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Prediction of diffusion coefficient for losses of minerals from potato during frying

Samir, Z.T., Saeed, S.K., *Mohammed, N.K. and Abdul-Rezzak, R.K.

Department of Food Science, College of Agriculture, Tikrit University, 34001 Tikrit, Iraq

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Abstract

This study assessed the diffusion coefficient (*Da*) for mineral losses from potatoes during the frying process under various conditions by using the solution to Fick's second law for a slab of infinite extent in non-dimensionalized form. Diffusion coefficient values increased as potato cube frying temperature increased from 65°C to 95°C in 16 mins. Calcium (Ca) had values ranging between 3.693×10^{-10} to 3.9872×10^{-10} M^2S^{-1}; Iron (Fe) ranged between 2.931×10^{-10} to 3.314×10^{-10} M^2S^{-1}; Magnesium (Mg) ranged between 5.576×10^{-10} to 7.666×10^{-10} M^2S^{-1}; Potassium (K) ranged between 7.841×10^{-10} to 8.516×10^{-10} M^2S^{-1}, and Sodium (Na) ranged between 2.823×10^{-10} to 3.513×10^{-10} M^2S^{-1}. It was found that the effect of temperature on the diffusion coefficient had an Arrhenius-type equation correlation. Activation energy values for Ca, Fe, K, Mg, Na loss in potato were 10.49 kJ/mol, 8.17 kJ/mol, 12.85 kJ/mol, 11.16 kJ/mol, and 9.98 kJ/mol, respectively. It was found that the diffusion coefficient (*Da*) values for minerals losses were independent of diameter in the 0.5 to 1.5 cm range. Diffusion coefficients (*Da*) for Ca were observed as 2.961×10^{-10} M^2S^{-1} and 2.632×10^{-10} M^2S^{-1} for 1.0 cm and 0.5 cm diameters, respectively, when tested at 75°C for 16 mins. Mg had *Da* values of 6.722×10^{-10} M^2S^{-1} and 6.891×10^{-10} M^2S^{-1}at 1.0 cm and 0.5 cm, respectively. Potassium had coefficient values of 8.013×10^{-10} M^2S^{-1} and 8.319×10^{-10} M^2S^{-1} at 1.0 cm and 0.5 cm, respectively, at similar testing conditions. Therefore, dimensions do not affect the diffusion coefficient significantly.

1. Introduction

Knowledge concerning the mass transfer and nutrient diffusivity during vegetable tissue processing is becoming an important factor for the food industry because mass diffusion rate determines the characteristics of the finished product, process modelling, and the nature of the equipment. While the literature contains additional information concerning the application of Fick's rule to estimate portion diffusivity in food (Siripatana 1997; Rittirut and Siripatana 2007), very few studies examine vegetable diffusivity and mass transfer characteristics as functions of time, temperature, concentration, and other factors (Rice *et al*., 1990; Selman 1994; Guine *et al*., 2017; Khan *et al*., 2017; González-Pérez *et al*., 2021). The numerical solution specific to the non-steady-state diffusion equation for diffusion pertaining to slabs and cylinders was analysed, considering diffusion as the primary rate-controlling step. It was successfully used to describe and predict reducing sugar loss from potato during blanching at 60, 75 and 90°C (Pedreschi *et al*., 2009).

Via experimental data, Crank *et al.* (1979), offer an excellent overview of mass transfer models based on Fick's diffusion differential equation. It is standard practice to characterize full mass transfer using the same equation as diffusion and to compensate for all secondary forms of mass transfer by simply substituting an effective diffusion coefficient for the diffusion coefficient (Vasić *et al*., 2014). Abdul-Rezzak (2011), determined the diffusion coefficients (*Da*) for heat-processing induced solute loss from pea were studied under various conditions. The values were 3.5×10^{-9} M^2S^{-1} at 65°C and 2.5×10^{-8} M^2S^{-1} at 85°C, it was found that the temperature coefficient varied with temperature according to the Arrhenius equation for 41.57 kJ/mol activation energy. Correa *et al*. (2017) studied the vacuum frying of breadfruit in terms of moisture and oil thermal diffusivity coefficients. The real oil absorption rate was measured using a first-order kinetic model, and mass transfer coefficients were determined from graphs of dimensional temperature and moisture content ratios vs. time. It was discovered that the diffusion coefficient increased with time.

*Corresponding author.
Email: *nameer@tu.edu.iq*

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Frying is one of the oldest unit operations and is used not only in industry but also at home. The most fried vegetable is potato, for important commercial products such as potato chips, pan-fried potatoes, and French fries. Therefore, the study of the mineral loss during frying is critical because knowledge regarding kinetics parameters will enable the prediction of the final quality of fried potatoes and improvements in the final product value by selecting properly the processing conditions. The objective of this study was to calculate activation energy values for mineral loss via diffusion using diffusion coefficient (*Da*) values for different tissue sizes (0.5, 1.0, and 1.5 cm), frying times (4, 7, 10, 13, 16 mins), and temperatures (65, 75, 85, and 95°C).

2. Materials and methods

2.1 Materials and sample preparation

Fresh potatoes were purchased from the local market in Tikrit, Iraq. They were washed and then dried at 10-15°C, subsequently, the potatoes were stored in polyethene bags until further analysis. About 5-7 potatoes were washed and used for sample preparation to ensure consistency. Potato samples were prepared in the form of 1 cm cubes. The cubes were placed in a sealed beaker to prevent surface evaporation. Sample testing was performed by frying the cubes. This preparation process was used to reduce compositional variation between potato cubes.

2.2 Frying apparatus

The frying technique was used, as described by Selman and Rolfe, (1979). An electrically heated hot plate was set at the required temperature (65, 75, 85 and 95°C) at different times (4, 7, 10, 13, 16 mins) and used with a Bunsen burner to maintain frying temperature. Blanch temperature drop caused by sample addition to oil was minimised by placing the metal beaker over Bunsen flame for 20 s before placing the metal beaker on the hot plate. The oil frying in the metal beaker was agitated using a magnetic stirrer (Gallenkamp, England) set at 120 rpm. An aluminium foil lid was used to cover the beaker to reduce oil evaporation during frying. Changes to oil temperature were measured using a thermometer (Memmert, Germany) kept inside the beaker.

2.3 Frying process

Samples (9 cubes of potato tuber) weighing about 10.50±0.30 g were fried using a 250 mL metal beaker having 100 mL oil. The frying sample had approximately a 1:5 oil-to-sample ratio (unless specified otherwise).

The nine untreated potato cubes were fried as one lot. Frying time ranged between 3- and 15-mins (4, 7, 10, 13, 16 mins). Frying time was recorded from the moment the potato cubes were dipped in the frying medium. After frying for the required duration, the potato cubes were drained over a funnel and blotted using absorbent paper to remove surface oil. The cubes were then placed in Petri dishes and weighed. The cubes were treated with caution during cooling.

2.4 Determination of minerals

Atomic Absorption type E LCO (Shimadzu- 6200 Japan) was used to estimate Ca, K, Fe, Na, and Mg in potato samples as per AOAC (2004).

2.5 Production of diffusion confident

If frying oil is agitated sufficiently, surface resistance becomes small because maximum agitation causes the mass transfer coefficient (K) to become large. Subsequently, relative resistance (m) approaches zero as specified below:

$$m = \frac{Da}{ka}$$

Thus, it may be assumed that the total resistance to mass diffusion is only due to 'internal' resistance. Therefore, we only require the solution to Fick's second law (Vasić *et al.*, 2014). For geometric shapes, slab having infinite dimensions, a cylinder having an infinite length, and a sphere, the average concentration is obtained after integration considering a position as a function of time, again in non-dimensional shape:

For slab:

$$\frac{C^{-}-C0}{C-C0} = \frac{6}{\pi^2} = \sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-n^2\left(\frac{4Dt}{d^2}\right)\pi^2\right)$$

For sphere:

$$E = \frac{C^{-}-C0}{C1-C0} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left[-n^2\left[\frac{Dat}{a^2}\right]\pi^2\right] = E_s$$

For cylinder:

$$E = \frac{C^{-}-C0}{C1-C0} = 4\sum_{n=1}^{\infty}\frac{1}{Rn^2}\exp\left[-\left[\frac{Dat}{a^2}\right]Rn^2\right] = Er$$

Where R_n is the root of the equation;

$J_0(X) = 1 + \sum_{n=1}^{\infty}(-1)^n\frac{x^{2n}}{(2n)!1} = 0$; A: linear dimension; half of ring diameter or circle, half of the slab thickness (m), C^-: mean (fried) sample concentration at time t (per cent), C_l: standardised concentration of the fresh non-fried initial sample (per cent), C_o: concentration of the medium, J: The Bessel zero-order function, N: Root count, *Da*: Mass diffused, T: time

In the case of a cube:

with three faces Z,Y,X, diffusion from

$$E = f\left(\frac{Dat}{X^2}\right) f\left(\frac{Dat}{Y^2}\right) f\left(\frac{Dat}{Z^2}\right) = E_x E_y E_z$$

$\frac{Dat}{a^2}$ can be obtained using the value of:

$$\frac{Dat}{a^2} \text{ Versus } \frac{C^- - C0}{C1 - C0}$$

2.6 Heat activation prediction

The most common and typically correct inference is that the temperature-dependence of diffusion coefficient fits the Arrhenius equation (Al-janaby, 2012). It can be stated as:

$$K = A \exp\left(\frac{-Ea}{RT}\right)$$

Where: A is constant having dimension M^2S^{-1}, E = activation energy (kJ/ mol), R = gas constant (8.314 J k^{-1} mol^{-1}), T = absolute temperature (K)

Activation energy is usually derived from the slope of ln (*Da*) vs T plot (which is the activation energy divided by the gas constant R), as specified below:

(Ea) = - SR

Where S is the straight-line slope and E and R were as specified.

2.7 Statistical analysis

The experimental results were analysed statistically, using the SAS program. Statistical analysis is described as mean±standard deviation and is found to be statistically significant at $p<0.05$.

3. Results and discussion

3.1 Effect of temperatures and time on concentrations

During the frying process, mass transfer mainly refers to the evaporation of water from the food material to the oil as well as the uptake of oil by food material (Xu *et al.*, 2020). Potato cubes were fried several times for up to 16 mins at 65, 75, 85 and 95°C. Figures 1, 2, 3, 4, and 5 depict the resulting mineral concentrations. A similar trend was found with increasing temperature, causing declining mineral concentration. All experiments exhibited a similar trend. The most significant concentration drop is observed during the first three mins, resulting in a greater total loss for every frying period. Similar results are observed for different temperatures and minerals, it is indicative of a common pattern of diffusive loss during frying. This finding was in agreement with the reported study of (Pedreschi *et al.*, 2005) which indicated diffusivity increased with the frying time and temperature and depended principally on the moisture content of the potato slices during frying.

3.2 Effect of temperatures on the diffusion coefficient

Da values are determined from the curves and listed in Table 1. It indicates the mean *Da* values during the 4-16 mins period when mineral losses tend to occur only by diffusion. The values of the diffusion coefficient were found to increase with frying temperature increasing from 65°C to 95°C. Within 16 mins, the values range from 3.693×10^{-10} to 3.9872×10^{-10} M^2S^{-1} for Ca, 3.044×10^{-10} to 6.921×10^{-10} M^2S^{-1} for Fe, 2.650×10^{-10} to 4.576×10^{-10} M^2S^{-1} for K, 1.416×10^{-10} to 4.444×10^{-10} M^2S^{-1} for K, and 2.931×10^{-10} to 4.189×10^{-10} M^2S^{-1} for Na. This is in agreement with the findings of (Al-janaby, 2019), concerning the blanching of potatoes and carrots. The diffusion coefficient values increased with an increase in medium temperature from 65°C to 95°C. The values ranged from 5.576×10^{-10} to 7.666×10^{-10} M^2S^{-1} for Ca, 3.044×10^{-10} to 6.921×10^{-10} M^2S^{-1} for Fe, 2.650×10^{-10} to 4.576×10^{-10} M^2S^{-1} for K, 1.416×10^{-10} to 4.444×10^{-10} M^2S^{-1} for Mg, and 2.931×10^{-10} to 4.189×10^{-10} M^2S^{-1} for Na for potatoes. The values for carrot ranged from 7.013×10^{-10} to 7.638×10^{-10} M^2S^{-1} for Ca, 1.855×10^{-10} to 4.314×10^{-10} M^2S^{-1} for Fe, 3.851×10^{-10} to 4.467×10^{-10} M^2S^{-1} for K, 2.103×10^{-10} to 4.308×10^{-10} M^2S^{-1} for Mg, and $1.946\times10^{-}$

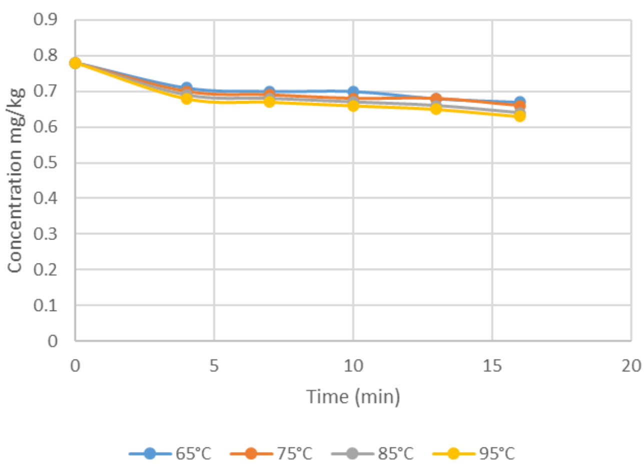

Figure 1. Concentration of calcium at different temperature and time for the potato cubes

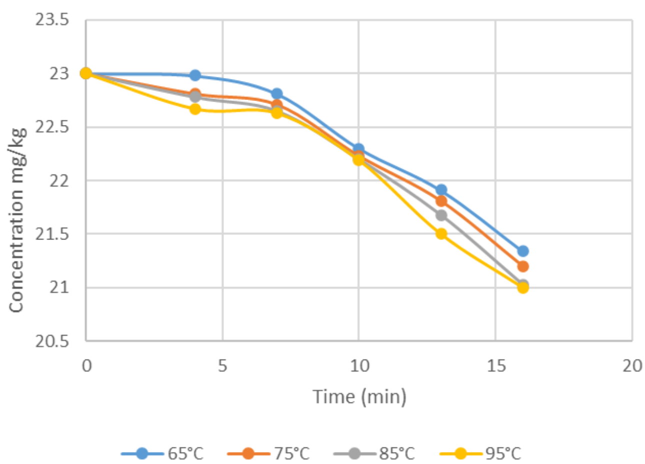

Figure 2. Concentration of iron at different temperature and time for the potato cubes

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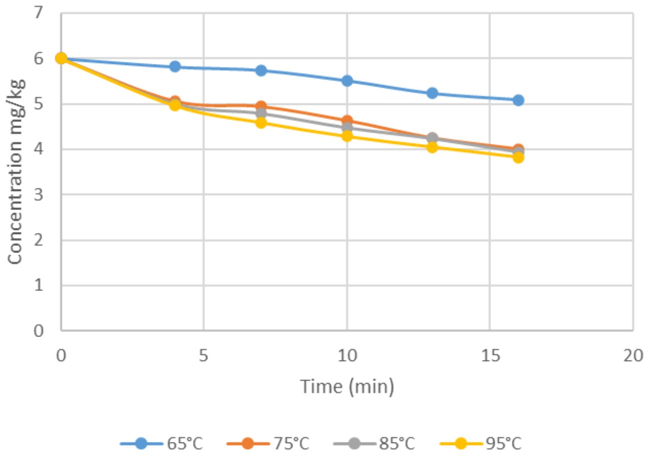

Figure 3. Concentration of magnesium at different temperature and time for the potato cubes

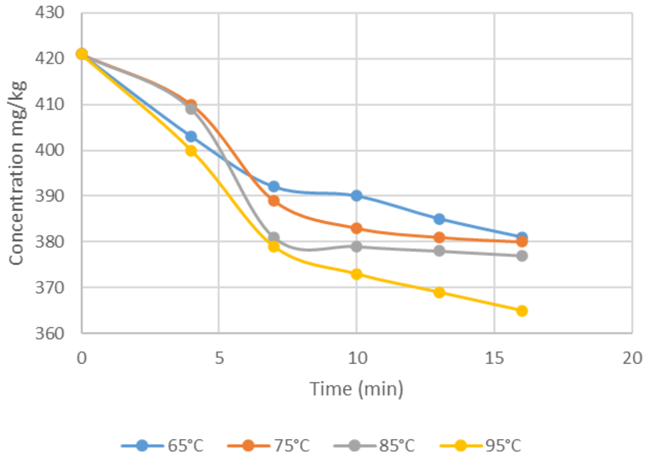

Figure 4. Concentration of potassium at different temperature and time for the potato cubes

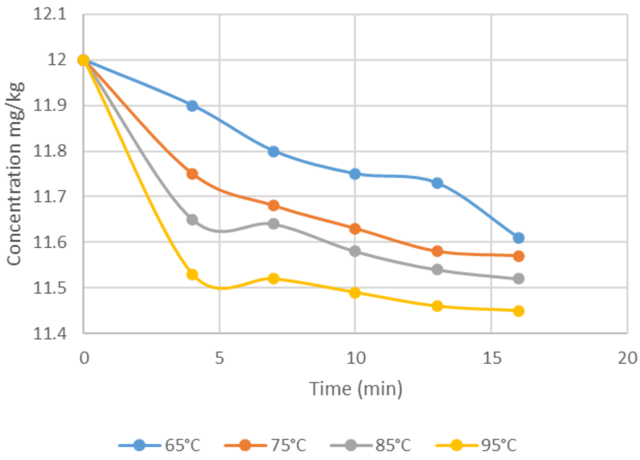

Figure 5. Concentration of sodium at different temperature and time for the potato cubes

Table 1. Apparent diffusion coefficients (*Da*) for the loss of minerals from potato cubes when fried in oil under the conditions given (data from curves in Figures 7, 8, 9, 10, and 11)

Temperature	Mineral	$Da \times 10^{-10}$ M^2S^{-1}					Mean
		Time (min)					
		4	7	10	13	16	
65°C	Ca	3.013	3.190	3.384	3.431	3.693	3.3422
	Fe	1.850	1.941	2.598	2.872	2.931	2.4384
	Mg	5.055	5.209	5.292	5.365	5.576	5.2994
	K	7.286	7.339	7.459	7.631	7.841	7.5112
	Na	2.220	2.508	2.703	2.789	2.823	2.6086
75°C	Ca	3.235	3.348	3.678	3.831	3.883	3.5950
	Fe	1.931	2.231	2.610	2.975	3.011	2.5506
	Mg	5.222	5.372	6.018	6.592	6.722	5.9852
	K	7.513	7.681	7.783	7.915	8.013	7.7806
	Na	2.401	2.738	2.795	2.855	2.961	2.7500
85°C	Ca	3.360	3.419	3.718	3.981	4.021	3.6998
	Fe	2.011	2.231	2.715	3.014	3.213	2.6322
	Mg	6.583	6.718	6.844	6.875	6.988	6.8016
	K	7.731	7.813	7.952	8.034	8.141	7.9342
	Na	2.738	2.923	3.011	3.123	3.278	3.0146
95°C	Ca	3.531	3.781	3.934	4.256	4.434	3.9872
	Fe	2.234	2.458	2.896	3.214	3.314	3.2600
	Mg	7.256	7.319	7.359	7.527	7.666	7.4254
	K	7.931	8.063	8.214	8.413	8.516	8.2274
	Na	2.981	3.121	3.234	3.451	3.513	3.2600

^{10} to 3.769×10^{-10} M^2S^{-1} for Na. As can be seen, the values obtained for *Da* are similar to those reported during the frying of potato slices (Yıldız *et al*., 2007). The values ranged from $3.86\pm0.05\times10^{-9}$ M^2S^{-1} at 150°C to $1.72\pm0.02\times10^{-8}$ M^2S^{-1} at 180°C while diffusivity values obtained by Barrios *et al* (2016) for frying pea were (0.1551×10^{-9}, 0.1787×10^{-9} y $0.2371x\ 10^{-9}$ M^2S^{-1}) at 160, 180 and 200°C, respectively. Also, heat transfer coefficient was found by Pedreschi *et al*. (2005) to decrease with increasing oil temperature. Mass transfer coefficient increased linearly, whereas moisture diffusivity increased exponentially with an increase in frying temperature. An Arrhenius type of relationship was found between the frying temperature and the effective moisture diffusivity.

The highest measured diffusion coefficients for a given temperature were 8.2274×10^{-10} M^2S^{-1} for K loss, 7.4254×10^{-10} M^2S^{-1} for Mg, 3.9872×10^{-10} M^2S^{-1} for Ca, 3.2600×10^{-10} M^2S^{-1} for Na, and 3.2600×10^{-10} M^2S^{-1} for Fe. Temperature variation shows a change between 65 and 95°C. It is probably due to the gelatinisation of the starch granules. An Arrhenius-type equation can correlate the effect of temperature on the diffusion coefficient. A graph of In *Da* (mean values) versus 1/T (Figure 6) shows that *Da* can be related to temperature by an Arrhenius type equation:

$$Da = Do \exp(-Ea/RT)$$

From this graph, the values of *Ea* were calculated as 10.49, 8.17, 12.85, 11.16, and 9.98 kJ/mol for Ca, Fe, K, Mg, and Na, respectively. This is in agreement with the study reported by Manjunatha *et al*. (2014), activation energies for other temperature-dependent changes occur in plant foods when undergoing processing. Water blanching of peas at 75-95°C was associated with an Ea of 41.57 kJ/mol, the activation energies for moisture loss and oil uptake were found to be 41.53 KJ/mol and 27.12 KJ/mol respectively. Also, the frying pea was evaluated by Barrios *et al*. (2016) and the Ea value was 18.13 kJ/mol. Additionally, Al-janaby, (2019) reported Ea of 45.12 kJ/mol for Ca loss, 48.14 kJ/mol for Fe loss, 50.10 kJ/mol for K loss, 46.11 kJ/mol for Mg loss, and 41.87 kJ/mol Na loss from potato. Carrot had 40.06 kJ/mol for Ca loss, 47.42 kJ/mol for Fe loss, 31.03 kJ/mol for K loss, 43.02 kJ/mol for Mg loss, and 45.10 kJ/mol for Na loss. As determined in these experiments, the differences in diffusion coefficient between the five minerals can be attributed to the relative difference in molecule size. Also, this difference may be partly due to the initial concentration difference between the tissues and minute structural differences between tissues.

Results indicated that increasing frying time led to a more rapid decrease in concentration, which resulted in a greater overall loss after frying. Other researchers have

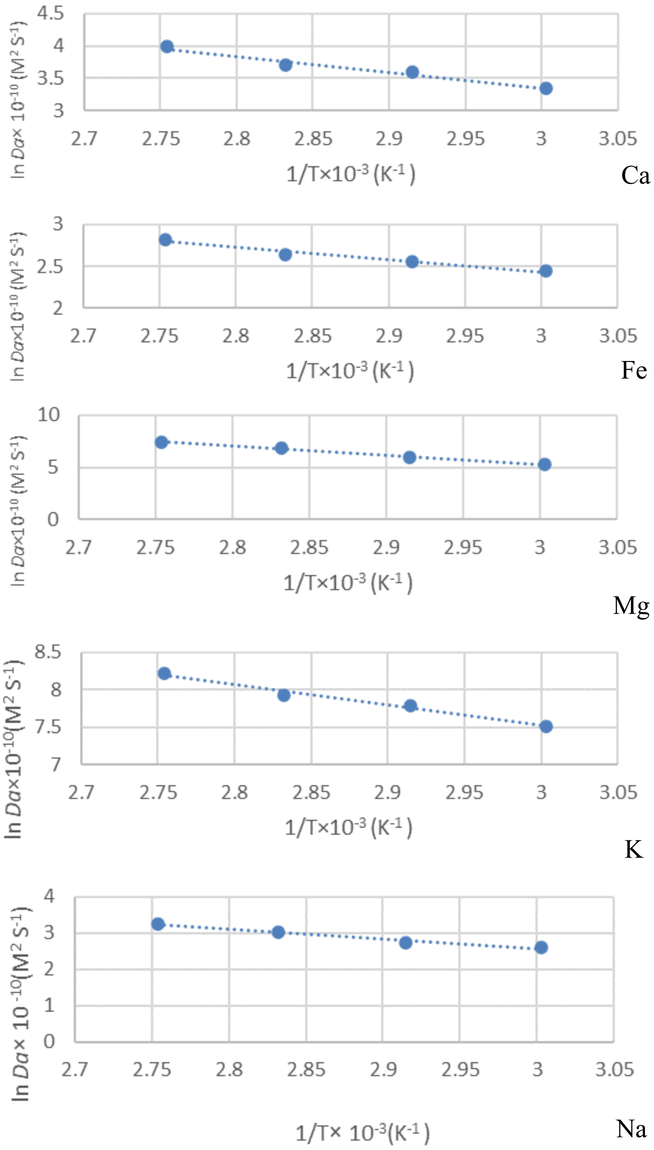

Figure 6. $10^{-3}(K^{-1}\times/1T$ versus)ln $Da\times10^{-10}(M^2S^{-1})$

reported similar results that frying for high temperatures and long times of potato strips resulted in higher losses of content than in normal conditions (Gupta *et al*., 2000; Krokida *et al*., 2001). Data concerning mineral diffusion rate was obtained from the literature; a similar behaviour is reported. Diffusion rate increases directly with frying time. In most cases, the concentration decrease rate slowed noticeably after five mins due to the lower concentration gradient between the frying medium and tissue. The deterioration of cell membranes during prolonged frying possibly increased the mineral loss in tubers. It also facilitated the leaching of soluble substances and minerals during frying. On the other hand, some authors reported that not only the frying temperature but also the time, dimension and pretreatment have a significant effect on the final oil content of the potato strips and nutrient losses (Gamble *et al*., 1987; Rice and Gamble 1989).

3.3 Effect of dimensions on the diffusion coefficient

Cubes having different dimensions – 0.5, 1.0, and

1.5 cm were prepared. These were fried several times up to 16 mins at 75°C. Concentration changes are shown in Figures 7, 8, 9, 10, and 11. The rate of decrease of mineral concentration appears to increase as cube diameter decreases. Table 2 indicates that diameter also influences *Da* values for the first three mins of frying; thereafter, *Da* values are similar for the three cases. Mean *Da* values are listed: $2.961\times10^{-10}\,M^2S^{-1}$ for 1.0 cm Ca cube, $2.632\times10^{-10}\,M^2S^{-1}$ for 0.5 cm Ca cube after 16 mins at 75°C; $6.722\times10^{-10}\,M^2S^{-1}$ for 1.0 cm Mg cube, $6.891\times10^{-10}\,M^2S^{-1}$ for 0.5 cm Ca cube; $8.013\times10^{-10}\,M^2S^{-1}$ for 1.0 cm K cube, $8.319\times10^{-10}\,M^2S^{-1}$ for 0.5 cm K cube at similar conditions.

$10^{-3}(K^{-1}\times/1T$ versus $\ln Da\times10^{-10}(M^2S^{-1})$ (Figure 6)

This indicates that *Da* is independent of diameter when the solute loss occurs by diffusion, as expected. However, the actual mineral loss is expected to increase with surface area, and it was found to be true.

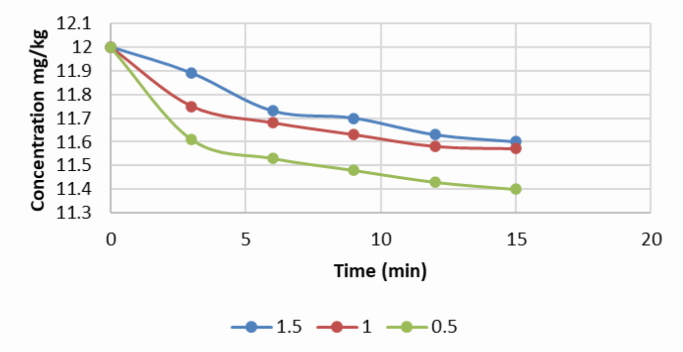

Figure 7. Concentration of calcium at 75°C at different dimension and time for the potato cubes

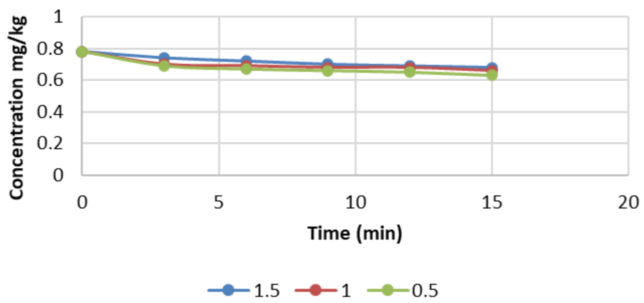

Figure 8. Concentration of iron at 75°C at different dimension and time for the potato cubes

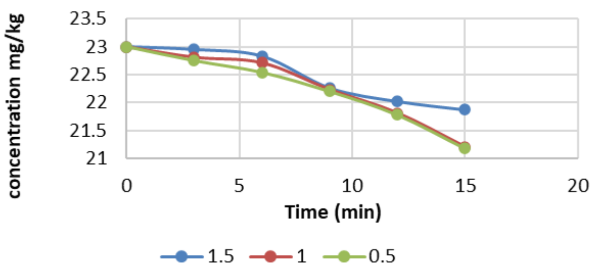

Figure 9. Concentration of magnesium at 75°C at different dimension and time for the potato cubes

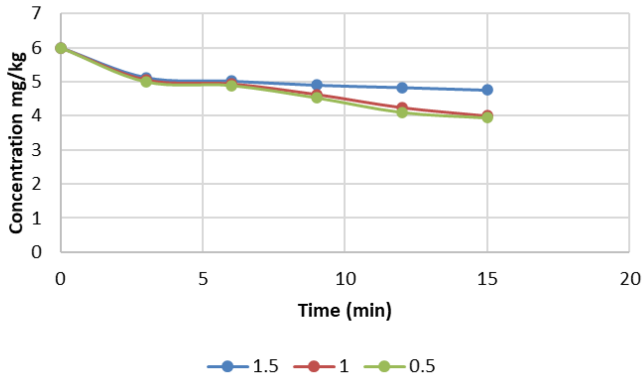

Figure 10. Concentration of sodium at 75°C at different dimension and time for the potato cubes

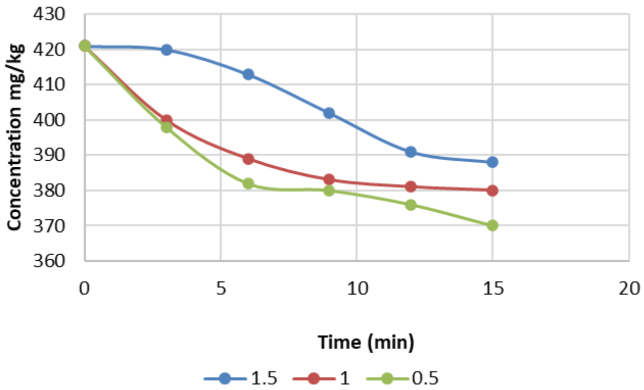

Figure 11. Concentration of potassium at 75ºC at different dimension and time for the potato cubes

4. Conclusion

A mass transfer model (the numerical solution for the unsteady state diffusion equation for diffusion from slabs), based on diffusion as the main rate-controlling step, was successfully used to describe and predict the mineral loss from potato tissue during frying. In general, *Da* values had the same order of magnitude as those reported for diffusive solids, vitamins, and minerals loss from other foodstuffs under different conditions. Between 65°C and 95°C, within 16 mins, the values range from 3.693×10^{-10} to 3.9872×10^{-10} M^2S^{-1} for Ca, 3.044×10^{-10} to 6.921×10^{-10} M^2S^{-1} for Fe, 2.650×10^{-10} to 4.576×10^{-10} M^2S^{-1} for K, 1.416×10^{-10} to 4.444×10^{-10} M^2S^{-1} for K, and 2.931×10^{-10} to 4.189×10^{-10} M^2S^{-1} for Na. Apparent diffusivities for all cases were found to be dependent on temperature; however, they were independent of tissue dimension and frying time. Recorded Ea values were 10.49, 8.17, 12.85, 11.16, and 9.98 kJ/mol for Ca, Fe, K, Mg, and Na, respectively. Further studies are required to investigate the effect of other shapes and dimensions on the potatoes in addition to the vitamins lost during deep frying.

Conflict of interest

The authors declare no conflict of interest.

Table 2. Apparent diffusion coefficients (*Da*) *f*or minerals loss from potatoes cubes when fried in oil under the given conditions (data from curves in Figures 7, 8, 9, 10, and 11)

Temperature 75°C	Dimension	$Da \times 10^{-10}$ M^2S^{-1} Time (min)					Mean
		4	7	10	13	16	
Ca	1.50 cm	2.631	2.891	2.951	3.033	3.159	2.933
	1.00 cm	2.401	2.738	2.795	2.855	2.961	2.750
	0.50 cm	2.231	2.416	2.576	2.595	2.632	2.490
Fe	1.50 cm	1.712	1.724	1.750	1.782	1.808	1.755
	1.00 cm	1.931	2.231	2.610	2.971	3.011	2.551
	0.50 cm	2.581	2.602	2.803	3.011	3.211	2.842
Mg	1.50 cm	5.032	5.101	5.236	5.438	5.534	5.268
	1.00 cm	5.222	5.372	6.018	6.592	6.722	5.985
	0.50 cm	5.456	5.891	6.234	6.631	6.891	6.221
K	1.50 cm	6.921	7.130	7.238	7.459	7.538	7.257
	1.00 cm	7.513	7.681	7.781	7.915	8.013	7.781
	0.50 cm	7.781	7.939	8.014	8.213	8.319	8.032
Na	1.50 cm	2.032	2.289	2.467	2.654	2.796	2.448
	1.00 cm	2.401	2.738	2.795	2.855	2.961	2.750
	0.50 cm	2.678	2.864	2.945	3.014	3.180	2.936

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