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Mathematical Modeling on Drying of Tamarind Fruits

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Tamarind is an indigenous tree in India and every parts of the tree such as root, stem, fruit and leaves are widely used in nutritional, medicinal and industrial applications. The stickiness of tamarind fruit is a major concern during the deseeding process, and it can be reduced by drying. The tamarind growers and processing industries are still using the sun drying method, which is time-consuming and unhygienic that produces a poor-quality product. In this context, a cabinet type tray dryer was used to reduce the moisture content from dehulled and de-fibered tamarind fruit. Drying study of tamarind was conducted at three different temperatures (50, 60 and 70°C) with different airflow rates (0.5, 1.0 and 1.5 m/s). Different drying models were adopted for analyzing the drying kinetics of dehulled tamarind fruit under different temperature conditions. The highest coefficient of determination of 0.9998 and reduced Chi square value of 0.00012 was favoring the optimized drying condition based on Wang and Singh model. The optimized temperature and airflow rate were found to be 60°C and 1.0 m/s, respectively. For the optimized drying conditions, the corresponding quality parameters *viz.,* L*, a* and b* values, total soluble solids, titratable acidity and pH were found to be 44.30 ± 1.16, 3.50 ± 0.11 and 13.2 ± 0.15, 25.60 ± 1.00 ^{o}brix, 17.40 ± 0.58% and 3.1 ± 0.08, respectively.

Keywords: Dehulled fruit, Moisture content, Quality, Temperature, Thin layer drying

Introduction

Tamarind (*Tamarindus indica* L.,) is a multifunctional fruit tree widely grown in the Southern States of India. It is predicted that India produces around 2,02,000 metric tonnes of tamarind fruits annually.[1] On average, the whole tamarind fruit comprises of 55–57% edible portion, 34–36% seeds, and 11–12% shell and fibers.[2] The whole tamarind fruits are oblong in shape, curved or straight with rounded ends. It is an excellent source for vitamins (thiamin, niacin and riboflavin) and minerals (calcium, iron and phosphorous) and also a good source for sugar (21% to 30%), however, it contains only minor quantities of vitamins A and C.[3] Tamarind fruits are also well-known for their therapeutic properties, as it is used to treat abdominal disorders and skin problems in tamarind producing countries.[4] Besides its nutritional and therapeutic benefits, tamarind fruit pulp is extensively used for domestic and industrial applications because it contains plenty of tartaric acid. The pulp from tamarind fruits are also utilized as an alternate substance for chemical preservatives and as a raw ingredient for the manufacture of certain hot and cold drinks and also used as flavor enhancer in the preparation of soups, sauces, jams, juices and chutneys.[5] The tamarind fruit pulp is one of the important acidulants in the South Indian dishes. In addition to this, the other value-added products obtained from tamarind processing are tamarind juice, concentrate, powder, pickles and paste.[6]

Tamarind fruit processing involves several unit operations *viz.,* dehulling, drying and deseeding.[7] The dehulling process is performed to remove the outer hull from the pods following by de-fibering. After that, tamarind fruits need to be dried to carry out the deseeding process. Traditionally, wet and dry methods of tamarind processing are followed in India. In the dry method, the whole tamarind fruits are sun-dried to reduce the stickiness of the pulp and then the hull and seed are removed from the pulp by beating with sticks. In the wet method, the dehulled tamarind fruit is soaked either in hot water or cold water. The wet pulp is passed through a metallic screen to obtain a pulp that is free of fibre and seed, and then the pulp

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is either concentrated or dried into powder form. The pulp obtained from the dry method has been widely used; however, this method of processing is time-consuming due to the stickiness property of tamarind pulp.[8] The tamarind pulp is sticky and hygroscopic at a moisture content of 25% (d.b.) while storing under atmospheric conditions.[9] Moisture present in the tamarind fruit imparts a major parameter in the stickiness of tamarind fruits during deseeding operation. This can be prevented by adopting proper drying method. For effective deseeding, the moisture content of the tamarind fruits has to be reduced to around 12% (d.b.).[6] The traditional sun drying method is cost-effective and can be easily performed. However, this method results in poor quality and contaminated products due to longer drying period.[10,11]

Mechanical drying has lot of advantages compared to the sun drying method. The total time required for drying under mechanical dryer is comparatively lesser than sun drying. Also, the losses in sun-drying are more when compared to mechanical drying.[12,13] Several drying studies of fruits and vegetables have been provided with mechanical dryers for instance, egg plant by Brasiello *et al.*[14], Wang *et al.*[12] for mushrooms and Oranges by Bozkir.[15] In a convective hot air drying process, the food product is exposed to a steady flow of convective hot air and this is widely used due to its lower cost, simplicity and could be effortlessly operated even by unskilled workers with no additional requirements.[16] Thin layer models have been investigated in many horticultural produces such as in tomatoes by Coskun *et al.*[17], Deshmukh *et al.*[18] for ginger, Doymaz[19] for mushroom and in tamarind seeds by Junior *et al.*[20] for predicting the best model, which defines the drying process and optimizing the process parameters. They are extensively used to know the basics of transport phenomenon.[21] Models such as Midilli, Page, Lewis, Modified Midilli, Logarithmic, Two term, Wang and Singh, Henderson-Pabis are most common. Page, Lewis, Wang and Singh and Midilli models for carrot slices by Sonmete *et al.*[22], in tomatoes by Coskun *et al.*[17], in Tamarind seeds by Junior *et al.*[20] and in Orange slices by Bozkir[15] have been used to define the drying process. So, these models aid in optimizing the processing parameter of a drying process leads to the production of better quality product.[23] Very few studies have been carried out in drying of tamarind fruits in various forms *viz.,* spray drying of tamarind pulp by Muzaffar & Kumar[5], Cynthia *et al.*[24], belt drying of tamarind fruits by Pandiarajan *et al.*[7], greenhouse drying of tamarind fruits at 60°C to obtain tamarind flour by Queiroga *et al.*[25], Drum drying of tamarind juice by Prangpru *et al.*[26] & Jittanit *et al.*[27], Modeling of tamarind seeds by Junior *et al.*[20] & Mohite *et al.*[28] But, very few studies were carried out on mathematical modelling for optimizing the drying conditions of the tamarind fruit as a whole. In India, after harvesting most of the tamarind fruits are dehulled, deseeded, dried and packed as a whole fruit and sold in the markets.

Hence, there is a need to obtain the suitable condition for drying. The tray dryer operating parameters need to be optimized based on the nature of the product. Tamarind growers and processing industries are looking for effective drying conditions for processing and production of high quality pulp. Therefore, this study aims to select the best model to analyze the effects of process parameters on drying kinetics and product characteristics.

Materials and Methods

Drying Procedure

Tamarind (*Tamarindus indica* L.,) fruits taken for the drying study was purchased from local farmers (Urigam variety), and the fruits were selected based on uniform color, shape and size. The tamarind fruits were dehulled and de-fibered using a mechanical tamarind dehuller. Immediately, after that the tamarind fruits were taken for the drying study. The graphical representation of the steps could be seen in Fig. 1. The drying trials were conducted during March, 2020. A lab model tray dryer consisting of 9 trays with a heating capacity of 2 kW was used for the study (Zigma International Private Limited, Coimbatore, India). The tray dryer was pre-heated to about half an hour to achieve a steady state condition

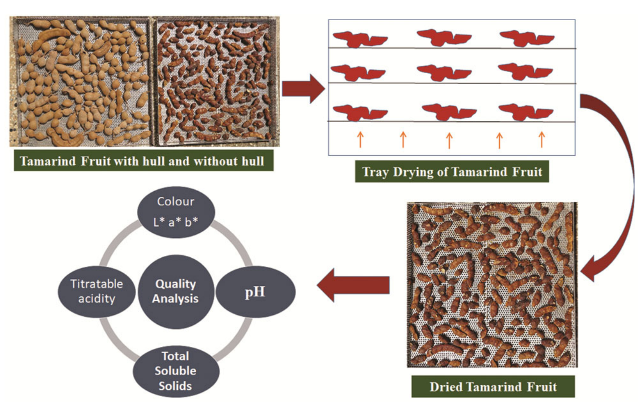

Fig. 1 — Graphical representation of tamarind processing

before starting the trial. Based on preliminary trials, drying temperature above 70°C affects the quality of tamarind fruits while below 50°C it prolongs the drying time.[7] Three selected temperatures of 50, 60 and 70°C and three different air velocities such as 0.5, 1.0 and 1.5 m/s were fixed and the experiments were carried out for 5 kg of dehulled tamarind fruits. The initial moisture content of the tamarind fruits was measured as 19% (d.b). The moisture reduction was measured at every ten minutes interval manually throughout the drying period with the help of an electronic weighing balance (Contech Instruments Ltd., India; sensitivity 0.01g).

The moisture content of the fresh tamarind fruit on dry basis was calculated using Eq. (1) as proposed by Poonia *et al.*[29]

$$M_I = \frac{W_I - W_F}{W_F} x100 \qquad \text{... (1)}$$

where, M_I denotes the moisture content of the fresh tamarind fruit at the start of drying process on dry basis (%), W_I and W_F represent the initial weight and final weight of tamarind fruits (kg).

The rate of drying (D_R) of tamarind fruits was calculated from moisture content data using Eq. (2) as reported by Bozkir.[15]

$$D_R = \frac{M_{t+\Delta t} - M_t}{d_t} \qquad \text{... (2)}$$

where, D_R represent the rate of drying in kg/min, $M_{t+\Delta t}$ and M_t denote the moisture contents at time t+Δt and t in min (kg water/kg d.m), d_t denotes the drying time in min.

Symbolic Modelling of Drying Curves

The Moisture Ratio (MR) of tamarind fruit was determined from the following Eq. (3) during the drying studies as followed by Kaveh *et al.*[30]

$$MR = \frac{M_T - M_E}{M_I - M_E} \qquad \text{... (3)}$$

where, M_T, M_E and M_I denote the moisture content of tamarind fruits at any time, equilibrium moisture content and initial moisture content, respectively (kg H_2O/ kg d.m).

The most frequently used thin layer drying equations are Page, Lewis, Logarithmic, Midilli, Wang and Singh and Henderson-Pabis. These equations have been fitted to define the drying processes in various agricultural commodities such as in tomatoes by Coskun *et al.*[17] Bozkir[15] for oranges, Walame & Kotwal[31] for mint leaves, Michalska *et al.*[32] for plum powder and Junior *et al.*[20] for tamarind seeds. Four well-known thin layer drying equations were used in this study to represent the drying phenomenon of tamarind fruits. The empirical thin layer drying equations used in this study are listed in Table 1.

To fit the drying curve and model the parameters, MATLAB – Math Works Statistical Software (R2013b, The Mathworks, Inc., Natick, MA, USA) was used to perform the nonlinear regression analyses with curve fitting tool.[33,34] The models performance to describe the drying behavior of tamarind fruits was evaluated based on the criteria such as coefficient of determination (R^2), percentage of Root Mean Square Error (RMSE) and reduced Chi-square (χ^2).[22] The best model to describe the drying kinetics of tamarind was selected based on the lowest RMSE value and reduced Chi square value (χ^2) and highest R^2 value.[35] These statistical parameters were calculated as in Eqs. (4 – 6):[(15,36)]

$$\chi^2 = \frac{1}{N-n}\sum_{i=1}^{n}(MR_{\exp,i} - MR_{pred,i})^2 \qquad \text{… (4)}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pred,i})^2\right]^{1/2} \qquad \text{… (5)}$$

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

where, $MR_{exp,I}$ represents the i^{th} experimentally observed moisture content and $MR_{pred,i}$ is the i^{th} predicted moisture content, N denotes the total number of observations and n signifies the number of constants in the drying models.

Physicochemical Analysis

The standard hot air oven method as described in AOAC[37] was applied to determine the moisture

Table 1 — Thin layer drying kinetic models for tamarind fruits

Model name	Model equation
Logarithmic	MR = aexp (−kt) + c[15,73]
Two Term	MR = aexp (−bt) + cexp(−dt)[20,22,74]
Wang & Singh	MR = 1 + at + bt^2[(75,76)]
Modified Midilli	MR = a exp (−kt) + b[77,78]

content. The tamarind color values were measured by means of a Hunter Lab Color meter (Hunter Lab, Reston, Virginia, USA) and the color values were exhibited in terms of L*, a*, and b*. The titratable acidity of tamarind fruit was measured as per the procedure given in AOAC[38], the Total Soluble Solids (TSS) and pH values were obtained from digital handheld refractometer (Hanna Instruments, India, Model: HI 96801) and a digital bench top pH meter (Hanna Instruments, India, Model: HI 2209) by following the standard procedures.

Statistical Analysis

Triplicate samples were evaluated and the results were reported as mean ± SD (standard deviation). The statistical analyses of the data were evaluated by analysis of variance (ANOVA) and Duncan's multiple range test in SPSS 20.0 software to determine the differences in statistical significance in the drying parameters at a significance level of $p \leq 0.01$.

Results and Discussion

Drying Kinetics of Dehulled Tamarind Fruit

Analysis of Moisture Content

The moisture content curve of tamarind fruits dried at 50, 60 & 70°C exposed to the hot air velocities of 0.5, 1.0 and 1.5 m/s is reported in Fig. 2. The final moisture content of tamarind fruits was 11.84, 11.68 and 11.57% (d.b.), respectively at 0.5, 1.0 and 1.5 m/s air velocities. The duration of drying tamarind fruits varied in the range of 60 to 140 minutes to attain the final moisture content at different temperatures and air velocities. Based on the moisture content data, it is inferred that using a higher air velocity, significantly reduced the moisture content. It was also found that the reduction in moisture content was lowered with increased feed rates. For tamarind fruits dried at 60°C, exposed with 0.5 m/s air velocity, the results indicated that as the drying time increased there is a continuous reduction in moisture content from 19% (d.b.) to 11.78% (d.b.), whereas the moisture contents were found to be 11.5, and 11.35, (d.b.), respectively at the air velocities of 1.0 and 1.5 m/s. From this figure, it could be inferred that the air velocity of tamarind fruits significantly influenced the drying time. The air velocity showed an important effect on the moisture content during the drying process. By increasing the air velocity increased the reduction in moisture content. The moisture content results obtained for drying tamarind fruits are in agreement with the earlier research study on thin-layer drying of carrot slices as reported by Sonmete *et al.*[22] and Gowda *et al.*[39] for red gram.

The moisture content variations of tamarind fruits dried at 70°C, exposed with 0.5, 1.0 and 1.5 m/s air velocities are presented in Fig. 2. The moisture content variations were found to be 11.73% (d.b.) at 0.5 m/s, 11.57% (d.b.) at 1.0 m/s and 11.14% (d.b.) at 1.5 m/s, respectively. Whereas in sun drying, the time required to dry tamarind from an initial value of 19.0% (d.b.) to a final value of 11.91% (d.b.) was 24 h (8 hours of drying per day) with a moisture reduction of around 3% (d.b.) on each day and is depicted in Fig. 3. The black dot on the Fig. 3 indicates the end of drying on each day which is interrupted due to the non-availability of the sun in the evening.

From the Fig. 2, it is evident that using high temperatures of 70°C and high air velocity of 1.5 m/s, decreased the drying time to 60 min, whereas drying at a low temperature of 50°C with 0.5 m/s air velocity, found to have the longest drying period (140 min). This is because at higher drying temperatures more heat was supplied to the tamarind fruits,[40] the driving force for water vaporization was

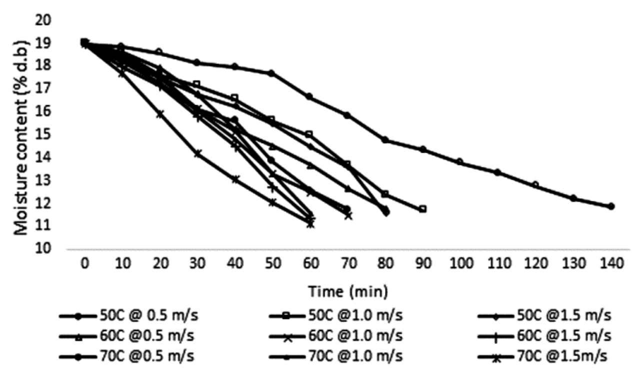

Fig. 2 — Moisture content curve of tamarind fruits dried at 50, 60 & 70°C exposed to the hot air velocities of 0.5, 1.0 and 1.5 m/s

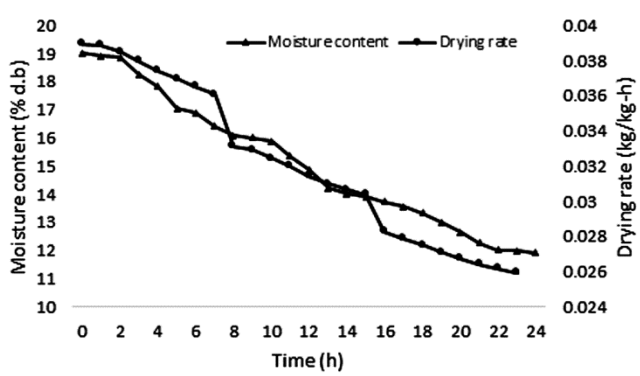

Fig. 3 — The moisture content variations of tamarind fruits dried at 70°C, exposed with 0.5, 1.0 and 1.5 m/s air velocities

also higher, which lead to faster drying of food materials.[41] Similar results were documented by Tajudin *et al.*[42] in roselle calyx drying, Srinivas *et al.*[43] for nutmeg mace, Jeevarathinam *et al.*[44] for turmeric slices and Richa *et al.*[45] for fish where the drying time was lesser at increased drying air temperatures.

Analysis of Drying Rate

The drying rate curve of tamarind fruits at different temperatures and air velocities is depicted in Fig. 4. At 50°C, the average drying rate (in kg/kg dry matter min) was determined as 0.0745 at air velocity of 0.5 m/s, 0.0768 at air velocity of 1.0 m/s and 0.0790 at air velocity of 1.5 m/s, respectively. At the drying temperature of 60°C the average drying rate of tamarind fruits were calculated as 0.0782 kg/kg d.m. min for the air velocity of 0.5 m/s, and for the air velocity of 1.0 m/s it was 0.0786 kg/kg d.m. min and whereas the drying rate was 0.0800 for 1.5 m/s air velocity, respectively. Whereas at 70°C, the average drying rate obtained at 0.5 m/s air velocity was 0.0702 kg/kg d.m. min, at 1.0 m/s it was 0.0802 kg/kg d.m. min and at 1.5 m/s it was 0.0806 kg/kg d.m. min, respectively. Whereas, in sun-drying of the tamarind fruit, the average drying rate obtained was 0.0335 kg/kg d.m. hour (Fig. 3). It is evident that the rate of drying of tamarind fruits increased with an increase in drying temperature at different air velocities. At all conditions, the drying rate was found to be faster at the start of the drying experiment and slows down constantly as the drying proceeds. Thus the falling rate of drying was observed in drying of tamarind fruit which is mainly controlled by diffusion process.[46] The rate of drying was higher during the initial period and this is because of the evaporation of free moisture due to the larger differences in moisture content of tamarind fruit and the equilibrium moisture content of dry air.[47,48] Indeed, the drying rate at the latter stages was found to be lower compared to the initial stages and this was due to the migration of bound moisture by diffusion process at a slower rate to the outer surface of the tamarind fruits. Similar results of lowered drying rate were reported for powder from fruits and vegetables by Karam *et al.*[49] and by Jeevarathinam *et al.*[50] for drying turmeric. The drying rate of tamarind fruit was mainly affected by hot air temperatures and air velocities of the tamarind fruits. Furthermore, as the air velocity increases, convection rate and moisture diffusion rate increases, thereby increasing the drying rate.

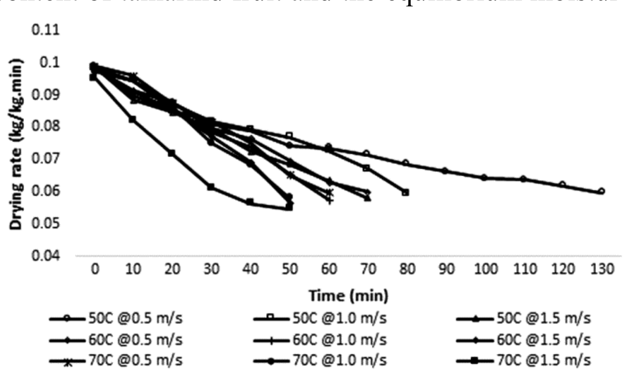

Fig. 4 — The drying rate curve of tamarind fruits at different temperatures and air velocities

From Fig. 4, it can be inferred that the average rate of drying was observed to be higher at higher temperature (70°C) and air velocity (1.5 m/s) due to the faster removal of moisture at the early stages and lowered at the falling rate drying period due to lower rate of bound moisture diffusion to the surface.[51,52] Similar results were obtained during the drying of Kothimbda (*Cucumis callosus*) with different slice thicknesses and feed rates.[53]

Fitting of Thin Layer Drying Equations

The drying parameters of tamarind fruit were exemplified by the behavior of moisture as a function of hot air temperature and air velocity. The effects of all drying process factors *i.e.* drying temperature, and air velocity on the drying models and its results are given in Table 2. The experimentally obtained moisture ratio values were used to evaluate the four models (Logarithmic, Two-term, Wang and Singh, Modified Midilli). The highest R^2 value and the lowest χ^2 and RMSE value are used to determine the goodness of fit of the thin layer drying models. The Wang and Singh model exhibited the highest value of R^2 which ranged from 0.9998 to 0.9772 for all the drying experiments conducted in this study. The χ^2 and the RMSE value for the Wang and Singh model varied from 0.00854 to 0.00012 and 0.06316 to 0.005264, respectively. From the tables, it is evident that the Wang and Singh model exemplifies the drying behavior of tamarind fruits in a better manner than the other models (Logarithmic, Two-term and Modified Midilli). This is similar to the observations of Pei *et al.*[54] for vacuum microwave drying of mushrooms and drying of red apple slices at 55, 65 and 75°C by Doymaz.[55] The highest R^2 (0.9998), lowest χ^2 (0.00012) and RMSE (0.005264) was obtained for the Wang and Singh model at a drying temperature of 60°C with an air velocity of 1.0 m/s

Table 2 — Statistical results of thin layer drying models used to predict drying behaviour of tamarind fruits

Model	Air velocity (m/s)	50°C				60°C				70°C			
		R^2	RMSE	Constants	χ^2	R^2	RMSE	Constants	χ^2	R^2	RMSE	Constants	χ^2
Logarithmic[15,73]	1.5	0.9954	0.02592	a = 0.8922 k = 0.1105 c = 1.005	0.00017	0.9863	0.06081	a = 0.08393 k = 0.1778 c = 1.028	0.00028	0.9706	0.0899	a = 0.4903 c = 0.9552 k= 0.08988	0.00087
	1.0	0.9820	0.05846	a = 0.07456 k = 1.507 c = 1.052	0.00035	0.9822	0.06783	a = 0.766 k = 0.2693 c = 1.045	0.00054	0.9839	0.0631	a=-0.06313 c = 1.058 k = -0.3279	0.00083
	0.5	0.9761	0.06458	a = 0.3859 k = 0.7398 c = 1.094	0.00020	0.9818	0.06147	a = 1.07 c = 1.043 k = 0.4771	0.00029	0.986	0.05481	a = 0.3544 c = 1.05 k = -0.1521	0.00020
Two term model[20,22,74]	1.5	0.9954	0.03346	a = 0.7918 b=−0.01701 c = 0.9631 d = 1.171	0.00024	0.9863	0.1053	a = 1.436 b=−0.1359 c = 2.316 d = 2.261	0.00047	0.9706	0.1557	a = 1.053 b = -0.1042 c = 0.8762 d = -3.867	0.00024
	1.0	0.9820	0.0716	a=-0.02139 b = 0.6591 c = 0.9646 d = 1.031	0.00101	0.9822	0.09592	a = 0.6212 b = −0.0279 c = 1.031 d = 1.134	0.00121	0.9839	0.1093	a = 0.5332 b =0.03963 c = -0.7208 d = -0.9844	0.00022
	0.5	0.9761	0.07139	a=−0.03267 b = 0.3014 c = 0.9994 d = 1.254	0.00070	0.9818	0.07936	a = 0.4118 b = 0.04635 c = 1.004 d = 1.23	0.00080	0.986	0.07752	a = 0.7605 b=-0.01937 c = 1.004 d = 0.9829	0.00074
Wang and Singh[75,76]	1.5	0.9965	0.01917	a =−0.01013 b = 0.000012	0.00044	0.9795	0.05944	a = −0.00914 b = −0.000117	0.00024	0.9927	0.0346	a=−0.02414 b=0.00012	0.00504
	1.0	0.9885	0.04043	a = 0.007956 b = −0.00004	0.00064	0.9998	0.005264	a = −0.01312 b = −0.000027	0.00012	0.9865	0.04675	a=−0.01452 b= 0.000036	0.00074
	0.5	0.973	0.06316	a = −0.005065 b = −0.000019	0.00074	0.9777	0.05751	a = −0.0116 b = −0.000027	0.00061	0.9913	0.03533	a = −0.00982 b = −0.00006	0.00854
Modified Midilli[77,78]	1.5	0.9954	0.02592	a = 0.8915 b = 1.005 k = 0.1124	0.00015	0.9863	0.06081	a = 0.1126 b = 1.028 k = 0.1492	0.00011	0.9706	0.0899	a = 0.4903 b = 0.9552 k= 0.08988	0.00011
	1.0	0.982	0.05846	a = 0.2816 b = 1.052 k = 0.8968	0.00028	0.9822	0.06783	a = 0.766 b = 1.045 k = 0.2693	0.00021	0.9839	0.0631	a = 0.2706 b = 1.058 k = 0.6535	0.00018
	0.5	0.9761	0.06458	a = 0.5369 b = 1.094 k = 0.6563	0.00016	0.9818	0.06147	a = −0.5955 b = 1.043 k = 0.1519	0.00016	0.986	0.05481	a = 0.4303 b = 1.05 k = −0.1005	0.00016

R^2 denotes Coefficient of Determination, RMSE denotes Root Mean Square Error and χ^2 denotes Chi square

Table 3 — Quality characteristics of dried tamarind fruits

Temperature (°C)	Air velocity (m/s)	L*	a*	b*	TSS (^{o}brix)	Titratable acidity (%)	pH
50	0.5	$52.3^{¥} \pm 1.55^{§a}$	2.2 ± 0.05^{g}	15.4 ± 0.36^{b}	23.5 ± 0.03^{d}	15.1 ± 0.67^{d}	3.9 ± 0.06^{a}
50	1.0	50.5 ± 0.27^{ab}	2.4 ± 0.01^{e}	13.5 ± 0.13^{c}	23.8 ± 0.90^{d}	15.6 ± 0.07^{cd}	3.8 ± 0.04^{a}
50	1.5	49.5 ± 1.29^{bc}	2.9 ± 0.01^{e}	11.5 ± 0.12^{d}	24.4 ± 0.26^{d}	17.8 ± 0.74^{b}	3.6 ± 0.11^{b}
60	0.5	48.3 ± 1.48^{c}	2.4 ± 0.02^{f}	19.9 ± 0.77^{a}	24.5 ± 1.03^{d}	16.1 ± 0.22^{c}	3.5 ± 0.09^{b}
60	1.0	44.3 ± 1.16^{d}	3.5 ± 0.11^{d}	13.2 ± 0.15^{c}	25.6 ± 1.00^{c}	17.4 ± 0.58^{b}	3.1 ± 0.08^{c}
60	1.5	43.2 ± 1.36^{de}	3.9 ± 0.11^{c}	10.2 ± 0.12^{e}	26.9 ± 0.12^{c}	19.1 ± 0.83^{a}	2.7 ± 0.01^{d}
70	0.5	44.5 ± 0.04^{d}	3.9 ± 0.02^{c}	13.1 ± 0.40^{c}	25.7 ± 0.83^{b}	17.2 ± 0.47^{b}	3.1 ± 0.13^{c}
70	1.0	42.0 ± 0.83^{e}	4.1 ± 0.14^{b}	11.9 ± 0.10^{d}	27.5 ± 0.51^{ab}	18.0 ± 0.34^{b}	2.4 ± 0.05^{e}
70	1.5	38.7 ± 1.08^{f}	4.5 ± 0.20^{a}	9.5 ± 0.05^{f}	28.3 ± 1.22^{a}	19.1 ± 0.40^{a}	1.7 ± 0.07^{f}
Fresh tamarind		65.5 ± 1.43	1.5 ± 0.03	27.5 ± 0.86	12.3 ± 0.01	8.1 ± 0.20	4.1 ± 0.01
Sun dried tamarind		60.5 ± 0.57	2.7 ± 0.01	25.5 ± 0.45	13.8 ± 0.15	7.8 ± 0.22	2.8 ± 0.08

$^{¥}$ represents the mean value; § signifies the standard deviation; superscripts (^{a} to ^{s}) denotes the significant differences within columns ($p \leq 0.01$)

for the tamarind fruits dried in the tray dryer respectively. Moreover, the similar results were reported in earlier studies for infrared drying of carrot slices by Doymaz[56] and vacuum infrared drying of orange slices.[15]

Quality Analysis of the Dried Tamarind Fruit

The color values of tamarind fruits during drying are reported in Table 3. There exists a significant difference at $p \leq 0.01$, for the color values L*, a* and b* of tamarind fruit dried at different temperatures (50, 60 and 70°C) and air velocities (0.5, 1.0 and 1.5 m/s). It is evident from the table that compared with fresh and sun-dried samples, the optimized hot air-dried samples (60°C and 1.0 m/s) showed the L* and b* values decreased at higher temperatures. In contrast, a* value increased at higher temperature of drying. The color values L*, a* and b* of fresh and sun-dried tamarind fruits are found to be 65.5, 1.5, and 27.5 and 60.5, 2.7 and 25.5, respectively. The L* value ranged from 38.7 to 52.3 for all the drying conditions compared to sun-dried tamarind fruits

(60.5). The effect of drying conditions on L* value of tamarind fruits was statistically significant at $p \leq 0.01$. As the drying temperature and hot air velocity increased, the L* value of the tamarind fruit decreased due to higher heat exposure. Furthermore, drying of tamarind exhibited a change in deep brown or black color at higher temperatures and this is because of pigment formation due to Maillard reaction.[57] Regarding color, L* is a vital factor for any drying process since bright/clear tamarind is usually attributed to the prime quality for consumer's acceptance.[58] Reduction in L* value or brightness in tamarind fruit during the drying process may be attributed to the Maillard reaction occurred by the chemical changes in amino acids and reducing sugars. At higher temperatures, especially non-enzymatic browning is hastened up.[59]

Compared to fresh and sun-dried samples, the optimized hot air-dried samples showed an increment in the a* value of samples dried at different drying conditions. There was a significant difference ($p \leq 0.01$) on a* value of tamarind fruits among the different drying conditions. The maximum and minimum a* values of 4.5 and 1.5 were observed at 70 and 50°C temperature respectively at 1.5 and 0.5 m/s air velocity. The increase in a* value indicated that the color change of tamarind fruit from reddish-brown to deep brown on prolonged exposure resulted in the formation of pigments during the drying study.[60] Similar to present results, Dereje & Abera[61] reported that the highest redness was observed in mango slices at higher drying temperatures. Takhellambam & Bharati[62] also reported the color change of tamarind fruit pulp under prolonged exposure to temperature and humidity.

A decrease in yellowness (b* value) was observed in dried tamarind fruit than that of fresh (27.5) and sun dried (25.5) samples as displayed in Table 3. The b* value of tamarind fruits dried at different temperatures and air velocities are found to be statistically significant ($p \leq 0.01$). The yellow color (b*) of dried products is intensely affected by temperature of the hot air and the relative humidity of the drying air.[63] The b* value at a drying temperature of 50°C ranged from 15.4 to 11.5, at 60°C it was from 19.9 to 10.2 and at 70°C it was found to be 13.1 to 9.5 at different air velocities. As the temperature and velocity of the drying air increased, b* value of the product drastically decreased, this might be attributed due to the destruction of the yellow pigment. The higher retention of carotenoids in fresh and sun-dried tamarind fruits contributed to the higher b* value.[64] Obulesu & Bhattacharya[57] reported Similar findings of color change in tamarind fruit from light brown to dark brown. The results of total soluble solids, titratable acidity and pH values of the dried tamarind fruits under different drying conditions are shown in Table 3. The fresh tamarind fruits contain a TSS of 12.3°brix and it varied from 23.5 to 28.3°brix in all drying combinations and the effect of drying parameters on total soluble solids was statistically significant ($p \leq 0.01$). Mwamba *et al.*[65] reported that solar dried and hot air oven-dried mango slices had a total soluble solids value of 22.36 to 52.02°brix. Similarly, Sinha & Choudhary[66] obtained a TSS value of 13.81 and 15.79°brix for sun-dried and hot air-dried tamarind fruits. The TSS of tamarind fruits using the convective drying method was observed to be higher than the fruits dried under sun drying method. It is evident that the total soluble solids of tamarind fruits increased with the increase in drying air temperature and velocity. The increase in TSS value is associated with the increase in the concentration of solids in the tamarind fruits because of the water reduction during the drying process. Furthermore, the increase in total soluble solids might be due to the modifications in the structure of the cell wall and also by the breakdown of complex carbohydrates into simple sugars.[67]

The titratable acidity of fresh and dried tamarind fruits at all drying combinations was determined as 8.1% and in the range of 15.1 to 19.1%, respectively. In all drying combinations, the drying parameters had statistically significant ($p \leq 0.01$) values of titratable acidity for tamarind fruits. The titratable acidity values of the dried tamarind fruits at 50, 60 and 70°C increased during the drying processes. Dereje & Abera[61] stated that the titratable acidity of sliced mangoes increased in tray dried sample (2.41 g/100g) at 70°C than the solar-dried mango slices with a titratable acidity value of 2.20 g/100g at a drying temperature ≤ 50°C. The titratable acidity of tamarind fruits dried using a convective dryer was found to be higher than sun-dried tamarind fruits. This shows that the acid value of tamarind fruits is less affected by heat, light and oxygen.[15] A significant difference at $p \leq 0.01$ was observed for the titratable acidity values of tamarind slices dried at 50, 60 and 70°C of hot air temperatures, air velocities of 0.5, 1.0 and 1.5 m/s, respectively. The pH value of the dried tamarind fruits was in the range of 3.9 to 1.7 at different drying temperatures and air velocities and these are in accordance with the values of 3.4 to 2.8 as reported by Rahman *et al.*[68] for dried tamarind leathers. The results from the table showed that the pH of fresh tamarind fruits reduced from 4.1 to 2.8 in sun-dried method. This reduction in pH might be due to the decrease in water content of the tamarind fruits during drying which in turn concentrated the organic acids.[69] The effect of drying temperature, air velocity and feed rate on the pH value of tamarind fruits is statistically significant ($p \leq 0.01$). As the hot air temperature increases, the pH value decreases, this could be due to the breakdown of carbohydrates and proteins. Furthermore, the low pH value extends the shelf stability of tamarind fruits by preventing microbial spoilage.[70–72]

Conclusions

The results revealed that a tray drying may be used with optimized drying conditions for efficiently drying the tamarind fruits with a minimal loss of quality. The hot air drying method (60°C and 1.0 m/s) reduced the drying time (60 min) and preserved the quality characteristics (colour and total soluble solids) of tamarind fruits compared to sun drying (24 hrs) method. The maximum quality characteristics were retained at the drying conditions of 60°C and 1.0 m/s, respectively. Wang and Singh model could be used to predict the drying characteristics of tamarind fruits.

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Conflict of Interest

The authors declare no conflict of interest.

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