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Mathematical modelling of the thin layer drying of banana blossoms

Abstract

In this study, the influence of air temperature on thin-layer drying of banana blossom was investigated. Drying characteristics of the flowers were determined using heated ambient air at temperature from 40°C to 60°C. The effects of air temperature and drying time were also determined. Results indicated that drying of the blossoms took place in the falling rate period. Moisture transfer from the blossoms was described by applying the Fick's diffusion model. The effective diffusivity coefficient of moisture transfer varied from 5.45x10-9 to 8.09x10-9m2/s over the temperature range. An Arrhenius relation with an activation energy value 50.06kJ/mol expressed the effect of temperature on the diffusivity. Mathematical models were fitted to the experimental data and by statistical comparison, it was concluded that the Logarithmic model represents drying characteristics better than the other equations. The results have shown that there was no significant difference between the fresh and dried samples.

Keywords: mathematical modelling, thin layer drying, banana blossom, diffusion coefficient, activation energy, nutritional properties

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Introduction

Banana blossom, an agricultural by-product, is obtained from the subtropical Musa species originating from India. It is being consumed as a vegetable in the Asian countries like India, Malaysia, Indonesia, Sri Lanka and the Philippines. It has been appreciated for its nutritional content in dietary fibers, proteins, fatty acids, vitamin E, flavonoids and minerals such as magnesium, iron and copper.[1] At ambient temperatures, the blossoms bloom continuously and drop the petals. At high temperatures the flowers start rotting and chilling turns the white heart of the flowers into black. Moreover, in spite of its high fiber content blossom consumption may be restricted due to the cumbersome preparation procedures. Convenience in preparation, promotion of the intake of fiber rich vegetables and increase in shelf life can be achieved by developing a preserved product from the banana blossom.

Drying is one of the techniques to develop a shelf stable and high quality products. The removal of moisture in the drying process prevents the growth of microorganisms and other deteriorative reactions. Drying induces a considerable reduction in weight and volume, minimizes packing, storage and transportation costs and as well as enables the product to be stored under ambient conditions.[2] Sun drying is one of the traditional methods used to preserve agricultural commodities in the tropical and sub tropical regions. However, hot air dry drying is the most widely used industrial method due to its uniform and rapid drying process.[3]

Numerous researches on the experimental studies and mathematical modelling of the drying characteristics of various fruits and vegetables such as apricot,[4] garlic,[5] green and red peppers,[6] okra,[7] egg plant,[8] peach[9] carrot[10] and tomato[11] have been carried out. Many mathematical models have proposed to describe the drying process. Limited research has been performed on the drying of banana blossoms.

The objectives of this research are to:

a. Determine the effect of air temperature on drying time of banana blossoms

b. Fit the drying curves with ten mathematical models and investigate the goodness of fit

c. Calculate effective diffusivity and activation energy for the blossoms

d. Analyze the properties of the blossoms before and after the drying process

Materials and methods

Drying experiments

Freshly harvested banana blossoms were procured from the local market in Perundurai. They were washed thoroughly in running cold water to remove adhering extraneous matter. The purple petals and the stamen were removed. From each clusters of flowers, the yellow tipped fronds that are responsible for the bitter flavor were separated manually. The edible portion was then washed in water and chopped into small pieces of length 1cm. To prevent enzymatic browning and to remove the characteristic bitter and starchy flavor the blossoms were soaked in buttermilk. They were soaked in 500ml of buttermilk for about 15minutes. After pre-treatment the flowers were dehydrated using a tray-dryer. Blossoms of 500-1000g were taken for dry drying and spread over perforated aluminum trays and trays were kept in the drying chamber. Initial moisture content was determined by the standard AOAC method.[12] The initial moisture content was found to be 87.3% (w.b.). Drying experiments were carried out at the temperature of 40°C, 50°C and 60 °C. A constant air velocity of 1.0m/s was maintained. The relative humidity of air was found using dry and wet bulb temperatures acquired from a psychrometric chart. To achieve steady state conditions, the dryer was started 45minutes before commencing the experiments. The blossoms were evenly distributed inside the dryer. The moisture loss was recorded every 15minutes to obtain the drying curves. After the drying process, the

samples were cooled in desiccators and then packed in polyethylene bags. The experiments were replicated thrice at the above mentioned air temperatures and mean values were used for plotting the drying curve.

Mathematical modelling of drying curves

Moisture contents of the blossoms during the thin-layer drying experiments were expressed as moisture ratios MR with the following equation[13]

$$D_{eff} = D_0 \exp\left(\frac{E_a}{R(T+273.15)}\right) \quad (1)$$

where M is the mean blossom moisture content (% w.b); M_0 is the initial moisture content (% w.b); and M_e is the equilibrium moisture content (% w.b).

For mathematical modelling, the drying curves were fitted to ten well-known drying models given in Table 1. MATLAB R2011 tool was used for curve fitting.

The goodness of fit was deduced using the parameters, i.e. coefficient of determination (R^2) and root mean square error (RMSE). These parameters can be described in equations from as (2) and (3)

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

$$RMSE = \left[\frac{1}{N}\sum_{x=1}^{n}\left(MR_{pre,x} - MR_{\exp,x}\right)^2\right]^{1/2} \quad (3)$$

Where, $MR_{exp,x}$ is the experimental moisture ratio at observation x, $MR_{pre,x}$ is the predicted moisture ratio at this observation, N is number of experimental data points, and z is number of constants in model.

Table 1 Mathematical models applied to drying curves

Model	Equation	References
Newton	MR=exp(-kt)	35–38
Modified Page	MR=exp(-kt) n	39
Henderson and Pabis	MR=a exp(-kt)	40–47
Modified Henderson and Pabis	MR=a exp(-kt) + b exp(-gt) + c exp(-ht)	48
Logarithmic	MR=a exp(-kt) + c	9,21,49,50
Two term	MR=a exp($-k_0$t) + b exp($-k_1$t)	51,52
Two term exponential	MR=a exp(-kt) + (1-a) exp (-kat)	53
Verma et al.	MR=a exp(-kt) + (1-a) exp (-gt)	54
Wang and Singh	MR=1 + at + bt2	55–60
Midilli et al.	MR=a exp(-kt) + bt	61,62

The R^2 value is the quotient of the variances of the fitted values and observed values of the dependent variable. The higher the value of the coefficient of determination, the greater is the success of the mathematical model. The RMSE gives the deviation between the predicted and experimental values and it is required to reach zero. The higher values of R^2 and the lower values RMSE are chosen as the criteria for goodness of fit[14] and same was followed in present study.

Nutritional properties

Samples of banana flower were analyzed for moisture, protein, fat, ash, total crude fiber, and total flavonoids following the standard methods published by Association of Official Analytical Chemists.[15] Moisture content was estimated by gravimetric measurement of weight loss after drying the sample in an oven at 105°C until constant weight was obtained. Protein was determined by Kjeldahl method,[16] and thereafter a conversion factor of 6.25 was used to calculate the total nitrogen to crude protein. The lipid content of the samples was done using Soxhlet type of the direct solvent extraction method. The solvent used was petroleum ether (boiling range 40-60°C).[17] The content of ash was measured by gravimetric measurement of the sample in the furnace at 550°C until the constant weight was achieved.

The total phenol content of extracts was determined by the Folin-Ciocalteau colorimetric method.[18] Briefly, 1ml of the extract solution was mixed with the Folin-Ciocalteau reagent (1ml) and 7.5% Na2CO3 (3ml). After 1h of incubation at room temperature, the absorbance was measured against water at 725nm (UV Spectrophotometer). Gallic acid was used for establishing the standard curve and the results were expressed asmg of gallic acid equivalents/g of extract. To quantify the total flavonoids content, quercetin was used as the reference,[19] which was expressed as quercetin equivalent (QE). A standard curve of known concentrations of quercetin was generated by preparing and testing five concentrations of quercetin standard solution, which were 0, 25, 50, 75, and 100mg/L. A stock quercetin solution was prepared by dissolving 25mg of quercetin in 100mL of 80% ethanol. Then, the standard working solutions were made up by pipetting 0, 1, 2, 3, and 4mL aliquots of the stock solution (250mg/L) into 10mL-volumetric flasks and adjusting the volume with 80% ethanol. By using test tubes, 1mL of each standard solution was reacted with 3mL of 95% ethanol, 0.2mL of a 10% aqueous dilution of AlCl3 reagent, 0.2mL of 1M sodium hydroxide, and 5.6mL of distilled water. The mixture was mixed thoroughly by vortex mixer for about 30s and allowed to stand at room temperature for 30min. Absorbance readings were taken by a UV/Visible Spectrophotometer at 510nm.

Results and discussion

Drying kinetics of the banana blossoms

The effect of three temperatures on the drying curve of banana blossoms is shown in Figure 1. It is obvious from the chart that increasing the drying temperature resulted in an increase in the drying rate, therefore decreasing the drying time. The time required to decrease the moisture ratio to any given level was dependent on the drying condition, being highest at 40°C and lowest at 60°C. The time taken to reduce the moisture content of the blossoms from the initial 87.3 (%w.b) to 8.9±0.1 (%w.b) was 300, 240 and 195min at 40, 50 and 60°C respectively. It is observed that there is no constant rate drying period in the drying of banana blossoms. In case of these blossoms, the drying takes place in the falling rate period. This indicates that diffusion is the main physical mechanism governing moisture migration in the samples. Similar results were obtained by Togrul IT[14] for apricots,[20] for red chillies,[21] for radish,[22] for broccoli, and[23] for okra. The effect of temperature used for the drying process was most remarkable with moisture ratio reducing rapidly with increased temperature. Several investigators have reported a significant increase in the drying rates when higher temperatures were used for drying various agricultural products such as red pepper,[24] eggplant,[25] okra,[7] canola,[26] pepino fruit[27] and chilli.[28]

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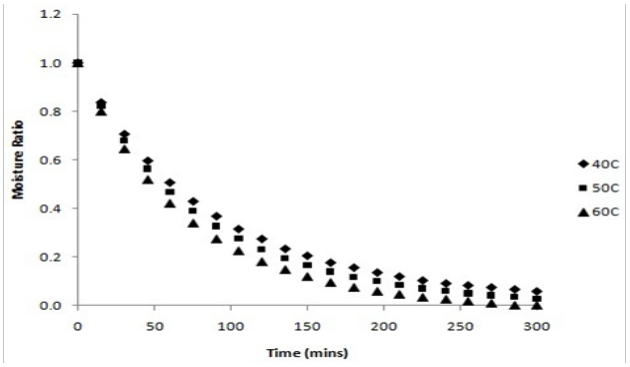

Figure 1 Effect of air temperature and time on the moisture ratio of banana blossoms.

Evaluation of the mathematical models

In order to determine the moisture content as a function of drying time, Newton, Modified Page, Henderson and Pabis, Modified Henderson and Pabis, Logarithmic, Two term, Two term exponential, Verma et al., Wang and Singh and Midilli et al. [35] empirical models were fitted. The statistical analysis values are summarized in Tables 2–4. All the models gave high coefficient of determination (R^2) values in the range 0.9697-0.9998 at 40°C, 0.9615-0.9998 at 50°C and 0.9474-0.998 at 60°C. This indicates that all the models could satisfactorily describe the air-drying of the banana blossoms. Among the thin layer drying models, the Logarithmic model obtained the highest R^2 values of 0.9998, 0.9998 and 0.9997 at 40°C, 50°C and 60°C respectively. Similarly, the lowest RMSE values were obtained in the logarithmic model over the specified temperature range. Thus, this model may be assumed to present the thin-layer drying behavior of the blossoms.

Calculation of moisture diffusivity and activation energy

Fick's second law gives the solution of the most widely studied theoretical model in thin layer drying of various foods. Considering a constant moisture diffusivity, infinite slab geometry and uniform initial moisture distribution,[29] a simplified equation can be formed by taking the first term of series solution.

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

where D_{eff} is the effective diffusivity (m^2/s), L is the half thickness of the samples (m), and n is a positive integer. The natural ln (MR) versus time was plotted and a straight line with a slope k_0 was obtained. The effective diffusivity is calculated from the slope.

$$k_0 = \frac{\pi^2 D_{eff}}{4L^2} \quad (5)$$

The effective diffusivity values of dried samples at 40-60°C were varied in the range of 5.45-8.09 x 10^{-9} m^2/s. The determined values of Deff for different temperatures are given in Figure 2. The values lie within the general range of $10^{-11}m^2/s$ to $10^{-9}m^2/s$ for food materials.[5] It can be observed that the values of Deff increased significantly with increasing temperature. Drying at 60°C gave the highest Deff values. Deff values for the banana blossoms are similar to those estimated by different authors for vegetables: 1.3x 10^{-9} to 7.76x10^{-10} m^2/s for okras dried from 50°C to 70°C, 0.776x10^{-9}-9.335x10^{-9} m^2/s for carrot dried from 50°C to 70°C.[30]These values are consistent with the present estimated Deff values for the blossoms.

To obtain the effect of temperature on the effective diffusivity, the values of ln (D_{eff}) versus 1/T, are plotted as shown in Figure 3. The plot was found to be a straight line over the temperature range investigated, thereby indicating Arrhenius dependence.

$$D_{eff} = D_0\, exp\left(\frac{E_a}{R(T+273.15)}\right) \quad (6)$$

Where D_0 is the pre-exponential factor of Arrhenius equation (m^2/s), Ea is the activation energy (kJ/mol), T is the temperature of air (°C) and R is the gas constant (kJ/mol K). The activation energy calculated from the slope of the straight line in Figure 3 and was found to be 50.06kJ/mol.

Table 2 Curve fitting criteria for the mathematical models and parameters at 40°C air temperature

Model name	Model constants	Determination of coefficient (R^2)	Root mean square error (RMSE)	Chi-square (χ^2)
Newton	k=0.0107	0.9971	0.0147	0.000218
Modified Page	k=0.1035 n=0.1038	0.9971	0.0151	0.000229
Henderson and Pabis	a=0.9758 k=0.0104	0.9979	0.0129	0.000166
Modified Henderson and Pabis	a=0.9534 b=0.0819 c=-0.0352 g=0.7681 h=0.8396 k=0.0102	0.9986	0.0116	0.000014
Logarithmic	a=0.9573 c=0.0358 k=0.0117	0.9998	0.0037	0.000119

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Table continued..

Model name	Model constants	Determination of coefficient (R^2)	Root mean square error (RMSE)	Chi-square (χ^2)
Two term	a=0.9534 b=0.0465 k_0=0.0102 k_1=4.0450	0.9986	0.0109	0.000102
Two term exponential	a=0.0533 k=0.1901	0.9987	0.0101	0.000113
Verma et al.	a=0.9534 g=9.9030 k=0.0102	0.9986	0.0106	0.002383
Wang and Singh	a=-0.0080 b=0.000017	0.9697	0.0488	0.000025
Midilli et al.	a=0.9905 b=0.000105 k=0.0112	0.9997	0.0050	0.000025

Table 3 Curve fitting criteria for the mathematical models and parameters at 50°C air temperature

Model name	Model constants	Determination of coefficient (R^2)	Root mean square error (RMSE)	Chi-square (χ^2)
Newton	k=0.0123	0.9993	0.0074	0.000055
Modified Page	k=0.1106 n=0.1113	0.9993	0.0076	0.000058
Henderson and Pabis	a=0.9864 k=0.0121	0.9995	0.0063	0.000040
Modified Henderson and Pabis	a=0.9714 b=0.0728 c=-0.0442 g=0.7681 h=0.8396 k=0.0119	0.9998	0.0050	0.000017
Logarithmic	a=0.9804 c=0.0121 k=0.0126	0.9998	0.0042	0.000022
Two term	a=0.9714 b=0.0285 k_0=0.0119 k_1=4.0430	0.9998	0.0047	0.000019
Two term exponential	a=0.0287 k=0.4154	0.9998	0.0044	0.000020
Verma et al.	a=0.9714 g=9.9170 k=0.0119	0.9998	0.0045	0.003175
Wang and Singh	a=-0.0085 b=0.000018	0.9615	0.0563	0.000022
Midilli et al.	a=0.9912 b=0.000035 k=0.0124	0.9997	0.0047	0.000022

Table 4 Curve fitting criteria for the mathematical models and parameters at 60°C air temperature

Model name	Model constants	Determination of coefficient (R^2)	Root mean square error (RMSE)	Chi-square (χ^2)
Newton	k=0.0144	0.9995	0.0063	0.001595
Modified Page	k=0.1433 n=0.1006	0.9995	0.0065	0.001679
Henderson and Pabis	a=0.9969 k=0.0143	0.9995	0.0064	0.001683

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Table continued..

Model name	Model constants	Determination of coefficient (R^2)	Root mean square error (RMSE)	Chi-square (χ^2)
Modified Henderson and Pabis	a=0.9927 b=0.0622 c=-0.0549 g=0.7681 h=0.8396 k=0.0143	0.9995	0.0071	0.001827
Logarithmic	a=1.0010 c=-0.0093 k=0.0139	0.9997	0.0048	0.001888
Two term	a=0.9927 b=0.0073 k_0=0.0143 k_1=4.0390	0.9995	0.0067	0.001684
Two term exponential	a=0.0073 k=1.9600	0.9995	0.0063	0.001783
Verma et al.	a=0.9927 g=9.9370 k=0.01432	0.9995	0.0065	0.006082
Wang and Singh	a=-0.0091 b=0.000020	0.9474	0.0670	0.001828
Midilli et al.	a=0.9923 b=-0.000003 k=0.0140	0.9998	0.0043	0.001828

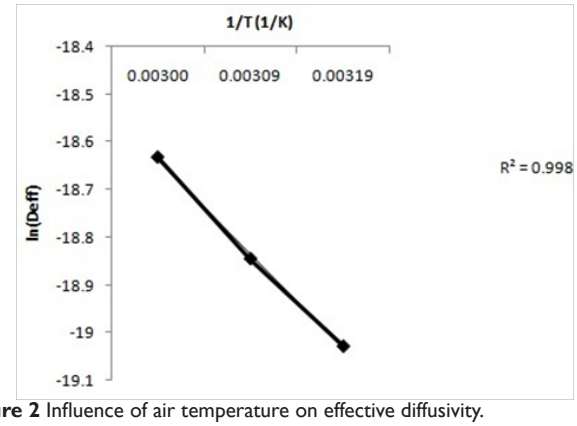

Figure 2 Influence of air temperature on effective diffusivity.

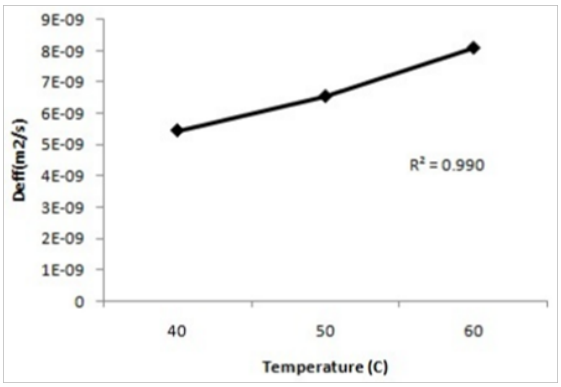

Figure 3 Effect of air temperature on effective diffusivity.

Table 5 shows the effective diffusivity of the present study as well as information available in the literature. The activation energy for water diffusion in banana blossom is higher than activation energies of dill leaves, parsley leaf, pistachio nuts and bean drying but lower than okra andmint leaves. The values of the energy of activation lie within the general range of 12.7-110 kJ/mol for food materials.[31]

Table 5 Activation energies of banana blossom and other agricultural products

Agricultural products	E_a (kJ/mol)	References
Okra	51.26	[7]
Dill and Parsley leaves	35.05 and 43.92	[63]
Mint leaves	82.93 and 62.96	[64,65]
Pistachio nuts	30.79	[66]
Beans	35.43	[67]

Effect of drying on the nutritional properties of banana blossoms

The chemical composition of fresh and dried banana blossom at temperatures of 40, 50 and 60°C are shown in Table 6. During the drying process, moisture loss occurs due to the difference in water vapor pressure between the product and the air surrounding it. This process increases the shelf life due to the lower availability of water for activity of microorganisms and enzymes, also resulting in fewer nutritional and sensorial alterations.[32] The initial moisture content of the banana blossoms were 87.3g/100g. Approximately similar values have been reported for the blossoms (89.42-90.58g/100g).[1] All these flowers had high moisture levels, implying they have very short shelf life. The time taken to reduce the moisture content of the blossoms

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from the initial 87.3 (% w.b) to 8.9±0.1 (%w.b) was 300, 240 and 195min at 40, 50 and 60°C respectively. The protein content of the dried sample was between 1.78 to 1.93g/100g, over the temperature range. Though there was a slight variation in the protein content, selected range of temperature does not significantly affect the protein content. Heating generally improves the digestibility of foods, making some nutrients more available as in the case of proteins in legumes.[33]

The fat content was low in banana blossoms and ranged from 0.31 to 0.58g/100g when dried at temperatures between 40 and 60°C, similar reduction in fat content during increasing air temperature during drying has been reported in previous literature. The ash content in fresh banana blossoms differed significantly from blossom subjected to drying. The ash content across the temperature range varied from 1.35 to 1.42g/100g. This might have resulted from the temperatures applied which degrade the micronutrients represented in the analysis of ashes. Regarding the total crude fiber content, there was no difference between the treatments. The fresh sample contains 20.97±0.02g/100g of total crude fiber. A considerable decrease in the crude fiber content was observed during the drying process. The higher crude fiber content of the banana blossoms usually leads to increase in absorption and adsorption of water. Therefore, the samples dried over the temperature range can easily rehydrate during consumption.

Usually, thermal treatments have destructive effect on the flavonoids and phenolic compounds as they are highly unstable compounds.[34] With respect to fresh samples, the dried ones presented lower total phenolic contents. There was no statistical difference when analyzing the effect of different temperatures in relation to the content of phenolic compounds. Therefore, the highest temperature can be considered to be the most viable, since it reduces the time and consequently the costs of processing, resulting in amounts of phenols statistically equal to the other temperatures. The content of total flavonoids expressed as quercetin equivalence varied from 281.81 to 335.85mg QE/100g from 40 to 60°C.

Table 6 Nutritional composition of fresh and dried banana blossoms

Analysis	Fresh sample	Dried sample		
		40°C	50°C	60°C
Moisture content, g/100g	87.3±0.11	8.9±0.16	8.9±0.04	9.0±0.01
Protein, g/100g	2.1±0.03	1.9±0.03	1.8±0.06	1.7±0.08
Fat, g/100g	0.6±0.01	0.5±0.08	0.5±0.03	0.4±0.09
Ash, g/100g	5.42±0.04	1.41±0.01	1.39±0.01	1.37±0.02
Total crude fiber, mg/100g	20.97±0.02	19.76±0.03	18.55±0.01	17.63±0.01
Total polyphenols, mg GAE/100g	5481.48±0.29	5470.16±0.52	5409.75±0.86	5373.58±0.75
Total flavonoids, mg QE/100g	359.26±0.10	335.59±0.26	304.94±0.52	281.32±0.49

Conclusion

Drying kinetics of banana blossoms was investigated in a laboratory scale hot-air dryer, at a temperature range 40-60°C. Based on this study, the following conclusions can be stated:

i. Drying air temperature is a significant factor in drying of banana blossoms.

ii. Higher drying air temperature resulted in a shorter drying time.

iii. Drying of the blossoms takes place in the falling rate period.

iv. The effective diffusivity was calculated from the data and varied from 5.45 x 10-9 to 8.09 x 10^{-9} m^2/s with the temperature dependence represented by a simple Arrhenius-type relationship. The activation energy for moisture diffusion was found to be 50.06kJ/mol.

v. The Logarithmic model with the generalized k and n fits the thin-layer drying characteristics of the blossoms well.

vi. Drying at the selected temperature range did not significantly affect the nutritional properties of banana blossoms.

vii. The quality of the dried product was found to be best when the blossom was dried at 60°C. The dried blossoms can be rehydrated and used in ready to eat foods.

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None.

Conflict of interest

Author declares that there is no conflict of interest.

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