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Drying Kinetics of Aonla shreds (*Emblica officinalis* Gaertn. Syn. *Phyllanthus emblica* L): Effect of Drying Methods

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Abstract

Aonla (*Emblica officinalis* Gaertn. Syn. *Phyllanthus emblica* L) fruits (var. BSR-1) shredded using a kitchen type shredder to an average size of 3±0.5 mm, was dried in a laboratory model batch type fluidised bed dryer, cabinet or tray type dryer and infrared dryer at temperatures of 50, 60 and 70°C. The sample was spread on trays at the rate 0.12 kg/m^2 and 0.3 kg/m^2 in cabinet dryer and infrared dryer, respectively. The velocity of air in the fluidised bed dryer was maintained in the range of 12.78 - 15.5 m/s. From the initial moisture content of 458.4 to 576.41% (d.b.) to the final moisture content of 3.62 to 8.99% (d.b.), it took 25 to 30, 120 to 180 and 270 to 315 min. for drying in fluidised bed, cabinet and infrared drying. The drying data of Aonla by fluidised bed, tray and infrared drying were fitted to Page, modified Page, Lewis, modified Midilli and Kucuk, Henderson and Pabis, and two term exponential models. The fit of the models were assessed following the standard statistical tools. Page model (R^2=0.99) well described the drying kinetics of aonla shreds in the temperature range studied in fluidised bed and tray drying and modified Page model (R^2=0.96-0.99) for infrared drying.

Keywords: Aonla Shreds, Drying Models, Fluidised Bed Drying, Infrared Drying, Tray Drying

1. Introduction

Indian Gooseberry (*E. officinalis* Gaertn. Syn. *P. emblica* L.) fruit commonly known, as "aonla" is one of the oldest minor fruits of India. It belongs to the family *Euphorbeaceae* and is native of India, Srilanka, Malaysia, and China. In India it is cultivated in 105,000 ha. and 1.28 million tonnes were produced during 2022-23[1]. Aonla is cultivated in the states of Maharastra, Rajasthan, Gujarat, Andra Pradesh, Telengana, Karnataka and Tamil Nadu. In Tamil Nadu, during 2023-24, aonla was cultivated in an area of 8100 ha[2]. Aonla fruit is a good source of various nutraceuticals and well known for its medicinal and nutritional qualities. It is rich in polyphenols, minerals and regarded as the richest source of vitamin C (200-900 mg/100 g of edible portion) among fruits. But due to highly acidic and astringent taste, low Total Soluble Solids (TSS), lack of flavour, and poor color; it is not popular as table fruit[3]. Aonla is said to have immune-boosting efficiency against multiple diseases and are also extensively applied in *Ayurveda*, an Indian ancient system of medicine[4]. Even if the fruit is eaten in its unripe state, it is considered to be health beneficial. It has also found its application in the food processing, pharmaceutical and cosmetic sectors.

Preservation of fruits and vegetables is essential for long time consumption without further deterioration in the quality of the product. Aonla has short shelf life and is prone to chilling injury at below 6°C, if cold storage is preferred[5]. As moisture content of fresh aonla varies from 600% to 800% (d.b.), it is needed to dry to 9% to 10% (d.b.) to prevent spoilage and preserve for use in preparation of value added products and medicinal preparations. Aonla

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fruits are dried both along with the seeds and after removal (pricking) of seeds. Hand operated and pedal operated devices were developed and used for aonla seed removal for use in preservation in many forms, like preserves, pickle, flakes, shreds, segments, *etc*[6,7]. Earlier researchers used aonla in the form of whole fruit, shreds, segments, slices *etc* for preservation and use in various preparations[8-16].

For drying aonla in any form, cabinet or tray or hot air dryer, fluidized bed dryer, vacuum dryer, low temperature dryer and solar dryer were used. Drying of aonla in the convective dryers and fluidised bed dryer was done by the earlier researchers in the temperature range of 50 to 80°C. Drying with osmosis treatment using salt and sugar at different concentrations followed by cabinet dryer, fluidised bed dryer and vacuum dryer were adopted by the earlier researchers and found reduction in drying time[8-18].

Though many researchers dried aonla in different forms, studies on developing drying models is less reported. Number of drying models has been proposed by many researchers for various food products dried under different methods and with pre-treatments. Such models were reviewed and given in a consolidated form by many authours, including Haydar *et al*[19]. Among the models, for tray or cabinet drying, Page model Logarithmic model and Newton model were proposed for mushrooms, amla-beet root shreds and aonla fruits, respectively. Under sun drying of ginger, diffusion approximation model and page model for drying black berry wastes were proposed[13,14,20-23].

Hence the drying kinetics of aonla shreds by fluidised bed, cabinet (tray) and infrared drying were studied to propose the appropriate drying model to facilitate design of drying systems for aonla shreds.

2. Materials and Methods

2.1 Raw Materials

Freshly harvested, fully matured aonla fruits (var. BSR-1) were procured from the Agricultural Experimental Station of Tamil Nadu Agricultural University located at Bhavanisagar in Erode district, Tamil Nadu state. Aonla variety BSR-1 is a high yielding (155 kg/tree, 42952 kg/ha), self-fruitful selection and matures late in the season[24]. Fruits are flattened at base and round at apex, ranged 25 to 30 mm in diameter and 22 to 31 g in mass. Fruits were filled in gunny bags and transported to the laboratory with care to avoid any damage to the fruits and used in the experiments within 72 hours. The fresh aonla was washed in running tap water to remove adhering extraneous matter and used in the experiments. After washing aonla thoroughly, the bruised fruits were removed and stored in refrigerated condition till they were used for the drying experiments. Aonla shreds were prepared using a kitchen type shredder, by holding the fruit firmly in the hand and rubbed against the serrated surface of the shredder to obtain the shreds. Prajapathi *et al.* also used such type of shredder in their experiments for shredding aonla[11]. The size of the shreds was in the range of 3±0.5 mm.

2.2 Drying Methods

A laboratory model batch type fluidised bed (Make: SM Science Tech., Kolkata) dryer consisting of a blower-motor assembly, heating coils (0.5 kW capacity), fluidising chamber (12 litre) with perforated bottom and an exhaust air outlet. The dryer is provided with temperature indicators for inlet and outlet air, thermostat and a timer switch. The cabinet or tray type dryer (Make: Kilburn; model-024E) used was provided with electrical heaters, axial blower and motor (0.5 HP) with provision to control the temperature in the range up to 200°C. An infrared dryer with a drying chamber of size 300 × 300 × 300 mm fitted with infrared lamp (250W; 220-240 V) was used. The light intensity and temperature were controlled through voltage regulation (dimmerstat) and PID controller, respectively.

About 200 g of aonla shreds treated as per the plan was placed in the drying chamber of the respective dryer and dried at temperatures of 50, 60 and 70°C. Earlier researchers and Visvanathan (2022) dried aonla and other samples in this temperature range[8,12-14,16,17,25]. An air flow with velocity of 0.75 m/s was followed in the cabinet dryer, in accordance with 1.2 m/s and 0.8 m/s followed by earlier researchers[8,10]. The velocity of air in the fluidised bed dryer was maintained in the range of 12.78-15.5 m/s, which was assessed from the adequacy to provide required fluidisation for the sample and measured using a digital anemometer. Pareek and Kaushik used hot air at the velocity of 90 m/min. in their experiments in drying aonla by fluidized bed drying[16].

The samples were weighed at 5 min interval using an electronic balance having an accuracy of 0.01 g. For drying in tray dryer, the treated aonla samples were spread on trays of size 500 × 350 × 80 mm and spread at the rate 0.12 kg/m^2. The samples were weighed at 15 min interval by means of an electronic balance having an accuracy of 0.01 g. For infrared drying, the aonla shreds were loaded in the trays (200 x 200 x 50 mm) at density of the 0.3 kg/m^2. The samples were weighed at an interval of 15 min. using an electronic balance with an accuracy of 0.01 g. Drying was conducted at an intermittency level of α = ½, calculated as,

$$\alpha = T_{on} / (T_{on} + T_{Off}) \quad (1)$$

Where, α is intermittency, T_{on} and T_{off} are the on and off periods, respectively, of the infrared lamps.

The value of α= ½ was chosen as reported by Chua and Chou, which resulted a minimal product colour change and better quality characteristics in infrared drying of potato and carrot[26].

2.3 Modeling of Drying Kinetics of Aonla

From the weight of the aonla shreds being dried, the percent moisture contents were estimated with drying time for the drying methods, *viz.*, fluidised bed drying, tray drying and infrared drying. Determination of moisture content of aonla shreds was done by placing replicated samples in a vacuum oven (Technico Laboratory Products Pvt. Ltd., TLPPL 143, 200°C, 760 mm Hg) under 100 mm Hg of vacuum at 70°C for 6 h following the procedures of AOAC[27]. Themoisture ratio (MR) was estimated from the percent moisture content as described below:

$$\text{Moisture ratio, } MR = \frac{M_t - M_e}{M_o - M_e} \quad (2)$$

Where,

MR is the moisture ratio

M_t *is the moisture content at time t, % (d.b.)*

M_o *is theinitial moisture content, % (d.b.)*

M_e *is the equilibrium moisture content, % (d.b.)*

For long drying period, the Equation (2) can be reduced to[21,28]

$$MR = \frac{M_t}{M_o} \quad (3)$$

Table 1. Drying models fitted to aonla shreds

Model name	Model	Reference
Page	$MR = e^{-kt^n}$	32
Modified Page	$MR = e^{-(kt)^n}$	32
Lewis or Newton model	$MR = e^{-kt}$	33
Henderson and Pabis	$MR = ae^{(-kt)}$	34
Modified Midilli and Kucuk model	$MR = ae^{(-kt^n)} + bt$	35
Two-term exponential	$MR = ae^{(-kt)} + (1-a)e^{(-kat)}$	36

Where, *k* is the rate constant (min^{-1}), *n*, *a*, *b*, *c* and *d* are dimensionless coefficient and *t* is the time (min).

Though number of models are available in literature, Page, modified Page, Lewis, Midilli, Henderson and Pabis and Two term exponential models (Table 1) popularly used by various researchers for various crops and food materials, *viz.*, dill and parsley leaves kale, figs ginger are used in this study[19,21,29-31].

Non-linear regression procedure was performed on all drying runs to estimate the parameters associated with the six selected models using the software Sigma Plot (version 10.0). The coefficient of determination R^2 was the primary criterion for selecting the best equation to describe the drying curve. In addition, the reduced chi-square (χ^2) and Root Mean Square Error Analysis (RMSE) were calculated to evaluate the efficiency of fitting a model to the experimental data. The highest value of R^2 and the lowest values of χ^2 and RMSE were used to determine the best fit[37].

These statistical parameters were calculated as follows:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)^2}{N-n} \quad (4)$$

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

Where,

$MR_{exp,I}$ is the i^{th} experimentally observed moisture ratio

$MR_{pre,I}$ is the i^{th} predicted moisture ratio

N is the number of observations

n is the number of constants in the model

3. Results and Discussion

3.1 Drying Kinetics of Aonla Shreds by Fluidised Bed

The aonla shred, from initial moisture content of 497.06 to 606.8% (d.b.) to final moisture content of 5.05 to 9.37 % (d.b.), took 25-30 min duration in fluidised bed drying in the drying temperature of 50-70°C and 12.7 to 15.5 m/s, air velocity. All the drying models given in equation (4) to (9) were fitted to the drying data at these drying temperatures and the coefficients were determined along with the coefficient of determination R^2, the reduced chi-square (χ^2) and Root Mean Square Error (RMSE) are given in Table 2. All these drying models have shown the good fit with coefficient of determination of above 0.98. With the chi-square (χ^2) and Root Mean Square Error (RMSE) values, the closeness of the fit can be judged in the rank of Page followed by modified Page and modified Midilli and Kucuk model.

Figure 1 shows the relationship between the drying time and the moisture ratio for the aonla shreds dried at 50, 60 and 70°C temperatures in fluidised bed drying for both the experimental values and the predicted values for the fit by the Page model. As indicated by the higher level of fit by the coefficient of determination, both the experimental and predicted values are seen closely at the drying temperatures studied. A plot between the experimental values of moisture ratio and predicted values using Page model shown in Figure 2A, also indicates the close agreement.

The drying model parameters, *k* and *n* are seen in a trend with drying air temperature. The following

Table 2. Values of drying constants and related statistical parameters for different drying models under fluidised bed drying of aonla shreds

Model Name	Temperature°C	*k*	*n*	*a*	*b*	*c*	*d*	Adj. R^2	χ^2	RMSE
Page	50	0.065	1.516	-	-	-	-	0.99	0.00007	0.0060
	60	0.095	1.425	-	-	-	-	0.99	0.00003	0.0038
	70	0.149	1.169	-	-	-	-	0.99	0.00006	0.0054
Modified Page	50	0.155	1.516	-	-	-	-	0.99	0.00007	0.0060
	60	0.182	1.425	-	-	-	-	0.99	0.00002	0.0029
	70	0.183	1.169	-	-	-	-	0.99	0.00006	0.0054
Lewis	50	0.168	-	-	-	-	-	0.98	0.00295	0.0458
	60	0.198	-	-	-	-	-	0.99	0.00126	0.0301
	70	0.188	-	-	-	-	-	0.99	0.00047	0.0164
Henderson and Pabis	50	-	-	1.021	0.171	-	-	0.98	0.00353	0.0449
	60	-	-	1.010	0.199	-	-	0.99	0.00154	0.0299
	70	-	-	1.005	0.189	-	-	0.99	0.00056	0.0172
Modified Midilli and Kucuk	50	0.060	1.503	1.000	0.000	-	-	0.99	0.00018	0.0064
	60	0.103	1.422	1.000	0.000	-	-	0.99	0.00014	0.0050
	70	0.159	1.154	1.000	0.000	-	-	0.99	0.00096	0.0174
Two term exponential	50	-	-	0.523	0.171	0.498	0.171	0.98	0.00699	0.0437
	60	-	-	0.551	0.200	0.459	0.191	0.99	0.00294	0.0276
	70	-	-	0.471	0.250	0.535	0.180	0.99	0.00025	0.0041

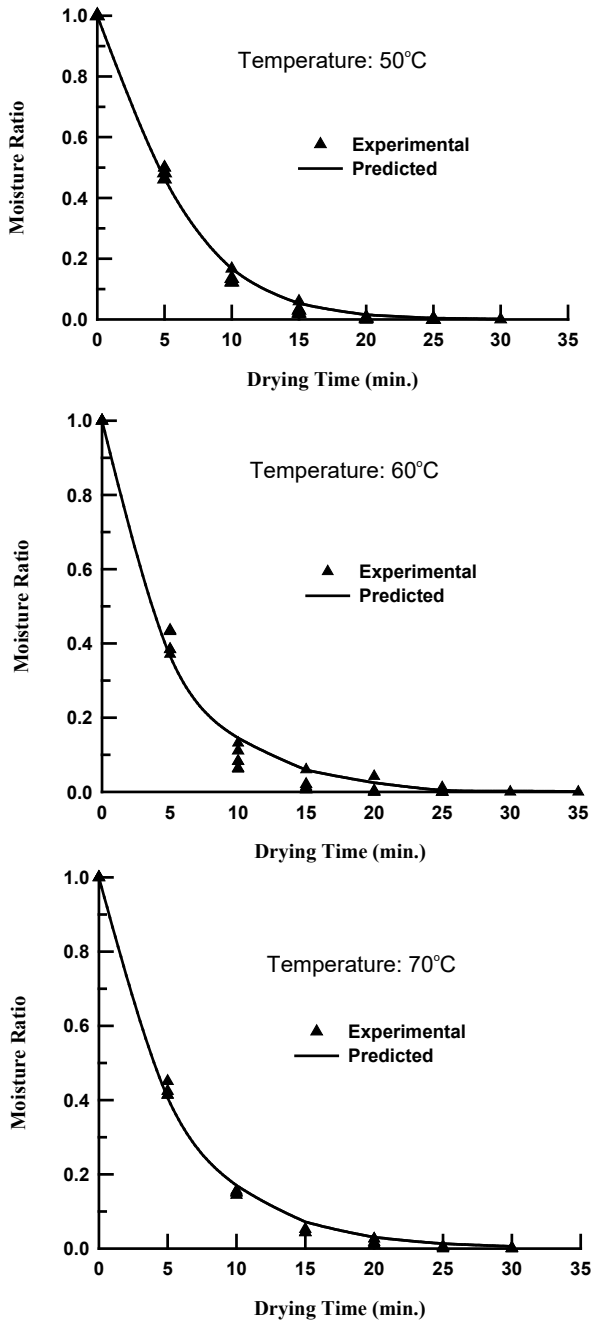


Figure 1. Drying kinetics of aonla shreds at indicated temperatures by fluidized dry.

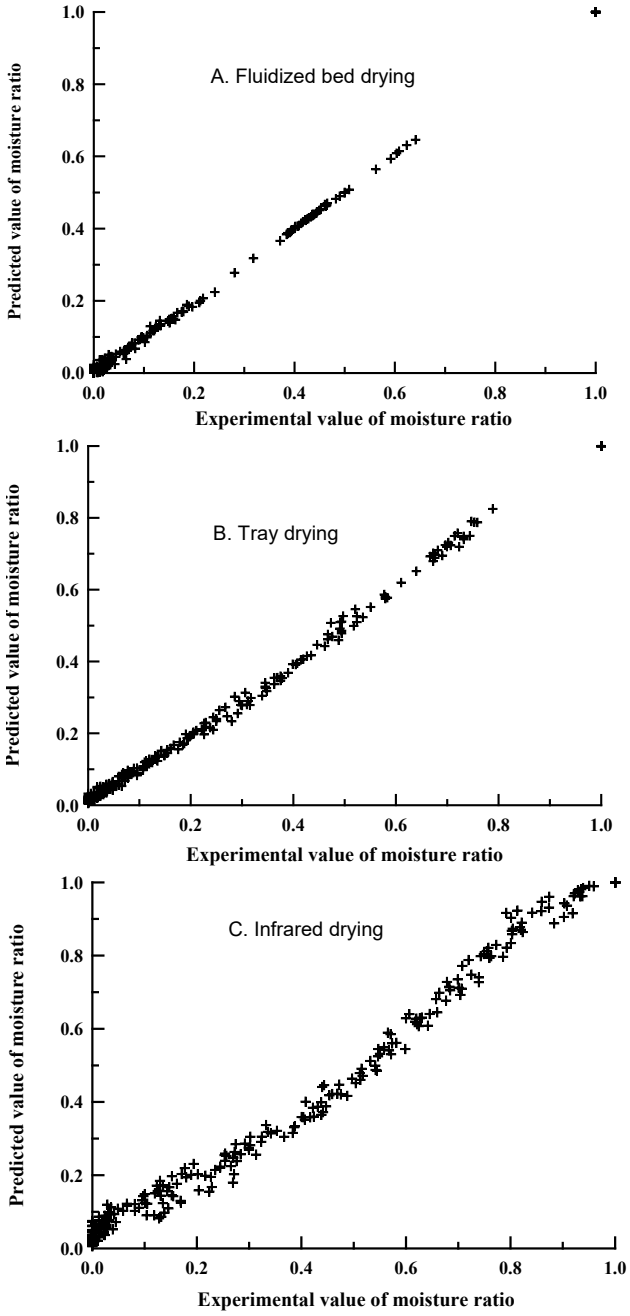


Figure 2. Plot showing trend between the experimental and predicted moisture ratio for aonla shreds in the indicated drying methods.

relationships generalise the linear trend between the temperature and the model parameters.

$$k_f = 0.005\ t - 0.189 \qquad (R^2 = 0.994) \qquad (6)$$

$$n_f = -\ 0.017\ t + 2.411 \qquad (R^2 = 0.929) \qquad (7)$$

Where, k_f is the rate constant (min^{-1}), n_f is the dimensionless coefficient, t is the drying time (min) and suffix f indicates the fluidised bed drying. Page model for drying black berry wastes[23] was proposed. Logarithmic model and Newton model were proposed for amla-beet root shreds and aonla fruits, respectively. Doymaz *et al.* found that Midilli model was capable of describing the drying behaviour of dill and parsley leaves, which are in the same moisture range[13,14,27].

Table 3. Values of drying constants and related statistical parameters for different drying models under tray drying of aonla shreds

Model name	Temperature, °C	*k*	*n*	*a*	*b*	*c*	*d*	Adj. R^2	χ^2	RMSE
Page	50	0.017	1.096	-	-	-	-	1.00	0.00025	0.0138
	60	0.019	1.095	-	-	-	-	1.00	0.00057	0.0206
	70	0.023	1.094	-	-	-	-	0.99	0.00087	0.0253
Modified Page	50	0.023	1.096	-	-	-	-	1.00	0.00025	0.0138
	60	0.024	1.095	-	-	-	-	1.00	0.00055	0.0201
	70	0.029	1.094	-	-	-	-	0.99	0.00087	0.0253
Lewis	50	0.024	-	-	-	-	-	0.99	0.00062	0.0221
	60	0.025	-	-	-	-	-	0.99	0.00083	0.0257
	70	0.030	-	-	-	-	-	0.99	0.00107	0.0304
Henderson and Pabis	50	-	-	1.014	0.024	-	-	0.99	0.00101	0.0211
	60	-	-	1.010	0.025	-	-	0.99	0.00090	0.0255
	70	-	-	1.008	0.030	-	-	0.99	0.00119	0.0300
Two term exponential	50	-	-	0.499	0.030	0.517	0.023	1.00	0.00101	0.0201
	60	-	-	0.488	0.037	0.524	0.025	0.99	0.00112	0.0251
	70	-	-	0.489	0.432	0.520	0.030	0.99	0.00163	0.0296

Table 4. Values of drying constants and related statistical parameters for different drying models under infrared drying of aonla shreds

Model Name	Temperature °C	*k*	*n*	*a*	*b*	*c*	*d*	Adj. R^2	χ^2	RMSE
Page	50	0.001	1.604	-	-	-	-	0.98	0.00275	0.0469
	60	0.003	1.586	-	-	-	-	0.99	0.00132	0.0340
	70	0.003	1.487	-	-	-	-	0.98	0.00227	0.0414
Modified Page	50	0.008	1.651	-	-	-	-	0.98	0.00221	0.0425
	60	0.008	1.586	-	-	-	-	0.99	0.00132	0.0340
	70	0.009	1.534	-	-	-	-	0.99	0.00156	0.0369
Lewis	50	0.008	-	-	-	-	-	0.92	0.01032	0.0920
	60	0.009	-	-	-	-	-	0.93	0.00834	0.0841
	70	0.010	-	-	-	-	-	0.94	0.00725	0.0790
Henderson and Pabis	50	-	-	1.105	0.009	-	-	0.94	0.00663	0.0828
	60	-	-	1.106	0.010	-	-	0.95	0.00646	0.0729
	70	-	-	1.088	0.010	-	-	0.95	0.00610	0.0709
Two term exponential	50	-	-	0.588	0.009	0.516	0.009	0.94	0.00745	0.0828
	60	-	-	0.586	0.010	0.520	0.010	0.95	0.00724	0.0729
	70	-	-	0.572	0.010	0.516	0.010	0.95	0.00691	0.0709

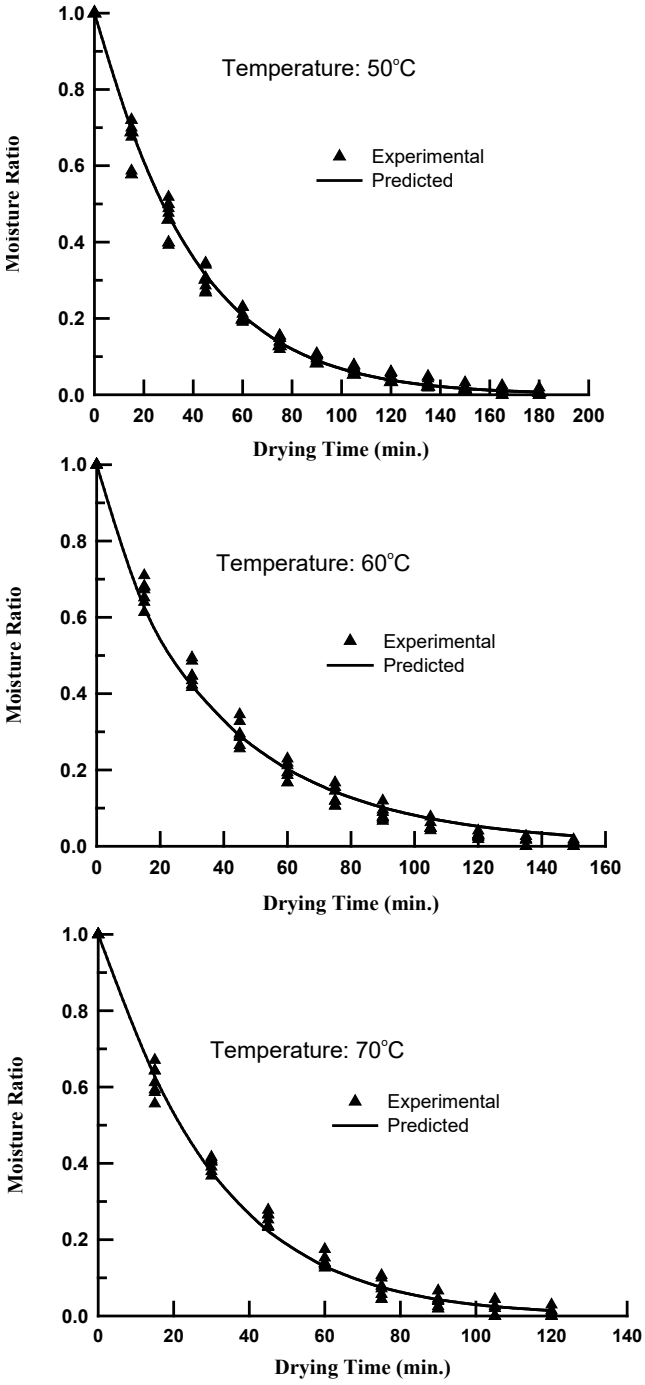


Figure 3. Drying kinetics of aonla shreds at indicated temperatures by tray drying.

3.2 Drying Kinetics of Aonla Shreds by Tray Drying

From the initial moisture content of 467.44 to 504.2% (d.b.), for the aonla shreds it took 120 to 180 min by tray drying to final moisture content of 5.08 to 8.99%

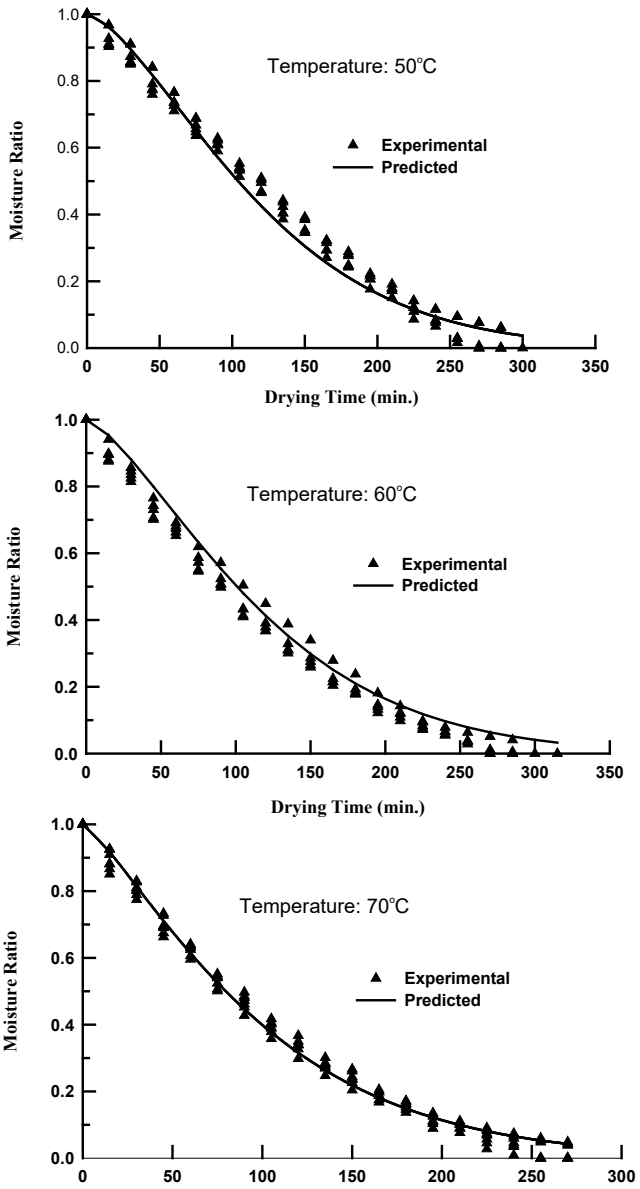


Figure 4. Drying kinetics of aonla at indicated temperatures by infrared drying.

(d.b.) in the drying temperature range of 50 to 70°C and 0.75 m/s air velocity. All the drying models equation (4) to (9) given in Table 1 were fitted to the drying data at these drying temperatures and the coefficients were determined along with the coefficient of determination R^2, the reduced chi-square (χ^2) and Root Mean Square Error (RMSE) and given in Table 3. All these drying models have shown the good fit with coefficient of determination of above 0.99. With the chi-square (χ^2) and Root Mean Square Error (RMSE) values, the closeness of the fit can be judged in the rank of Page

followed by modified Page, Lewis, Henderson and Pabis and two term exponential model. From Table 3, it could be further judged that the change in the values of *k* is well noted with temperature of drying in the case of Page model. Being a rate constant, *k* is influenced by the duration of drying, which is also governed by the temperature of drying.

Drying kinetics of aonla shreds by tray drying is shown in Figure 3 at the temperatures of drying with both experimental values of moisture ratio and the predicted values as per Page's model. As seen from the figure 3, the experimental and predicted values are seen closely. Also the plot of trend between the experimental and predicted values (Figure 2B) is in close agreement.

The drying model parameter, *k* is seen in a trend with drying air temperature and the parameter *n* is not seen to vary with the temperature, which is close to 1. The following relationship generalises the linear trend between the temperature and the model parameter *k*.

$$k_t = 0.003\ t + 0.016 \qquad (R^2 = 0.964) \qquad (8)$$

Where, k_t is the rate constant (min^{-1}), *t* is the drying time (min) and suffix *t* indicates tray or cabinet drying.

Page model is reported to fit well to many crops by the earlier researchers, lettuce and cabbage, okra, purslane, green beans sweet potato and onion slices[30,38-43].

3.3 Drying Kinetics of Aonla Shreds by Infrared Drying

It took 270 to 330 min. by infra red drying for the aonla shreds from the initial moisture content of 458.41 to 482.71% (d.b.) to 3.62 to 5.62% (d.b.). All the drying models shown close fit to the drying data as seen from the coefficient of determination in the range of 0.92 to 0.99. Among the models (Table 1), modified Page model has shown higher values of coefficient of determination (R^2) and least chi-square (χ^2) and Root Mean Square Error (RMSE) values, the closeness of the fit can be judged in the rank of modified Page followed by Page, Lewis, Henderson and Pabis and two term exponential models (Table 4). For the modified Page model, the values of the coefficients, *k* and *n*, are not influenced by the temperature and the mean values are noted as 0.008 and 1.59, respectively.

Figure 4 shows the drying trend of the aonla shreds at 50, 60 and 70°C temperatures with the experimental values and the moisture ratio predicted using the modified Page model. As indicated by the higher degree of fit, the experimental and predicted values have shown a close fit at all temperatures of drying. The relationship between the experimental and predicted values of moisture ratio for aonla shred by infrared drying (Figure 2C) also shows the close fit for drying of aonla shreds by infrared drying.

Modified Page model was found fitting well to basil and mint under open sun drying[44]. Under thin layer or convective drying of *Echinacea angustifolia*, kale and carrot slice and the coefficients were found dependent of drying parameters[28,45,46]. Infrared drying of fresh apple slices and carrot were found to follow the modified Page model and the coefficients were found dependent of drying parameters[47,48].

4. Conclusions

Aonla shreds (var. BSR-1) dried in a laboratory model batch type fluidised bed dryer, cabinet or tray type dryer and infrared dryer, at temperatures of 50, 60 and 70°C, took 25 to 30, 120 to 180 and 270 to 315 min. duration from the initial moisture content of 458.4 to 576.41% (d.b.) to the final moisture content of 3.62 to 8.99% (d.b.). Among the Page, modified Page, Lewis, modified Midilli and Kucuk, Henderson and Pabis, and two term exponential models, Page model (R^2=0.99) well described the drying kinetics of aonla shreds in fluidised bed and tray drying, and modified Page model (R^2=0.96-0.99) for infrared drying.

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