Convective dehydration kinetics of noodles prepared from taro (*Colocasia esculenta*), rice (*Oryza sativa*) and pigeonpea (*Cajanus cajan*) flours

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Abstract: Drying characteristics of noodles prepared from 50% taro and remaining equal proportions of rice and pigeonpea flours were investigated in a convective type dryer for a temperature range of 50°C to 80°C at a constant air velocity of 1.5 m s^{-1}. Results indicated that drying took place in falling rate period. The sample dried at 50°C was found better in color as compared to samples at 60°C, 70°C and 80°C. The rehydration weight of noodles decreased with the increase in drying temperature. Moisture transfer from noodles was described by applying Fick's diffusion model and the effective moisture diffusivity was calculated. Effective moisture diffusivity increased with increase in temperature. An Arrhenius relation with activation energy of 38.53 kJ mol^{-1} expressed the effect of temperature on moisture diffusivity. Mathematical models were fitted to the experimental data and the performance of these models were evaluated by comparing the coefficient of determination (R^2), Root mean square error (*RMSE*), reduced chi-square (χ^2), percent mean relative deviation modulus (*E*%) between observed and predicted moisture ratio. Verma model gave the best results for describing the drying behaviour of noodles.

Keywords: Noodle, taro, dehydration kinetics, temperature, moisture

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1 Introduction

Taro commonly known as *Colocasia esculenta* is a tropical tuber crop largely produced for its underground corms which are important sources of carbohydrates and minerals for the populations of the tropical areas. The different varieties of taro available in the world include *Cyrtosperma chamissonis* (giant swamp taro), *Xanthosoma sagittifolium, Colocasia esculenta* (taro) and *Alocasia macrorrhiza* (giant taro). It is rich in gums (mucilage) and has been reported to have 70%-80% starch with small granules due to which it is highly digestible and as such has been reported to be used for the preparation of various foods (Kaushal et al., 2012a). It is also a rich source of calcium, phosphorous, iron, Vitamin C, thiamine, riboflavin and niacin which are the important constituents of human diet. Taro consumption has been affected by the presence of acridity factors, which cause sharp irritation and burning sensation in the throat and mouth on ingestion. The acridity factor can be reduced by peeling, grating, soaking and fermentation operations during processing (FAO, 1990). Taro flour is unique because of its extremely small particle size (1-5 μm) and high mucilage or gum content, making it a possible replacement for corn or wheat flour.

Rice (*Oryza sativa* L.), a major cereal crop is an important source of energy, hypoallergenic, low in fat, easily digested, providing protein with higher nutritional

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quality and has versatile functional properties. When rice is to be processed into various traditional products, snacks, breakfast cereals and other cooked or extruded products, it is first milled and ground into flour. The particle size distribution of rice flour is known to play an important role in its functional properties and the quality of end products (Chen et al., 1999). Modifying the rice flour can change its functional properties in such a way that it may also be used as a substitute in other value-added products. Pregelatinized rice flour has been widely used as a major ingredient, bulking agent or thickening agent. Many popular oriented foods, such as delicate Chinese rice cakes, baby foods and instant rice milk are also made from Pregelatinized rice flour.

Pigeonpea (*Cajanus cajan*) is a perennial member of the family *Fabaceae* which contains high amounts of vitamin B, carotene, ascorbic acid, high levels of protein and the important amino acids: methionine, lysine and tryptophan. Sprouting enhances the digestibility of dried pigeonpea via the reduction of indigestible sugars that would otherwise remain in the cooked dried peas. In combination with cereal, pigeonpea makes a well balanced human food.

Kaushal et al. (2012a) compared the physicochemical, functional, antinutritional and pasting properties of taro, rice, pigeonpea flours and their blends. Taro flour was significantly ($P < 0.05$) different from other flours due to its highest ash, crude fiber, lower fat and protein content and exhibited lowest L*, ΔE value, foaming capacity (FC) and highest WSI (water solubility index), WAC (water absorption capacity) and OAC (oil absorption capacity) as compared to rice and pigeonpea flour. Kaushal and Sharma (2012b) studied the effect of incorporating taro (*Colocasia esculenta*), rice (*Oryza sativa*) and pigeonpea (*Cajanus cajan*) flour blends on noodle properties. The suitability of noodles from 50% taro flour and equal proportions of rice and pigeonpea flour in terms of color, taste, firmness and overall acceptability was observed.

Noodles are one of the extruded products, which are popular on the account of their sensory appeal, low cost, ease of preparation and storage stability and consumer interest in food. The utilization of different substrates for starch noodles that have been studied includes rice flour (Juliano, 1993), legume starches (Jin et al., 1994) and tuber and tuber- legume starch blends (Collado and Corke, 1997). Rice flour, taro flour and pigeonpea flour have very unique attributes. The method of preparation of noodles from rice flour, wheat flour and their combination with other flours have been reported but the reports on the utilization of taro flour with other flours are scarce.

No systematic methodology is reported so far for studying the drying kinetics of noodles from taro, rice and pigeonpea flour and its subsequent rehydration. Drying is an essential process for food industry in order to preserve food quality and food stability by lowering the water activity through the decrease of moisture content. The drying kinetics of food is a complex phenomenon and requires dependable models to predict drying behaviour (Sharma et al., 2003). Basically, there are three types of thin layer drying models which are used to describe the drying rate of agricultural products, namely, theoretical, semi-theoretical and empirical models. The theoretical approach deals either with the diffusion equation or simultaneous heat and mass transfer equations. The empirical model neglects the fundamentals of drying processes and presents a direct relationship between average moisture and drying time by means of regression analysis. The semi-theoretical model is a trade-off between the theoretical and empirical ones, derived from a widely used simplification of Fick's second law of diffusion or modification of the simplified model, such as page model, the modified page model etc. Moisture diffusivity is an important mass transport property of foods used in calculations and modeling various food processing operations, such as dehydration, drying, packing, and storage. Average moisture diffusivity depends on the temperature, moisture content, bulk porosity, and the composition of the product. The average moisture diffusivity for an infinite slab was therefore calculated by the using Equation (1):

$$D_{avg} = \sum_{i=1}^{n} \frac{D_{eff(i)}}{n} \quad (1)$$

where, i varies from 1 to n; n is the number of data points used only for positive values of effective diffusivity.

Equation (1) was proposed by Crank (1975) considering assumptions: (a) moisture is initially uniformly distributed throughout the mass of a sample (b) mass transfer is symmetric with respect to the centre (c) surface moisture content of the sample instantaneously reaches equilibrium with the condition of surrounding air (d) resistance to the mass transfer at the surface is negligible compared to internal resistance of the sample (e) mass transfer is by diffusion only (f) diffusion coefficient is constant and shrinkage is negligible. There are several studies describing the drying behaviour of various products. Number of fruits, vegetables and plants are dried for their use in foods and medicines, but the generally adopted method is empirical in nature that requires systematic methodology for adopting a good quality product.

Rehydration is one of the important properties used to measure the quality of dried food materials. Rehydration process is affected significantly by drying conditions and pretreatments before drying. Most of the dried food materials must be rehydrated by immersion in water before use. Rehydration is a complex process in which adequate reconstitution of material properties occurs. The understanding of rehydration mechanism in case of noodles is extremely important. Water migrates from the noodle surface toward the center, while structure of noodle is changed during boiling. These phenomena may be the key processes, which govern the boiling time of the dried noodle.

Therefore the present study focuses to investigate the drying behaviour of taro, rice and pigeonpea flour based noodles and to investigate a suitable drying model to describe the drying kinetics of noodles.

2 Materials and methods

2.1 Samples

Raw taro corms (commercial variety) were purchased from local market, Sangrur, Punjab, India. The raw materials were physically examined to ensure disease-free and then stored in a cool (10°C) temperature and used within 24 h. Rice brokens were purchased from rice sheller (Located at Dhuri, Punjab, India). These rice brokens were milled in Chakki" to obtain rice flour which was then passed through mesh no. 72 sieve (0.26 mm). The pigeonpea flour was obtained from a mill located in Parbhani, Maharashtra, India and then it was passed through mesh no. 72 sieve (0.26 mm). The taro flour was made from taro cormels by following the different processing operations as given in Figure 1.

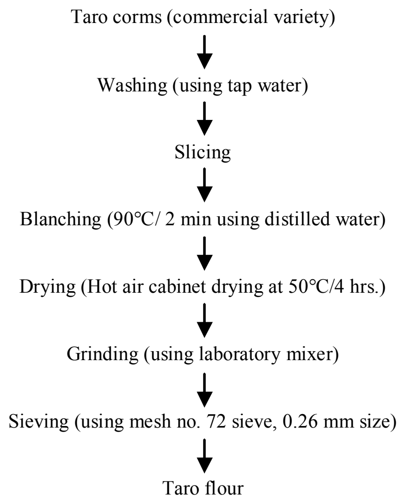

Figure 1 Flow chart for the preparation of taro flour (Kaur et al., 2010)

Preparation of Blends: - Blends were prepared by mixing 50% taro flour and 25% proportions of rice and pigeonpea flour each. The appropriate amounts of rice, pigeonpea and taro flour were weighed using an electronic balance to give the composite flour mixed and stored in airtight containers for use.

2.2 Noodle making

Dough was prepared by mixing 200 g flour with measured amount of distilled water (50%). Mixing of dough was carried out for five minutes. After preparation of dough, it was kept for 10 minutes at room temperature (28°C). Noodles were prepared by extruding the prepared dough through a hand-extruding machine (Anjali, New Delhi) fitted with 1.5 mm die. Immediately after extrusion, the noodle strands were cut with sharp knife to the appropriate length (12 cm). Initial and final moisture content of noodles were determined by the Standard method (AOAC, 1990).

2.3 Drying experiments

To study the dehydration kinetics, the noodle samples were convectively dehydrated at 50°C, 60°C, 70°C and 80°C with air velocity of 1.5 m s^{-1} airflow in perforated trays. The moisture loss of noodles was recorded at every 10 min during drying. The drying process was stopped when the moisture content reached to about 10%-12% (w.b) (Surojanametakul et al., 2002). The initial and final moisture content of samples were determined for each drying experiment by using oven method at 105°C until it reached to constant weight in two subsequent intervals. The drying curves (moisture content vs. time) were plotted to observe the effect of process variables and correspondingly drying rate vs. moisture content curves were also plotted.

2.4 Mathematical modeling

Thin layer equations aimed to describe the drying phenomena, despite of the controlling mechanism, have been used to estimate drying times for several products and to access drying curves. Several thin layer equations, varying widely in nature, are available in the literature and have been extensively used by investigators to successfully explain the drying of several agricultural products. The drying kinetics was monitored in terms of evolution of the moisture content along drying, and the data was then expressed in terms of the dimensionless variable moisture ratio. The moisture ratio (MR) of noodles during drying experiments was calculated using the following equations:

$$MR = \left(\frac{M_t - M_e}{M_0 - M_e}\right) \quad (2)$$

where, M_t is the moisture content at time t (db); M_0 = initial moisture content (db); M_e = equilibrium moisture content (db).

The instantaneous drying rate (DR) of noodles was calculated from the drying data by estimating the changes in moisture content, which occurred in each consecutive time interval and was expressed as g (water)/ g (dry matter) per minutes.

Instantaneous drying rate, DR (g water/ g dry matter per min) $= \left(\frac{\delta M}{\delta t}\right) = \frac{M_t - M_{t+1}}{t_{t+1} - t_t}$ (3)

2.5 Estimation of effective moisture diffusivity and activation energy

Drying of most food materials generally occurs in the falling rate period and moisture transfer during drying is controlled by internal diffusion. Fick's second law of diffusion has been widely used to describe the drying process during the falling rate period for most biological materials. The basic equation of Fick's unsteady state law of diffusion is of the form:

$$\frac{\partial M}{\partial t} = D\frac{\partial^2 M}{\partial Z^2} \quad (4)$$

The different analytical solutions of Equation 4 have been given by Crank (1975) for several geometries and boundary conditions. Noodles were assumed as infinite cylinders i.e. moisture diffusion occurring radially outwards only. Based on the assumptions of uniform initial moisture distribution, negligible external resistance, and negligible shrinkage during drying and constant diffusion coefficient, the analytical solution of diffusion equations for the infinite cylindrical shaped body is given by the following equation (Crank, 1975).

Moisture ratio (MR) =

$$\frac{M - M_e}{M_0 - M_e} = \sum_{n=0}^{\alpha} \frac{4}{\beta_n^2} \exp\left[\frac{-\beta_n^2 D_{eff} t}{r^2}\right] \quad (5)$$

where, MR is dimensionless; M = moisture content at time t; M_e = equilibrium moisture content; M_0 = initial moisture content; D_{eff} = moisture diffusivity (m^2 s^{-1}); r = radius of the cylinder (m); t = drying time (s); β_n = roots (2.405, 5.520, 8.640......) of the Bessel function of zero order J_o (r) = 0, n is the number of data points used only for positive values of effective diffusivity. Some researchers calculated effective diffusivity by using only first term of the analytical solution of Fickian model (Equation (5)) assuming that the effect of terms other than first one value of diffusivity was non-significant (Rastogi et al., 1999; Sharma et al., 2003). Therefore, Equation 5 can be rewritten as Equation (6), since other terms are small enough to be ignored. Equation (5) has been modified as it is not possible to calculate the moisture ratio by expanding this equation; thereby for calculating long drying times, this equation has been reduced in such a way that its first term has been used by substituting the value of n=1 (Lopez et al., 2000). Therefore, the effective moisture diffusivity (D_{eff}) values for noodles during convective drying were calculated by considering only the first term of the equation assuming that the effects of the other terms are negligible (Mundada et al., 2010). Therefore, by considering only the first term, Equation (5) reduces to:

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{4}{\beta_1^2} \exp\left[\frac{-\beta_1^2 D_{eff} t}{r^2}\right] \quad (6)$$

where, β_1 is the first root of Bessel Function (Mundada et al., 2010). Substituting the value of n = 1 in the Equation (5) results in Equation (6). Bessel functions of this kind are the solutions of Bessel differential equation that are finite at the origin and diverge as the value further approaches. Using Taylor's series for higher order functions, the value of Bessel function is obtained which need not to be applicable in this case as it is considered that the effects of higher order terms are negligible based on Fickian model (Equation (5)) (Mundada et al., 2010). Only the first term of Equation (5) is used for long drying times (Lopez et al., 2000). D_{eff} represents the conduction term of all the moisture transfer mechanisms which is usually determined from experimental drying curves. The average effective moisture diffusivity was calculated by using Equation (1) as specified earlier.

The dependence of average moisture diffusivity on drying air temperature was obtained by Arrhenius relationship to calculate the activation energy (Kaleemullah and Kailappan, 2006; Mundada et al., 2010). Therefore, using Arrhenius equation, as a relation between temperature and effective moisture diffusivity, activation energy can be calculated using Equation (7).

$$(D_e)_{avg} = D_o \exp\left(\frac{-E_a}{R(T+273)}\right) \quad (7)$$

where, T is temperature (°C); R is gas constant having constant value of 8.314 KJ mol^{-1} ^{o}K; D_o is the effective diffusivity at 0°C (273 K) temperature or it is a line intercept which is always constant; E_a is the activation energy (kJ mol^{-1}).

The linear form of Equation (7) can be obtained by applying the logarithms. Both kinetic parameters (E_a and D_o) can be estimated from slope and intercept of the plot (ln D_{eff} versus T^{-1}). The slope of line is E_a R^{-1} and intercepts equals ln D_o (Mundada et al., 2010).

2.6 Adequacy of model fitting

To select a suitable model for describing drying process of different noodle samples, the drying curves were fitted with thin layer drying equations (Table 1). For model fitting, the moisture ratio was considered as the dependent variable. The statistical validity of the models were evaluated and compared by means of various statistical parameters. In addition to coefficient of determination (R^2), the various statistical parameters such as reduced chi- square (χ^2) and root mean square error ($RMSE$) were also used as primary criterion to select the best equation. Reduced chi-square (χ^2) is the mean square of the deviations between experimental and predicted values for the models and was used to determine the goodness of fit. The lower the values of reduced chi-square, better is the goodness of fit. The RMSE gives the deviation between the predicted and experimental value, which was calculated as follows:

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\{MR_{exp,i} - MR_{pre,i}\}^2\right]1/2 \quad (8)$$

$$x^2 = \sum_{i=1}^{N}\frac{\{MR_{exp,i} - MR_{pre,i}\}^2}{N-n} \quad (9)$$

where, $MR_{exp,\,i}$ is the experimentally observed moisture ratio; $MR_{pre,\,i}$ is the predicted moisture ratio; N is the number of observations and n is the number constants.

Table 1 List of models with references

Model name	Model	References
Newton	MR = exp (-k t)	Mujumdar (1987)
Logarithmic	MR = a exp (-k t) + c	Yagcioglu et al. (1999)
Two-term	MR = a exp (-k t) + (1−a) exp(-k a t)	Sharaf-Eldeen et al. (1980)
Exponential		
Henderson and Pabis	MR = a exp (-k t)	Henderson and Pabis (1961)
Verma et al.	MR = a exp (-k t) + (1−a) exp (-g t)	Verma et al. (1985)
Magee	MR = a+kt1/2	Magee et al. (1983)
Modified Page	MR = exp (-(kt^n)	White et al. (1981)
Midilli	MR = a exp (kt^n) + bt	Midilli et al. (2002)

These parameters are not a good criterion for evaluating the non-linear mathematical models, therefore another statistical parameter which is percent mean relative deviation modulus (E%) was also used to select the best equation to account for variation in the drying curves of the dried samples as recommended by several authors in their drying studies (Ertekin and Yaldiz, 2004; Mundada et al., 2010). The mean relative deviation modulus (E %) is an absolute value that was used because it gives a clear idea of the mean divergence of the estimated data from the measured data. The mean relative percentage deviation modulus (E%) is widely adopted throughout the literature; a modulus value of 10% is indicative of good fit for practical purposes (Berg et al., 1981; Mundada et al., 2010). E% indicates the deviation of the observed data from the predicted line. Therefore, the best model was chosen as one with the highest coefficient of correlation (R^2); and the least χ^2, *RMSE* and mean relative deviation modulus (E%). E% was calculated as follows:

$$E(\%)=\frac{100}{n}\sum_{i=1}^{n}\left|\frac{Experimental\ Value-predicted\ value}{Experimental\ value}\right| \quad (10)$$

The values of E less than or equal to 10.0 indicate an excellent fit, while values greater than 10 are indicative of a poor fit (Oluwamukomi, 2009; Mundada et al., 2010).

2.7 Color evaluation of noodles

Color values (L*, a*, b*) of noodles were carried out using Hunter colorimeter Model D 25 (Hunter Associates Laboratory Inc., Reston, VA, USA). The instrument was calibrated against a standard red-colored reference tile (L_s = 25.54, a_s = 28.89, b_s = 12.03). Total color difference was calculated by applying the equation:

$$\Delta E=\{(L_s-L)^2+(a_s-a)^2+(b_s-b)^2\}^{1/2} \quad (11)$$

2.8 Rehydration weight of noodles

The rehydration weight is an important quality parameter that indicates the ratio of weight of cooked noodles to the weight of the noodles before cooking. Rehydration weight was assessed by the method suggested by Purwani et al. (2006). In this method, 3 g of noodles were cooked in 40 ml boiling water for nine minutes, placed it in a strainer and allowed to drain and weighed. Rehydration weight was calculated as percentage of initial weight.

2.9 Statistical analysis

The non-linear regression analysis of the experimental data was carried out by the software STATISTICA, 7.0 for checking the validity of empirical models for all the dehydration processes.

3 Results and discussion

3.1 Color characteristics of noodles

The color of the food products is the first attribute that affects the decision of consumer for purchasing or consuming any food products. The results depicted in Table 2 indicated that the increase in temperature affected the color of noodles. The L* values for noodle samples at different temperatures varied from 75.606 to 81.102. It was observed that with the increase in temperature from 50°C to 80°C, a decrease in L* was observed in all noodle samples. Hunter a* and b* values for noodle samples ranged between 6.296 to 8.935 and 15.442 to 21.244, respectively. It has been hypothesized that the variation in b* value among samples may be attributed to the amount of carbohydrate and protein content due to their role in the development of non-enzymatic browning (Jamin and Flores, 1998). ΔE represents the total color difference which decreased with the increase in temperature. The difference in the color characteristics of different samples may be attributed to differences in colored pigments of the flours, which in turn depends on the botanical origin of the plant and also to the composition of the flour (Aboubakar et al., 2008). The noodle samples dried at 50°C were found better as compared to sample obtained at 60°C, 70°C and 80°C because of degradation of color occurred at faster rate at higher temperatures. However, drying at higher temperature is not suggested due to harmful effects on food components like proteins, vitamins, colour etc (Kaushal et al., 2013). In the present study, the drying temperature effect on color revealed that the temperature 50°C produced the product with better color values and overall acceptability. The drying time required to reduce the moisture content at any given level was dependent on drying condition of drying air being highest at 50°C and lowest at 80°C (Figure 2). But higher temperatures resulted in adverse affects like starch gelatinisation, harmful effects on various food components (Kaushal et al., 2013). Kaushal et al. (2012) reported that 50°C is the recommended and suitable temperature for taro and taro based products particularly concerning with drying and color characteristics. Therefore, 50°C is the recommended temperature as far as drying and the color characteristics of taro based noodles are concerned.

Table 2 Color characteristics of noodle samples at different temperatures after drying kinetic study

Temperature/°C	L*	a*	b*	ΔE
50	81.102	6.296	21.244	60.683
60	77.866	7.304	17.541	56.871
70	76.570	8.114	16.214	55.255
80	75.606	8.935	15.442	54.004

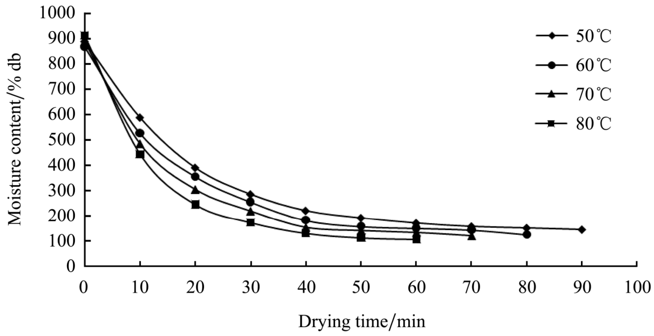

Figure 2 Drying curves of noodles (containing 50% taro flour) at different temperatures

3.2 Effect of drying temperature on drying time and drying rate of noodles

The moisture content of noodles as a function of drying time is presented in Figure 2 for different temperatures (50°C to 80°C). The moisture content rapidly reduced and then slowly decreased with increase in drying time. The rate of moisture loss was higher at higher temperatures and the total drying time was reduced substantially with the increase in air temperature. However, drying at higher temperature is not suggested due to harmful effects on food components (Kaushal et al., 2013). The drying curve (Figure 2) indicates that drying rate of noodle samples at different temperatures occurred in falling rate period without occurrence of constant rate during drying. The absence of constant rate convective drying may be due to that the sample could not provide constant supply of water for appreciable period of time. Arumuganathan et al. (2009) reported the occurrence of only falling rate period during drying of mango slices and milky mushroom. As the temperature increased from 50°C to 80°C the drying time decreased. The results indicated that diffusion is the most likely physical mechanism governing moisture movement in the noodle samples.

The variations of drying rate of noodles with drying time at temperatures of 50°C, 60°C, 70°C and 80°C are given in Figure 3. Drying continued until the equilibrium moisture content was reached. Increasing the drying temperature decreased the total drying time since heat transfer increased. Experimental results showed that drying temperature is an effective parameter for the drying of noodles. It can be seen that, at higher moisture content, the increase in temperature has more considerable effect on the drying rates as compared to lower temperatures, which is almost negligible towards the end (Figure 3). It was further observed that the drying rate or moisture loss was faster at the beginning. The reduction in drying rate with progression of drying process may be due to the reduction in the available moisture and due to development of case hardening. Reduction of drying rate might also be due to the development of the shrinkage which causes the reduction in porosity of the noodles with advancement of the drying process. Premi et al. (2010) also reported the reduction in the drying rate at the end of drying of drumstick leaves due to the reduction in moisture availability with advancement of drying. Thus, a higher drying air temperature produced a higher drying rate and consequently the moisture ratio decreased.

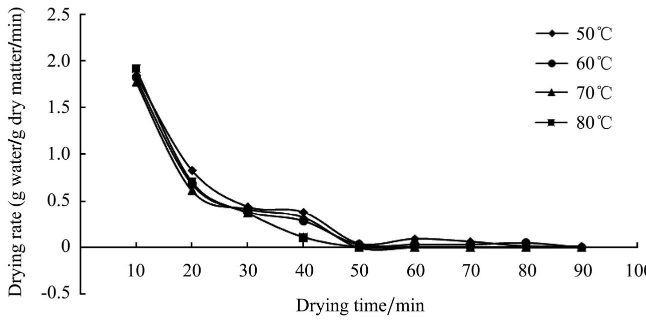

Figure 3 Drying rate versus drying time of noodles (containing 50% taro flour) at different temperatures

3.3 Effective moisture diffusivity and activation energy of noodles

Effective diffusivities (D_{eff}) at 50°C, 60°C, 70°C and 80°C for noodles were in the range of 5.43 10^{-9} m^2 s^{-1} to 6.60×10^{-9} m^2 s^{-1} (Table 3). These values lie in the range of 10^{-11} to 10^{-9} m^2 s^{-1} for food materials (Babalis and Belessiotis, 2004). The variation of effective diffusivity with inverse of temperature for noodles is presented in

Figure 4. It can be seen that the values of D_{eff} increased with increasing temperature. This behaviour might be due to reason that the moisture diffusivity is product temperature dependent. During drying, product temperature rises to the wet bulb temperature of drying air and finally may become equal to the dry bulb temperature of the drying air. The increase in product temperature with progression of drying process results in increase of effective diffusivity. Further, in the last phase of each experiment of convective dehydration, there was a sharp decrease of moisture diffusivity, although the product temperatures were high. The reduction in moisture diffusivity beyond moisture content of 0.3% (db) might be due to unavailability of free water for diffusion at finishing stage of convective dehydration. This phenomenon of decrease of moisture diffusivity may be due to occurrence of high shrinkage and superficial hardening of the product in later stage of drying. The sample shrinkage and the superficial hardening impede the moisture transfer from sample to the air, introducing additional resistance and resulting in a low effective diffusivity value. Adu & Otten (1996) also reported the decrease in average effective moisture diffusivity in later stages. This may be attributed to unavailability of free water for diffusion during the finishing of convective dehydration. The differences in the D_{eff} were due to different initial water content in the samples allowing greater diffusion coefficients since the process of diffusion is favoured in products with higher proportions of water and lower proportions of solids (Guiné and Fernandes, 2006; Mundada et al., 2010). As the hypothesis was presumed that the diffusion has governed the internal mass transfer which was highest at 80°C and can also be verified from the values of effective moisture diffusivity for all noodle samples. Similar behaviour of D_{eff} has been reported for onions (Mota et al., 2010).

Table 3 Effective moisture diffusivity (D_{eff}) and activation energy of noodles at different drying temperatures

Temperature /°C	Effective diffusivity (Do×10^{-9})	Activation energy (kJ/mol)
50	5.43	
60	6.16	38.53
70	6.53	
80	6.60	

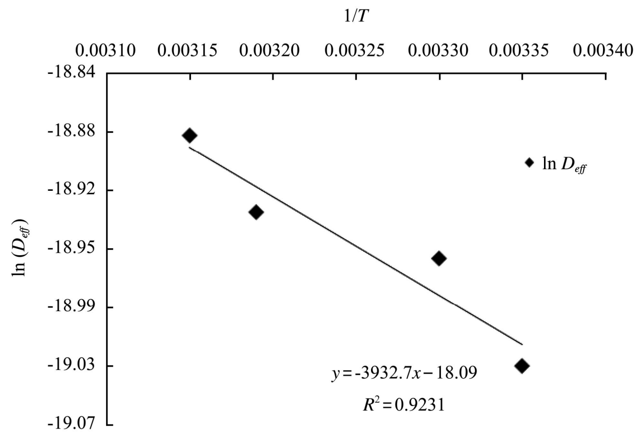

Figure 4 Variation of effective diffusivity (m^2 s^{-1}) with inverse of temperature for noodles (50% taro flour)

The energy level of the molecule to initiate a chemical reaction is generally expressed as activation energy. The activation energy of noodles was evaluated as 38.53 kJ mol^{-1} (Table 3). The values of activation energy lie from 12.7 to 110 kJ mol^{-1} for most food materials (Zogzas et al., 1996).

3.4 Validity of various mathematical models for convective drying of noodles

The coefficient of correlation and results of statistical analysis is represented in Table 4 for noodle samples. The results of statistical analysis indicates the R^2, $RMSE$, χ^2 and E% obtained for fitting the experimental data to selected drying models in order to determine the best model. All the models presented different values at different temperatures. Furthermore, the highest value of R^2, lowest $RMSE$, E% and χ^2 values were selected as optimal criteria to evaluate the fitting quality of eight proposed models. In all cases, the R^2 values for the mathematical models were greater than 0.90, indicating a good fit. Generally R^2, $RMSE$, χ^2 and E% values for noodle samples ranged between 0.94 to 0.99, 0.01 to 1.81, 6.43×10^{-5} to 3.30, 2.80-60.19 respectively. For noodle samples, the highest values of R^2 and lowest values of χ^2 $RMSE$ and E% were obtained with Verma model. Therefore, Verma model can be considered to be the best model for describing the thin layer drying behaviour of noodles in a convective type dryer for temperature range, 50°C to 80°C. Similar findings were reported for hot air drying of plum (Goyal et al., 2007).

Table 4 The fitness of different models at different temperatures for noodles

Model	Temperature/℃	Coefficient	Coefficient of determinan on (R^2)	Chi-square (X^2)	*RMSE*	*E* %
Newton	50	k:0.02188	0.94196	0.006100555	0.07811	60.19617417
	60	k:0.040667	0.93136	0.01357	0.1165	43.7720065
	70	k:0.039280	0.94356	0.00705	0.08398	35.195226502
	80	k:0.057120	0.95768	0.00906	0.0952	44.40229501
Logarithmic	50	a:0.817357, k:0.038678, c:0.169232	0.99883	0.000126881	0.011264	2.9043732
	60	a:0.800055, k:0.098346, c:0.196943	0.99852	0.000171997	0.013115	5.2564804
	70	a:0.845467, k:0.068770, c:0.155984	0.99803	0.000264	0.016256	16.31632829
	80	a:0.848721, k:0.101853, c:0.143238	0.99259	0.001052819	0.032447	7.0677619
Two-term exponential	50	a:0.243533, k:0.069115	0.97204	0.002985	0.05633	20.52451
	60	a:0.250297, k:0.101938	0.92145	0.008793	0.09377	34.28269
	70	a:0.273807, k:0.107203	0.96765	0.004269	0.06534	27.29918
	80	a:0.266065, k:0.159735	0.95622	0.006108	0.078152	35.75662
Handerson and Pabis	50	a:0.875054, k:0.018519	0.95761	0.004492	0.067019	23.26765
	60	a:0.851397, k:0.032211	0.8975	0.011331	0.106445	36.87442
	70	a:0.920484, k:0.035390	0.95149	0.00635	0.079688	32.90405
	80	a:0.923082, k:0.051359	0.93902	0.008432	0.091825	41.69989
Verma et al.	50	a:0.768580, k:0.036489, -0.005625	0.99864	0.000188710	0.013140	3.464102
	60	a:0.534966, k:0.064321, g:0.045168	0.99856	0.000245610	0.012156	3.167104
	70	a:0.905591, k:0.076259, g:-0.008725	0.99654	0.002347214	0.024651	6.235472
	80	a:0.915516, k:0.088623, g:-0.012361	0.99182	0.001242603	0.035251	10.60042
Magee	50	a;0.865920, k:-0.068349	0.95087	0.005188	0.072029	24.18095
	60	a:0.802992, k:-0.078336	0.90222	0.010836	0.104096	31.55868
	70	a:0.854174, k:-0.086541	0.92891	0.009197	0.095901	36.37647
	80	a:0.807213, k:-0.090129	0.90405	0.013027	0.114137	47.67802
Midilli	50	a:1.000170, k:0.055613, n:0.822637, b:0.000960	0.99941	6.43249E-05	0.00802	2.803839
	60	a:1.000820, k:0.198201, n:0.599994, b:0.001525	0.99864	0.000158856	0.012604	3.615423
	70	a:0.999013, k:0.065625, n:0.935634, b:0.001854	0.9988	0.000161456	0.12707	4.529644
	80	a:0.999024, k:0.195364, n:0.659282, b:0.001385	0.99527	0.000673557	0.025953	7.793027
Modified Page	50	k:0.147921, n:0.147921	0.94196	3.304556	1.817844	28.51672
	60	k:0.201679, n:0.201679	0.8578	0.013573	1.116504	43.77695
	70	k:0.198184, n:0.198184	0.94596	0.007053	0.083983	35.19164
	80	k:0.238989, n:0.238989	0.93429	0.009063	0.952	44.39957

3.5 Rehydration weight of noodles

The rehydration weight indicating the ratio of weight of cooked noodles to the weight of the noodles before cooking varied widely for the noodle samples dried at different temperatures. It can be taken as a quality parameter which is used to predict the cooking quality of noodles because lesser the degree of hydration, the stronger the noodles texture. It was observed that with the increase in drying temperature (50°C to 80°C), the rehydration weight of noodles decreased (Table 5). The highest % rehydration weight (366.66%) was observed in the case of noodles dried at 50°C whereas least (166.66%) was observed in the case of noodles dried at 80°C. It is well known that with increase in drying temperature, moisture loss of product occurs at a faster rate that results in decreasing the rehydration rate thereby affecting the texture of noodles. But apart from this, the higher temperatures result in color degradation, starch gelatinization and create many harmful effects on various food components (Kaushal et al., 2013) thereby affecting the decision of consumers for the choice of noodles which was not desirable. Therefore, higher temperature is not desirable as far as rehydration weight and color characteristics are considered from the point of view of consumer acceptability.

Table 5 Rehydration weight of noodles at different drying temperatures

Temperature	Rehydration weight/%
50°C	366.66
60°C	333.33
70°C	233.33
80°C	166.66

3.6 Conclusions

Noodles prepared from 50% taro and remaining equal proportions of rice and pigeonpea flours were dried at 50°C, 60°C, 70°C and 80°C temperature. The drying rate decreased continuously throughout the drying period. Constant rate period was absent and the drying process of noodles took place in falling rate period. Drying time decreased considerably with increased temperature. Verma model was the best among the selected models for describing the drying behaviour of noodles. The effective moisture diffusivity ranged from 5.24-9.1×10^{-9} m^2 s^{-1} when dried at 50°C to 80°C. The activation energy of noodles was 38.53 kJ mol^{-1}. It was observed that with the increase in drying temperature (50°C to 80°C), the rehydration weight of noodles decreased. For noodles used in this drying kinetic study, the temperature of 50°C was found to be optimum in terms of energy efficiency and product quality when evaluated on the basis of colour by colorimeter, L*, a*,b* values and drying time.

Nomenclature

D_{eff}	Effective moisture diffusivity (m^2 s^{-1})
$\frac{\delta M}{\delta t}$	Instantaneous drying rate (g water/g dm min)
$E\%$	Mean standard deviation modulus
E_a	Activation energy (KJ $mole^{-1}$)
M_t	Moisture content at time t on db.
$M_{(t+1)}$	Moisture content at time $t_{(t+1)}$ on db
M_o	Initial moisture content on db
χ^2	Reduced chi-square
M_e	Equilibrium moisture content on db.
MR	moisture ratio
M_t	moisture content at time t %(db)
n	the number of data points
R	gas constant (8.314 kJ mol^{-1})
T	the temperature in °C
$RMSE$	Root mean square error
R^2	Root mean square error
t	time (min)

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