-k t)+ (1- a) Exp(-k b t)		65	0.99176	0.00132	0.00051	0.00962
			60	0.99602	0.00066	-0.00215	0.00662
			55	0.99723	0.00035	-0.00176	0.00458
			50	0.99039	0.00099	-0.00562	0.00728
			45	0.99845	0.00019	-0.00078	0.00299
			40	0.99586	0.00058	-0.00244	0.00507
10	Modified Henderson and Pabis						
	MR = a Exp(-k t) + bExp(-n t) + c Exp(-mt)		65	0.97440	0.00719	-0.01045	0.01696
			60	0.96452	0.00946	-0.01457	0.01977
			55	0.99081	0.00168	-0.00783	0.00834
			50	0.99017	0.00135	-0.00514	0.00736
			45	0.98280	0.00268	-0.01015	0.00997
			40	0.96479	0.00608	-0.01436	0.01480
11	Verma *et al.*						
	MR = a Exp(-k t)+ (1 - a) Exp(-m t)		65	0.98737	0.00203	-0.00421	0.01191
			60	0.99308	0.00115	-0.00762	0.00873
			55	0.99563	0.00056	-0.00486	0.00575
			50	0.99039	0.00099	-0.00561	0.00728
			45	0.99388	0.00076	-0.00667	0.00594
			40	0.98529	0.00206	-0.01007	0.00956
12	Midilli-Kucuk						
	$MR = a\,Exp(-k\,t^n) + b\,t$		65	0.06939	0.17434	0.13295	0.10228
			60	0.99598	0.00077	0.00001	0.00665
			55	0.99805	0.00028	0.00001	0.00384
			50	0.99690	0.00035	-0.00004	0.00414
			45	0.99874	0.00017	0.00003	0.00270
			40	0.99623	0.00056	-0.00011	0.00484

Table 5a. Mathematical models statistical analyses constants and standard errors of thin layer tunnel drying of Henna leaves

S. no.	Model name	Model equation	Drying temp. (°C)	Constant			Std Error		
				K	N	A	K	N	A
1	Newton								
	MR = Exp(-k t)		65	0.011828			0.000873		
			60	0.008577			0.000745		
			55	0.008234			0.000300		
			50	0.006917			0.000194		
			45	0.005400			0.000254		
			40	0.004861			0.000335		
2	Page								
	MR = Exp(-k t^n)		65	1.403437	0.000000		0.375025	0.000000	
			60	1.157232	0.000000		0.319137	0.000000	
			55	1.278839	0.000000		0.279142	0.000000	
			50	1.250749	0.000000		0.226350	0.000000	
			45	1.163550	0.000000		0.231642	0.000000	
			40	1.109421	0.000000		0.233868	0.000000	
3	Modified Page 1								
	MR = Exp (-(k t)^n)		65	0.011312	1.397826		0.000398	0.102615	
			60	0.008219	1.563206		0.000173	0.076078	
			55	0.007991	1.206282		0.000131	0.036930	
			50	0.006893	1.018002		0.000204	0.050701	
			45	0.005201	1.378942		0.000047	0.026223	
			40	0.004658	1.625569		0.000067	0.055497	
4	Henderson and Pabis								
	MR = a Exp(- k t)		65	0.012430		1.057635	0.001064		0.052995
			60	0.009437		1.110480	0.000856		0.060281
			55	0.008601		1.046831	0.000355		0.026411
			50	0.006842		0.989086	0.000259		0.023182
			45	0.005917		1.101172	0.000275		0.032313
			40	0.005552		1.154763	0.000364		0.048090

Table 5b. Mathematical models statistical analyses consiantsand standard errors of thin layer tunnel drying of Henna leaves

S. no.	Model name	Model equation	Drying temp.(°C)	Constant K	Constant N	Constant A	Constant B	Constant C	Std Error K	Std Error N	Std Error A	Std Error B	Std Error C
5	Logarithmic												
		MR = a Exp(- k t) + c	65	0.010191		1.124493		-0.085655	0.001686		0.066261		0.064661
			60	0.006074		1.312793		-0.243194	0.001136		0.100574		0.112957
			55	0.006916		1.114694		-0.092894	0.000401		0.022674		0.023978
			50	0.005558		1.048864		-0.084069	0.000424		0.028110		0.030927
			45	0.004401		1.203500		-0.139822	0.000337		0.032357		0.036503
			40	0.003743		1.315613		-0.209647	0.000489		0.063425		0.073244
6	Two-term												
		MR = a Exp(-k t)+ b Exp(-n t)	65	1.000000	0.014647	-0.267967	1.267967		0.000000	0.001394	0.117866	0.107363	
			60	1.000000	0.011412	-0.362067	1.362067		0.000000	0.000632	0.072821	0.063121	
			55	1.000000	0.009290	-0.133976	1.133976		0.000000	0.000368	0.043935	0.036197	
			50	1.000000	0.006746	0.024702	0.975298		0.000000	0.000345	0.050132	0.037815	
			45	1.000000	0.006470	-0.207868	1.207868		0.000000	0.000219	0.042497	0.031440	
			40	1.000000	0.006221	-0.302343	1.302343		0.000000	0.000312	0.068639	0.050098	
7	Two-term exponential												
		MR = a Exp (-k t) + (1 - a) Exp(-k a t)	65	6.894096		0.001707				421.472894	0.116786		
			60	6.808698		0.001256				591.273531	0.120329		
			55	4.365043		0.001880				106.353312	0.049891		
			50	0.273781		0.024642				0.398160	0.034862		
			45	3.711693		0.001448				130.470032	0.057152		
			40	3.856530		0.001254				220.757201	0.081620		
8	Wang and Singh												
		$MR = 1 + a t + b t^2$	65			-0.008591	0.000019				0.000341	0.000000	
			60			-0.006228	0.000010				0.000315	0.000000	
			55			-0.006012	0.000009				0.000124	0.000000	
			50			-0.005074	0.000007				0.000185	0.000000	
			45			-0.003986	0.000004				0.000078	0.000000	
			40			-0.003556	0.000003				-0.003556	0.000000	

Table 5c. Mathematical models statistical analyses constants and standard errors of thin layer tunnel drying of Henna leaves

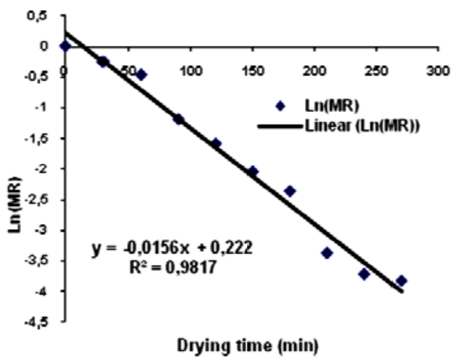
S. no.	Model name / Model equation	Drying temp.(°C)	Constant						Std Error					
			K	N	A	B	C	M	K	N	A	B	C	M
9	Diffusion approach													
	MR = a Exp(-k t)− (1- a) Exp(-k b t)	65	0.025151		-5.376747	0.858802			0.069194		182.4629	4.223544		
		60	0.020756		-5.452366	0.831049			0.024624		65.05097	1.756778		
		55	0.014703		-4.702405	0.886850			0.030915		148.5565	3.312333		
		50	0.224515		0.024682	0.030046			52.202869		0.054871	7.090273		
		45	0.011694		-4.376389	0.833857			0.007193		27.10980	0.898172		
		40	0.011675		-7.814641	0.871906			0.011833		108.38962	1.624833		
10	Modified Henderson and Pabis													
	MR=aExp(-kt)+bExp(-nt)+cExp(-mt)	65	0.012433	0.012425	0.453135	0.410554	0.193936	0.012430	42365.0503	36679.2359	3818307.3657	5400632.3181	4659588.4969	176566.9151
		60	0.009438	0.009436	0.336407	0.565152	0.208919	0.009438	159146.5521	40810.3507	0.000000	1626478.8966	1107992.7237	145866.6381
		55	0.008600	0.008601	0.387794	0.489312	0.169731	0.008604	39587.9895	17346.0108	2442849.9688	3163593.9120	1420548.6888	40512.3606
		50	0.006841	0.006843	0.369564	0.457351	0.162170	0.006839	11791.8409	12465.0893	0.000000	0.0000	0.0000	8297.3145
		45	0.005917	0.005917	0.389005	0.518821	0.193347	0.005917	55465.6116	49848.6969	2250803.3630	2261165.6365	1349684.3862	22167.6813
		40	0.005553	0.005552	0.335496	0.583768	0.235508	0.005553	59394.9853	5850.5560	6978719.7541	11189654.6409	4603090.4172	99206.3588
11	Verma *et al.*													
	MR = a Exp(-k t)+ (1 - a)Exp(-m t)	65	0.014647		1.267975			1.000000	0.001291		0.099389			0.0000
		60	0.011412		1.362059			1.000000	0.000591		0.059048			0.0000
		55	0.009290		1.133973			1.000000	0.000349		0.034341			0.0000
		50	0.006746		0.975299			1.000000	0.000330		0.036204			0.0000
		45	0.006470		1.207866			1.000000	0.000212		0.030374			0.0000
		40	0.006221		1.302332			1.000000	0.000302		0.048511			0.0000
12	Midilli-Kucuk													
	MR = a Exp(-k t^n)+ b t	65	1.000000	1.000000	1.000000	0.00653			0.000000	0.000000	0.417540	0.000824		
		60	0.000778	1.492092	1.019456	-0.00041			0.000462	0.125075	0.025728	0.000095		
		55	0.004004	1.134934	1.005132	-0.00089			0.001137	0.059528	0.016066	0.000054		
		50	0.014100	0.819776	0.996263	-0.00323			0.004197	0.063870	0.018442	0.000088		
		45	0.000930	1.327473	1.014047	-0.00022			0.000222	0.045477	0.011357	0.000023		
		40	0.000232	1.564158	1.023611	-0.00002			0.000110	0.088503	0.018884	0.000032		

Moisture Diffusivity

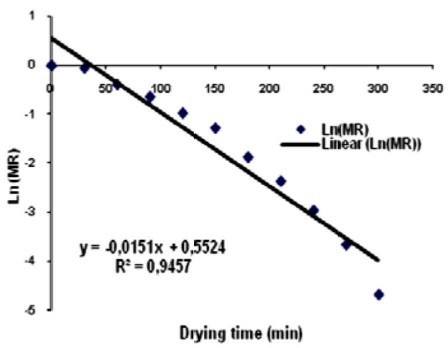
Values of D_{eff} with coefficient of correlation and r^2 are given in Table 6. Effective moisture diffusivity of henna leaves ranged from $2.24 \cdot 10^{-10}$ to $4.31 \cdot 10^{-10}$ $m^2 \cdot s^{-1}$. These values are within the general range 10^{-9} - 10^{-11} $m^2 \cdot s^{-1}$ for drying of food materials [24]. The moisture diffusivity increased as drying air temperature was increased. Plots of moisture diffusivity during drying are shown in Figures 2 (a-f) for different temperature regimes.

Table 6. Moisture diffusivity and its linear equation for henna leaves at different temperatures

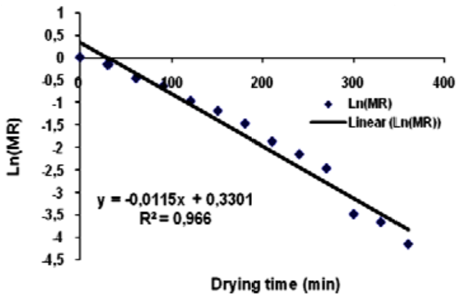
Drying temperature (°C)	Equation	K_o	D_{eff}	R^2
65	y = -0.0156x + 0.2220	-0.0156	4.31E-10	0.9817
60	y = -0.0151x + 0.5524	-0.0151	4.17E-10	0.9457
55	y = -0.0115x + 0.3301	-0.0115	3.18E-10	0.9660
50	y = -0.0089x + 0.2449	-0.0089	2.46E-10	0.9537
45	y = -0.0081x + 0.4028	-0.0081	2.24E-10	0.9697
40	y = -0.0081x + 0.4799	-0.0081	2.24E-10	0.9764



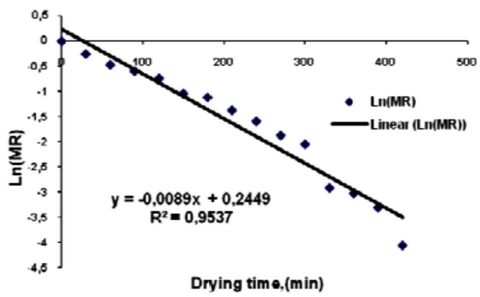
a.



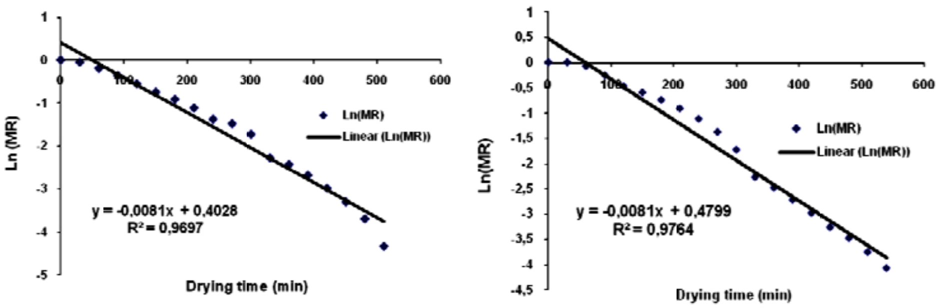
b.



c.



d.



e. f.

Figure 2. Effect of different drying air temperature on moisture diffusivity during tunnel drying (Ln (MR) Vs. Drying time) of henna leaves
a. 65°C, b. 60°C, c. 55°C, d. 50°C, e. 45°C, f. 40°C

Activation Energy

Activation energy is the minimum energy required to initiate the moisture migration from the product. Moisture diffusivity (on log scale) values were plotted against temperature and the slope of the plot was used to calculate the activation energy as discussed in material and methods section. The activation energy of henna leaves was 27.04 kJ·mol^{-1}, which is within the range of 12.87 – 58.15 kJ·mol^{-1} reported by [25] for other highly perishable commodities. The dried henna leaves were ground using home mixer to an average particle size of 0.2069 mm with a fineness modulus of 1.3685 [26].

CONCLUSIONS

The drying studies on henna leaves was carried at different temperatures from 40 to 65°C at an interval of 5°C in a tunnel dryer with belt speed of 30 rpm. Tunnel dryer took about 270 to 540 minutes to dry a 300 g of henna leaves samples. The thickness of henna leave was about 0.2611mm and having moisture content of 66.95% w.b. The drying of henna leaves occurred mainly in falling rate period. The drying time required was minimum in case of 65°C temperature samples and it increased with the decrease in drying air temperature. Midilli-Kucuk model described the drying behavior of henna leaves with highest r^2 value of 0.9987. Effective moisture diffusivity of henna leaves ranged from $2.24 \cdot 10^{-10}$ to $4.31 \cdot 10^{-10}$ m^2·s^{-1} and it increased with the increase in drying air temperature. The activation energy for the henna leaves was found to be 27.03 kJ·mol^{-1}. The fineness modulus of powder was 1.3685 and average particle size was 0.2069 mm.

BIBLIOGRAPHY

[1] Hosein, H., Zinab, D. 2007. Phenolic Compounds and Antioxidant Activity of Henna Leaves extracts (*Lawsonia Inermis*). *World Journal of Dairy and Food Sciences*, 2(1), 38-41.

[2] Kikuzaki, H., Nakatani, N. 1993. Antioxidant effects of some ginger constituents. *Journal of Food Science*, 58(14), 1407-1410.

[3] Muhammad, H, Muhammad, S. 2005. The use of *Lawsonia inermis linn*. (henna) in the management of burn wound infections. *African Journal of Biotechnology*, 4 (9), 934-937.

[4] Verma, N., Mehra, D., Niyogi, U., Khandal, R. 2008. Retention of color intensity in henna paste during storage. *Radiance*, 7(2), 118-121.

[5] Dev, V., Venugopal, J., Sudha, S., Deepika, G., Ramkrishna, S. 2009. Dyeing and antimicrobial characteristics of chitosan treated wool fabrics with henna dye. *Carbohydrate Polymers*, 75 (4), 646–650.

[6] Chaudhary, G., Goyal, S., Poonia, P. 2010. Lawsonia inermis Linnaeus: A Phytopharmacological Review. *International Journal of Pharmaceutical Sciences and Drug Research*, 2(2), 91-98

[7] Midilli, A. 2001. Determination of pistachio drying behaviour and conditions in solar drying systems. *International Journal of Energy Research*, 25, 715-725.

[8] Erenturk, S., Gulaboglu, M., Gultekin, S. 2004. The thin layer drying characteristics of rosehip. *Biosystems Engineering*, 89 (2), 159 – 166.

[9] Kadam, D., Samuel, D. 2006. Convective flat-plate solar heat collector for cauliflower drying. *Biosystems Engineering*, 93 (2), 189-198.

[10] Kadam, D, Goyal, R., Gupta, M. 2011. Mathematical modeling of convective thin layer drying of basil leaves. *Journal of Medicinal Plants Research*, 5(19), 4721-4730.

[11] Kadam, D., Goyal, R., Singh, K., Gupta, M. 2011. Thin layer convective drying of mint leaves. *Journal of Medicinal Plants Research*, 5(2), 164-170.

[12] Pangavhane, D., Sawhney, R., Sarsavadia, P. 1999. Effect of various dipping pre-treatment on drying kinetics of Thompson seedless grapes. *Journal of Food Engineering*, 39, 211-216.

[13] Kadam, D., Dhingra, D. 2011. Mass transfer kinetics of banana slices during osmo-convective drying. *Journal of Food Process Engineering*, 34 (2), 511–532.

[14] Kadam, D., Nangare, D., Singh, R., Kumar, S. 2011. Low-cost greenhouse technology for drying onion (*Allium cepa l.*) Slices. *Journal of Food Process Engineering*, 34 (1), 67–82.

[15] Doymaz, I. 2004. Effect of pre-treatments using potassium metabisulphite and alkaline ethyl oleate on the drying kinetics of apricots. *Biosystems Engineering*, 89(3), 281 – 287.

[16] Ozdemir, M., Devres, Y. 1999. The thin layer drying characteristic of hazelnuts during roasting. *Journal of Food Engineering*, 42, 225-233.

[17] Yaldiz, O., Ertekin, C., Uzun, H. 2001. Mathematical modeling of thin layer solar drying of sultana grapes. *Energy – An International Journal*, 26, 457 – 465.

[18] Sarsavadia, P., Sawhney, R., Pangavhane, D., Singh, S. 1999. Drying behavior of brined onion slices. *Journal of Food Engineering*, 40, 219 – 226.

[19] Togrul, I., Pehlivan, D. 2002. Mathematical modeling of solar drying of apricots in thin layers. *Journal of Food Engineering*, 55, 209 – 216.

[20] Goyal, R., Kingsly, A., Manikanthan, M., Ilyas, S. 2007. Mathematical modeling of thin layer drying kinetics of plum in a tunnel dryer. *Journal of Food Engineering*, 79, 176 – 180.

[21] Doymaz, I., Tugrul, N., Pala, M. 2006. Drying characteristics of dill and parsley leaves. *Journal of Food Engineering*, 77, 559-565.

[22] Crank, J. 1975. *Mathematics of diffusion*. Clarendon Press, Oxford, UK.

[23] Simal, S., Mulet, A., Tarrazo, J., Rosello, C. 1996. Drying models for green peas. *Food Chemistry*, 55, 121-128.

[24] Maskan, A., Kaya, S., Maskan, M. 2002. Hot air and sun drying of grape leather (pestil). *Journal of Food Engineering*, 54, 81-88.

[25] Senadeera, W., Bhandari, B., Young, G., Wijesinghe, B. 2003. Influence of shapes of selected vegetable materials on drying kinetics during fluidized bed drying. *Journal of Food Engineering*, 58, 277–283.

[26] Sahay, K., Singh, K. 1994. *Unit Operations of Agricultural Processing*. 1st Ed. Vikas Publishing House Pvt. Ltd, New Delhi, India.

KINETIKA SUŠENJA TANKOG SLOJA LISTOVA KANE

Dattatreya M. Kadam[1], Manoj Kumar Gupta[2], Vaijayanta M Kadam[3]

[1]Centralni institut za post-žetveni inženjering i tehnologiju,
PO: PAU campus, Ludhiana-141004 (Pendžab), Indija
[2]Infosys Limited, Electronic City, Phase I, Bangalor, Karnataka, Indija
[3]Državni institut za hortikulturu, Karnataka, Indija

Sažetak: Listovi kane su dobro poznati po svojim kozmetičkim agensima sa anti-kancerogenim, anti-inflamatornim, analgetskim i anti-piretičkim svojstvima. Laboratorijski modeli tunelske sušare su korišćeni za sušenje listova na 40, 45, 50, 55, 60 i 65°C i ispitivanje uticaja različitih uslova kinetiku sušenja listova kane. Period sušenja listova kane se skraćivao i sušenje je bilo brže pri višoj temperature. Dvanaest modela sušenja tankog sloja je poređeno sa eksperimentalnim podacima o odnosima vlage. Među matematičkim modelima koji su ispitivani, model Midilli-Kucuk je na zadovoljavajući način opisao ponašanje pri sušenju sa najvišim vrednostima r^2. Efektivna difuzija vlage (D_{eff}) listova povećala se sa povećanjem temperature vazduha za sušenje. Efektivna difuzija vlage listova kane iznosila je od $2.24\cdot10^{-10}$ do $4.31\cdot10^{-10}$ $m^2\cdot s^{-1}$, a energija aktivacije 27.03 $kJ\cdot mol^{-1}$. Osušeni listovi su mleveni u prah sa prosečnim dimenzijama čestica od 0.2069 mm i modulom finoće 1.3685.

Ključne reči: *kana, matematičko modeliranje, sušenje, difuzija vlage, energija aktivacije*

Prijavljen: *Submitted*:	23.06.2013.
Ispravljen: *Revised*:	07.07.2013.
Prihvaćen: *Accepted*:	30.07.2013.