Mathematical modeling on drying of *Syzygium Cumini* (L.)

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Abstract: In this study, drying characteristics of *Syzygium cumini* was experimentally investigated under the temperatures of 50℃, 60℃ and 70℃ and the mathematical models were used to fit the drying of *Syzygium cumini*. Moisture transfered from *Syzygium cumini* was described by applying the Fick's diffusion model and the effective moisture diffusivity was calculated. The temperature dependence of the effective moisture diffusivity for the drying of *Syzygium cumini* samples was described by an Arrhenius-type relationship with activation energy. Drying data were fitted to seven drying models, namely Lewis, Henderson and Pabis, Logarithmic, Twoterm, Page, Wang and Singh and modified Henderson and Pabis. The Logarithmic model was found as the best fitted model in describing the drying behavior of *Syzygium cumini*.

Keywords: activation energy, drying, effective moisture diffusivity, mathematical model, *Syzygium cumini*

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1 Introduction

Syzygium cumini (L.) is an evergreen tropical tree in the flowering plant series that belongs to the plant family Myrtaceae, with surplus medicinal values. It is native to India and Indonesia. It is also grown in other areas of Southeast Asia including Malaysia, Myanmar, Pakistan and Afghanistan. The other common names of *Syzygium cumini* are jamun, java plum, jambul and Indian blackberry. Syzygium cumini, a fairly fast growing species, can reach heights of up to 30 m and can live for more than 100 years. *Syzygium cumini* is always appreciated for the color, flavor and taste of its fruit. The extracts of the bark, seeds and leaves are used for the treatment of diabetes. A decoction of the bark and powdered seeds is believed to be very useful in the treatment of diarrhea, dysentery and dyspepsia. Recently, the plant extract of *Syzygium cumini* used for the prevention of diabetes[1]. Also, *Syzygium cumini* fruit is one of those that contain a variety of important nutritional compositions. For instance, the fruit syrup is very useful in curing diarrhea. It also cures stomachache and act as carminative and diuretic, apart from having cooling and digestive properties[2].

Syzygium cumini is a berry consisting of a single seed surrounded by a fleshy pulp and the fruit skin. *Syzygium cumini* is unique in that it constitutes a set of properties and characteristics, which distinguishes it from all major fruits. *Syzygium cumini* has significance as a stable food as well as an ornamental fruit plant, whilst their use in industrial applications could be increased. According to variety and growth conditions, *Syzygium cumini* varies in shape, size and weight. Usually they are elliptical and ovoid shape though certain varieties may reach a near round shape.

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Syzygium cumini have very short shelf-life since they are highly perishable. To extend their shelf life, drying can be suggested as one of the best option. Dried fruits having a very long self-life can replace the fresh fruits, allowing the availability during off season[3]. To minimize biochemical, chemical and microbiological deterioration, one of the best industrial preservation methods is drying, in which the water content of fruits and vegetables are reduced by heated air. The major advantages in drying agricultural products are the reduction of their moisture content to a level, which allows safe storage over an extended period, minimizing packaging requirements and lower shipping costs due to the reduced weight[4]. Numerous drying methods are available that are used to remove moisture from a wide variety of food products, fruits and vegetables. The most common method is the sun drying that is used to preserve agricultural products. This method of preservation is very cheap because it uses a natural source of heat sunlight. The major disadvantages of this method of drying are the slowness of the process, the exposure to environmental contamination, the unstable monsoon, insect infestation and the manual labor requirements[5,6]. The sun drying technique should be replaced with industrial drying methods such as solar and hot air drying for the improvement of the best quality of products[7-9]. The objectives of this study were to 1) investigate the effect of the temperature on the drying kinetics; 2) to estimate the effective diffusivity and activation energy from the drying conditions; 3) to select the best mathematical model for the drying curves.

2 Materials and methods

2.1 Sample preparation

Fresh and fully matured *Syzygium cumini* were collected from the gardens which are located in and around areas of Erode, Tamil Nadu, India, during June to September, 2012. After that those fruits were weighed about 150 g.

2.2 Drying procedure

Tray dryer consists of heating elements that are placed in ribs at the sides with double walled inside with anodized aluminum/stainless steel. The door has synthetic rubber gasket. Outside mild steel is painted with epoxy powder coating with perforated adjustable shelves and work on (220/230) volts A.C, with one number air circulating fan and digital temperature controller cum indicator. The air temperatures to be used for drying are 50℃, 60℃ and 70℃. The initial moisture content of *Syzygium cumini* was 121.5% and it was monitored every 30 minutes until constant mass was observed. The electronic balance used to monitor the mass of drying samples was of 0.01 g precision. Three drying replicates will be performed and the mean result will be used for the calculation of drying kinetics.

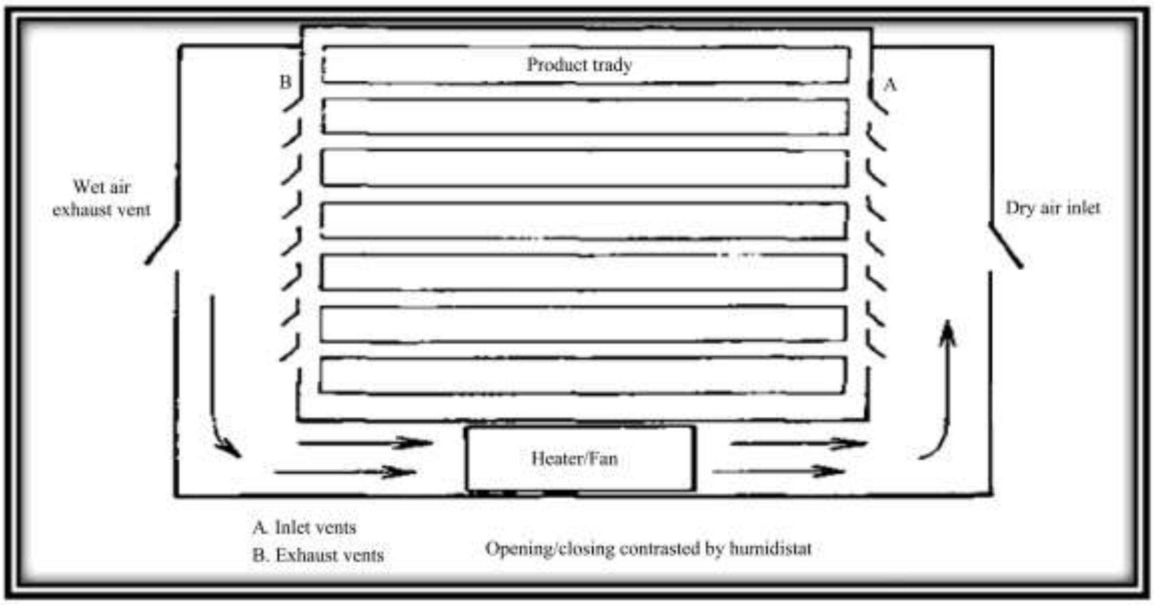

Figure 1 Schematic diagram of tray dryer

2.3 Mathematical modeling of drying curves

The moisture ratio (*MR*, dimensionless) and drying rate of the *Syzygium cumini* was calculated using the following equations:

$$MR=\frac{M-M_e}{M_o-M_e} \tag{1}$$

$$Drying\ rate=\frac{M_{t+dt}-M_t}{dt} \tag{2}$$

where M, M_o, M_e, M_t and M_{t+dt} are the moisture contents at any time of drying, initial moisture content, equilibrium moisture content, moisture content at t and moisture content at $t+dt$ (kg water/kg dry matter), respectively. The equilibrium moisture contents of *Syzygium cumini* at different temperatures used in the drying runs were obtained by the dynamic model. About 5 g samples were exposed to 50, 60 and 70℃ air temperatures in the dryer until the weight loss of sample remained constant. Then, the equilibrium moisture content of the samples were determined and used to calculate the moisture ratio. The drying curves were fitted by means of seven different moisture ratio models that are widely used for most food and biological materials; Table 1 shows the models to select the best model for describing the drying curve of the black plum.

Table 1 Drying models used for mathematical modeling

Model name	Model	References
Lewis	$MR=\exp^{-kt}$	[10]
Henderson and Pabis	$MR=a\exp^{-kt}$	[11]
Logarithmic	$MR=a\exp^{-kt}+c$	[12]
Two term	$MR=a\exp^{-k_0t}+b\exp^{-k_1t}$	[13]
Page	$MR=\exp^{-kt^n}$	[14]
Wang and Singh	$MR=1+at+bt^2$	[15]
Modified Henderson and Pabis	$MR=a\exp^{-kt}+b\exp^{-gt}+c\exp^{-ht}$	[12]

In the proposed models, a, b, c, n are the drying coefficients and k is the drying constant (per minute). There are different empirical and theoretical models described in the literature and used to fit the drying kinetics of foodstuffs[16,17]. Even if the applicability of a given model depends on the type of material and on the mechanisms occurring during the drying process, it is often indicated that the above listed models are commonly used to describe the kinetics of fruits and to design industrial dryers[18,19]. So, these models were used to fit the kinetics of *Syzygium cumini*.

2.4 Data analysis

Non-linear least square regression analysis was performed using the Levenberg-Marquardt procedure in the Sigma Plot computer program. The determination of coefficient (R^2) was the primary criterion for selecting the best model to describe the drying curve. In addition, the reduced chi-square (χ^2) and root mean square error (*RMSE*) were used to evaluate the goodness of fit. These parameters can be calculated by using the following equations:

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

$$RMSE=\left[\frac{1}{N}\sum_{i=1}^{N}(MR_{pre,i}-MR_{exp,i})^2\right]^{1/2} \tag{4}$$

In these equations, N is the number of observations, z is the number of constants, $MR_{\exp,i}$ and $MR_{pre,i}$ are the i^{th} experimental and predicted moisture ratios, respectively. The model was considered best when *RMSE* and χ^2 were at a minimum value and R^2 at a maximum value (nearing one) [7,20,21].

2.5 Determination of effective moisture diffusivity

Drying process of food materials generally occurs in the falling rate period[22]. To predict the moisture transfer during the falling rate drying period, several mathematical models have been proposed using Fick's second law. By using Fick's second law and considering the following assumptions[23], proposed Equation (5) for the effective moisture diffusivity for an infinite slab.

1) Moisture is initially distributed uniformly throughout the mass of a sample.

2) Mass transfer is symmetric with respect to the centre.

3) Surface moisture content of the sample instantaneously reaches equilibrium with the condition of surrounding air.

4) Resistance to the mass transfer at the surface is negligible compared to internal resistance of the sample.

5) Mass transfer is by diffusion only.

6) Diffusion coefficient is constant and shrinkage is negligible.

$$MR = \frac{M}{M_o} = \frac{8}{\pi^2}\sum\frac{1}{(2n-1)^2}exp^{\frac{(2n-1)^2\pi^2 Dt}{4r^2}} \tag{5}$$

where, *MR* is moisture ratio; *M* is the moisture content at any time (kg water/kg dry matter); M_o is the initial moisture content (kg water/kg dry matter), n = 1, 2, 3… is the number of terms taken into consideration; *t* is the time of drying in second; *D* is effective moisture diffusivity in m^2/s and r is the radius (m).

For longer drying time, in the Equation (5), n=1 is used[24].

Hence

$$MR = \frac{M}{M_o} = \frac{8}{\pi^2}exp^{\frac{\pi^2 Dt}{4r^2}} \tag{6}$$

2.6 Computation of activation energy

The energy of activation will be calculated by using an Arrhenius type equation[24,25]:

$$D = D_0 exp(E_a/RT) \tag{7}$$

where, E_a is the energy of activation (kJ/mol); R is universal gas constant (8.3143 kJ/mol); T is absolute air temperature (K); and D_0 is the Pre-exponential factor of the Arrhenius Equation (m^2/s). The activation energy can be determined from the slope of the Arrhenius Equation (m^2/s).

From Equation (7), a plot of ln D against $1/T$ gives a straight slope of K_1

$$K_1 = E_a/R \tag{8}$$

3 Results and discussion

3.1 Drying characteristics

The *Syzygium cumini* fruits were dried at the different temperatures of 50, 60 and 70℃ in a tray dryer. The variations in moisture content of the *Syzygium cumini* as a function of drying time at different temperature are presented in Figure 2. It can be observed that the moisture content of the *Syzygium cumini* decreased with the increase in drying time. The rate of moisture loss was higher at higher temperature and then total drying time reduced substantially with the increase in air temperature. From the Figures 3 and 4 the drying rates also increased with the increase in drying air temperature. Drying of *Syzygium cumini* occurred in falling rate period and no constant rate period was observed[26]. Drying in falling rate period indicates that, internal mass transfer has occurred by diffusion. It took 14 h to dry *Syzygium cumini* samples from initial moisture content of 425.21 kg water/kg dry matter to a final moisture content of 57.56 kg water/kg dry matter at 70℃ of drying air temperature, and it took 22 h at 60℃ and 46 h at 50℃, respectively. It indicated that increasing the drying temperature decreases the drying time[27,28].

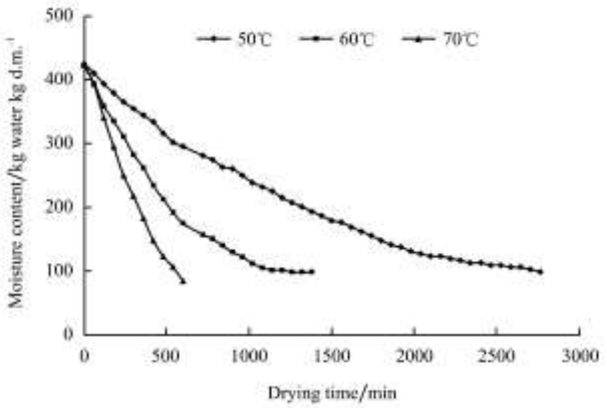

Figure 2 Effects of drying air temperatures at 50, 60 and 70℃ and drying time on the moisture content of *Syzygium cumini*

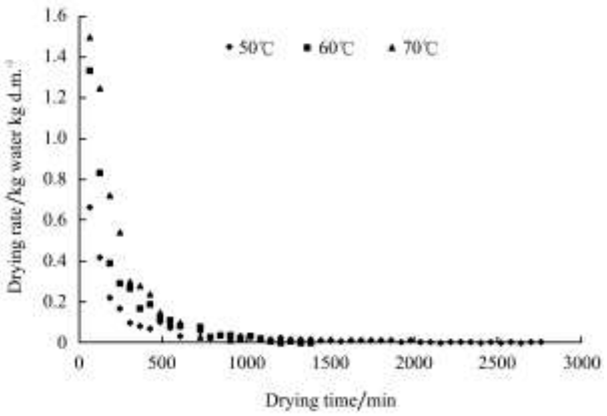

Figure 3 Drying rate changes with moisture ratio of *Syzygium cumini* at 50, 60 and 70℃

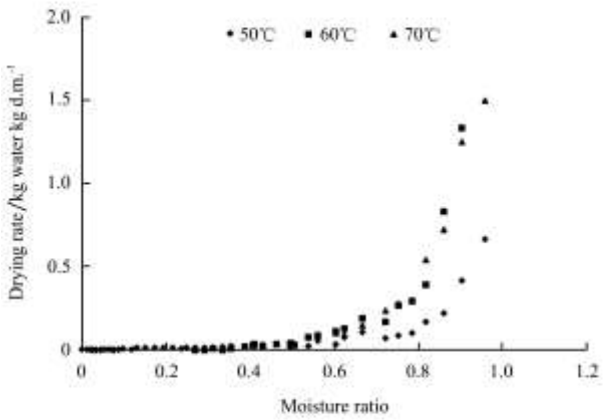

Figure 4 Drying rate changes of *Syzygium cumini* with drying time at 50, 60 and 70℃

3.2 Moisture diffusivity and activation energy

The moisture diffusivity values are 1.67×10^{-6}, 3.69×10^{-6}, and 5.75×10^{-6} m^2/s for the samples dried at 50, 60, and 70℃ drying air temperatures, respectively. In Figure 5 it was noted that diffusivity increased progressively with the increase in drying air temperature. This might be explained by the increased heating energy, which would increase the activity of water molecules. When samples are dried at higher temperature, activity of water molecules leads to higher moisture diffusivity[29]. This finding is similar to the study of Hayaloglu et al.[30] for drying strained yogurt using a convective type tray-dryer[31].

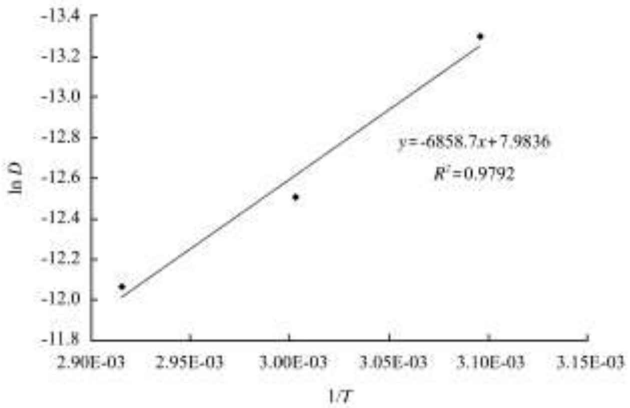

Figure 5 Plot of ln D versus $1/T$ for calculating the activation energy

Temperature dependence of the effective moisture diffusivity values is described by an Arrhenius-type relationship. The activation energy values are determined as 30.23, 28.46 and 27.67 kJ/mol, respectively by plotting a graph between ln D and $1/T$ as shown in Figure 6. The values of activation energy lie within the general range of 12.7-110 kJ/mol for food materials[32].

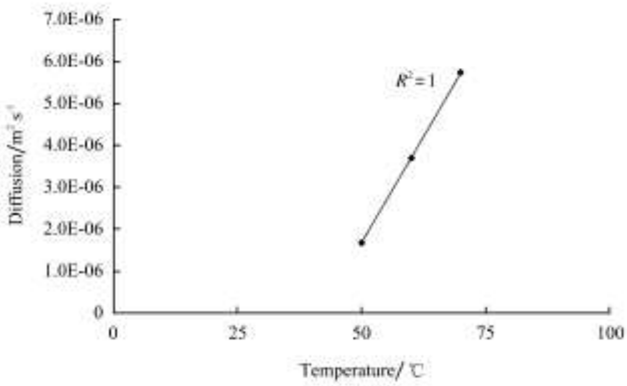

Figure 6 Influence of the drying air temperature on the diffusion coefficient

3.3 Mathematical modeling

The experimental moisture content data on a dry weight basis of *Syzygium cumini* at different drying temperatures curve are converted to the moisture ratio and fitted to the seven selected drying models listed in Table 1. The results of statistical tests (R^2, *RMSE*, χ^2 and model parameters), performed in the proposed models were shown in Table 2. Best fitted curve could be evaluated from the statistical tests which have been used in various food drying studies[33,34]. In all cases, statistical parameter estimations showed that R^2, χ^2 and *RMSE* values ranges from 0.9650 to 0.9991, 0.000001 to 0.145705, and 0.000001 to 0.359941, respectively. Based on higher R^2 and lower values of χ^2 and *RMSE*, it can be found that logarithmic model gave best results than the other models. Hence, it was selected to represent the drying characteristics of *Syzygium cumini*. Figure 7 shows the comparison of the predicted moisture ratios obtained by Logarithmic model and the experimental moisture ratio values at various drying air temperatures 50, 60 and 70℃. According to Figure 7, logarithmic model is found to be in good agreement with the experimental data obtained from the drying experiments. Similar observations were reported for many food stuffs such as long green pepper[35], green bell peppers[36], Asian white radish[34] and peeled and unpeeled whole figures[37].

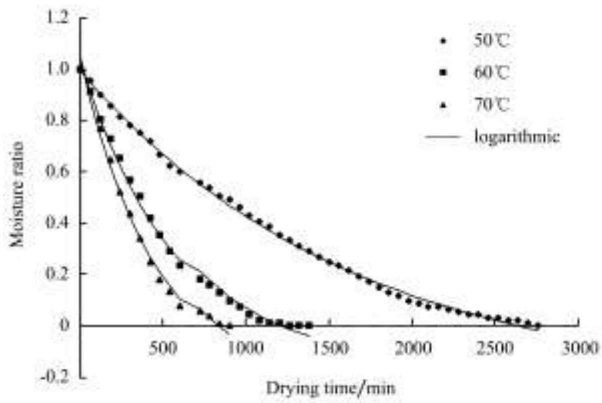

Figure 7 Drying curves of *Syzygium cumini* determined at 50, 60 and 70℃. Solid curve represents curve fitting using logarithmic model

Table 2 Modeling of moisture ratio with drying time during drying of *syzyium cumini* at different temperatures

Model name	T/°C	Model parameters						R^2	*RMSE*
Lewis	50	k = 0.0000153						0.9650	0.012793
	60	k = 0.000038						0.9722	0.067408
	70	k = 0.000053						0.9759	0.034363
Henderson and Pabis	50	k = 0.000016	a = 1.0566					0.9752	0.051393
	60	k = 0.000041	a = 1.0828					0.9793	0.015208
	70	k = 0.000057	a = 1.0936					0.9798	0.065252
Logarithmic	50	k = 0.000010	a = 1.2430	c = -0.2464				0.9949	0.000001
	60	k = 0.000029	a = 1.1896	c = -0.1526				0.9955	0.009516
	70	k = 0.000037	a = 1.2714	c = -0.2249				0.9980	0.000003
Two term	50	k_0 = 0.00001	k_1 = 0	a = 0.5500	b = 0.5066			0.9752	0.051574
	60	k_0 = 0.00004	k_1 = 0	a = 0.5735	b = 0.5093			0.9793	0.015233
	70	k_0 = 0.00005	k_1 = 0	a = 0.5716	b = 0.5219			0.9798	0.065281
Page	50	k = 0	n = 1.7176					0.9802	0.355356
	60	k = 0	n = 1.8402					0.9834	0.17161
	70	k = 0	n = 1.8182					0.9873	0.359941
Wang and Singh	50	a = -0.000011	b = 0.000000000032899					0.9970	0.017445
	60	a = -0.000027	b = 0.00000000019169					0.9991	0.004008
	70	a = -0.000038	b = 0.00000000036452					0.9979	0.018881
Modified Henderson and Pabis	50	k = 0.000016	g = 0	h = 0	a = 0.364	b = 0.3562	c = 0.3358	0.9752	0.0516
	60	k = 0.000041	g = 0	h =0	a = 0.380	b = 0.3637	c = 0.3383	0.9793	0.043642
	70	k = 0.0001	g = 0.0001	h =0	a = 0.378	b = 0.3682	c = 0.3464	0.9798	0.065281

4 Conclusions

The drying characteristics of *Syzygium cumini* were carried out in a tray dryer at the drying air temperatures of 50, 60 and 70 ℃. *Syzygium cumini* drying rate did not fall into a constant drying rate period. The entire drying took place in the falling rate period. The moisture content and drying rate were influenced by the drying air temperature. Drying air temperature increases, with the decrease in drying time and increase the drying rate. The effective diffusivity increased with the increase in the drying air temperature. The effective diffusivity varied from 1.67×10^{-6} m^2/s to 5.75×10^{-6} m^2/s with the temperature ranging from 50 ℃ to 70 ℃. The effective diffusivity increased with increasing temperature and it followed an Arrhenius relationship. The activation energy values ranged from 27.67 kJ/mol to 30.23 kJ/mol. Based on the non-linear regression analysis, the Logarithmic model were found as the best model with the highest determination of coefficient (R^2), lowest reduced chi-square (χ^2) and root mean square error (*RMSE*) values.

Nomenclature

℃	-Degree Centigrade
Cm	-Centimetre
D	-Effective moisture diffusivity
D_o	-Pre-exponential factor of the Arrhenius Equation
E_a	-Energy of Activation
G	-Gram
H^o	-Hue angle
Hz	-Hertz
K	-Drying rate
K_1	-Slope
Kcal	-Kilocalorie
KJ	-Kilo joule
M	-Meter
M	-Moisture content at any time
m^2	-Square meter
M_e	-Equilibrium Moisture Content
mg	-Milligram
ML	-Millilitre
M_o	-Initial moisture content
Mol	-Moles

MR	-Moisture ratio
n	-Number of terms into consideration
r	-Radius
R	-Universal gas constant (8.3143 kJ/mol)
R^2	-Correlation coefficient
RMSE	-Root mean square
S	-second
T	-time taken
T_a	-Absolute air temperature
V	-Volts
W_L	-Amount of moisture evaporated
X^2	-Reduced Chi-square

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