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ORIGINAL RESEARCH ARTICLE

MODELLING OF MOISTURE LOSS AND OIL UPTAKE DURING DEEP-FAT FRYING OF PLANTAIN *(DODO)*

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ABSTRACT

In this study, model was developed to predict moisture loss and oil uptake during deep-fat frying of plantain (*dodo*). Plantain samples were sliced and fried at different frying temperatures (150, 160, 170, 180 and 190 °C) in a deep fryer for periods varying from 2 to 4 min. Moisture and fat analyses were determined based on the AOAC standard method. Mathematical model was developed from fundamental law of mass diffusion with the aim of predicting moisture loss and oil uptake rate during DFF of *dodo*. The model was solved numerically using explicit Finite Difference Technique (FDT). Computer codes were written in MATLAB environment for moisture loss and oil uptake in the slices at different frying conditions. The predicted results were compared with experimental data and good agreement was obtained. The correlation coefficients between the predicted and experimental values of moisture and oil transfer models ranged from 0.988 to 0.994 and 0.958 to 0.978, respectively. The results show that the model is consistent and it may be used to predict moisture loss and oil uptake during deep-fat fried of *dodo*.

1. Introduction

Plantain (*Musa paradisiacal* AAB) belongs to the *Musacace* family and is cultivated in many tropical and subtropical countries of the world. Nigeria and Cameroon are the two major plantain producing, consuming and exporting countries in Africa and are ranked among the twenty most important plantain producing countries worldwide (FAO, 2013). It ranks third after yam and cassava for sustainability in Nigeria (Akomolafe and Aborisade, 2007). Plantain production in Nigeria was estimated at 2,722,000 metric tons in 2011, with an average consumption level of 190 kg/person/year (FAO, 2012).

Plantain is rich in carbohydrates, antioxidants like dopamine and minerals like potassium and calcium and caters for the calorific needs of people in many developing countries. (Kanazawa and Sakakibara, 2000; Mohapatra *et al.*, 2010). It is commonly consumed in fried form in Nigeria. Ripe plantain can be eaten raw on account of its content of vitamin C and other essential minerals. It is one of the green vegetables with the richest iron and other

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nutrient contents (Aremu and Udoessien, 1990). However, they are highly perishable and susceptible to fast deterioration, as a result of the high moisture content and high metabolic activity, which persists after harvest (Demirel and Turhan, 2003). Over the years, many value-addition processing had been applied to plantain to form many food products like fully ripe fried plantain (*dodo)*, boiled plantain, plantain flour, plantain chips (*ipekere*), beverage and others in order to curb deterioration and also add value to the product.

Deep-Fat Frying (DFF) can be considered as a high temperature and a short time process which involves both mass transfer, mainly represented by water loss and oil uptake, and heat transfer (Vitrac *et al.,* 2002). It is one of the major value addition processes for plantain of various ripening stages. DFF as a method of food processing combines high processing speed with good product appearance, although lower yield and higher fat content of fried products was also reported for the method (Ziaiifar *et al.,* 2008).The primary reason for the popularity of DFF foods may be desirable characteristics like soft, juicy interior as well as thick and crispy outer crust (Garcia *et al.,* 2002).

Fried plantain products remain popular in spite of all the health issues associated with high intake of dietary fibre. This is attributed to the unique textural and quality characteristics imparted by DFF. Consumers' knowledge of health implications of high calorie has necessitated the resolve by food manufacturers to seek means to optimize the process for minimal fat absorption while the desired qualities are preserved. Many previous studies on DFF of plantain have been limited to the parameter estimation of the solid-liquid phase contacting systems (Diaz *et al*., 1996) and effect of ripening stages on DFF qualities of plantain chips (Mba *et al*., 2013). The understanding of mass transfer phenomena, especially moisture loss and fat uptake, and how they relate to processing conditions namely; frying temperature and time would help in designing an optimal process for DFF of plantain. Therefore, the study is aimed at modelling the moisture loss and oil uptake during DFF of *dodo*.

2. Materials and Methods

2.1 Preparation of Sample

Plantain (*Musa paradisiacal* AAB) fruits were purchased from a local farm in Ogbomoso. Fresh, matured plantains were kept at 30 ± 2 ^oC and allowed to ripen slowly until they reached the desired yellow stage of ripeness using colour index chart according to Aurore *et al.* (2009). The fruits were peeled and sliced with stainless steel knife. The pulps were sliced to slice thickness of 5 mm using an electric slicing machine (Berkel, model EAS65).

2.2 Frying conditions

Ten slices per sample time were deep fried in 2.5 liters of hot oil contained in an electrical fryer (Beckers, Model F1-C, Italy) at each of the frying temperatures tested: 150, 160, 170, 180 and 190 °C, with three replicates at each temperature. Plantain-to-oil weight ratio was maintained at 1:20 in order to keep the temperature of frying constant (±1°C). Slices were fried at different temperature and time intervals. For each selected sampling time, the fried slices were drained over a wire screen for 5 minutes and allowed to cool to room temperature before oil and water content analysis were done. The oil was preheated for 1 hr prior to frying, and discarded after 6 hr of use (Blumenthal, 1991).

2.3 Moisture and oil content Determination

Moisture content of plantain sample was measured by drying the samples in a convection oven at 105 °C until constant weight. Five gram (5 g) of sample was weighed into a pre-weighed moisture dish. The dish plus sample taken was transferred into the oven pre-set at 105 °C to dry to a constant weight for 24 hours overnight. At the end of the 24 hr, the dish plus sample was removed from the oven and transferred to desiccator, cooled for 30 min and weighed (AOAC, 2005). The oil content was determined following the AOAC (2005) method. Fried plantain samples were ground using a grinder. Five gram of sample was weighed into thimbles for fat extraction in a solvent extractor (SER 148, VelpScientifica, Usmate, Italy) using petroleum ether. Oil content was determined as the ratio of the mass of extracted fat and dry matter of the sample.

2.4 Mathematical Model

Mathematical model for moisture and oil transfer during the process is developed from mass diffusion into and out of the slice. The following assumptions were made: homogeneous tissue is assumed and two - dimensional diffusion occurs, the sample is considered to be almost a slab, the initial moisture and fat concentration is uniform, external resistance to mass transfer is negligible and diffusing mass enters through plane faces and negligible amount through the edge, moisture transfer to and from the plantain is due to concentration gradient and the amount of moisture loss in the plantain during frying was negligible. Therefore, moisture and fat transfer can be described by Fick's first law (Crank, 1975).

Rate of mass transfer = Influx of mass into the slice – Out flux of mass from the slice

Time rate of change of moisture in the slice $= \frac{\partial(m)Ax}{\partial t}$ (1)

Influx of moisture into the slice = j (2)

Out flux of moisture from the slice = $j + \frac{\partial_j}{\partial_x}$ (3)

Substitute equation 1, 2, 3 into statement of species conservation and gives:

$$\frac{\partial(m)Ax}{\partial t} = j - \left(j + \frac{\partial_j}{\partial_x}Ax\right) \quad (4)$$

$$\frac{\partial(m)Ax}{\partial t} = -\left(+ \frac{\partial_j}{\partial_x}Ax\right) \quad (5)$$

Divide equation (5) by Ax and it becomes:

$$\frac{\partial m}{\partial t} = -\frac{\partial j}{\partial x} \quad (6)$$

Recall, Fick's first law of diffusion:

$$j = -D_{eff}\frac{\partial c}{\partial x} \quad (7)$$

D_{eff} =Effective diffusion coefficient

M = moisture concentration of species in a mixture, mol (or mass)/m^3.
x = plantain thickness (mm)
j = flux of the mass relative to the chip (number of species crossing unit plane per unit time)

Now, combine equation 6 and 7 and obtain:

$$\frac{\partial m}{\partial t} = \frac{\partial m}{\partial t}\varepsilon.D\frac{\partial m}{\partial t} \quad (8)$$

Where $\frac{\partial m}{\partial t} =$ left hand side (LHS), $\frac{\partial m}{\partial t}\varepsilon.D\frac{\partial m}{\partial t}$ =right hand side (RHS)

Equation 8 is an appropriate equation for the prediction of mass transfer rate during *dodo* frying.

The following initial and boundary conditions were used:

Initial condition: $M(t = 0, x) = M_0$ (9)
Boundary condition: $M(t = 0, x) = M_e$ (10)
$M(x = L, t) = M$ (11)

2.5 Numerical Solution Technique

The equation was solved using explicit finite difference solution method. It was transformed into different equation by dividing the domain of solution to a grid of points in the form of mesh and the derivatives are expressed along each mesh point referred to as a node. Knowing the dependent variable at each node initially and it is approximated for the next time step until the final step. The numerical grid of the solution domain consists of two perpendicular lines representing the x- direction and t-direction. Thus, the finite difference representation of the mesh points is shown as follows:

$Xi = i\delta x \; for \; i = 0, 1, 2.........m$ (12)
$Yi = j\delta t \; for \; i = 0, 1, 2.........n$ (13)

Where δx and δt represent grid sizes in the *x* and *t* directions respectively and subscripts denote the location of the dependent variable under consideration.

The finite difference representations of various derivatives that appear in the governing equation are derived from Taylor's series expansion. Applying Taylor's series expansion in *t* (time) direction but keeping *x* (space) constant and truncate second term of the series for the left hand of the governing equation, therefore, Finite Difference Equation (FDE) of LHS of equation 8 was obtained:

$$\frac{\partial c}{\partial t} = \frac{M_{i.j+1} - M_{i,j}}{\delta t} \tag{14}$$

Similarly, Taylor's series expansion in the x (space) direction, keeping t constant; and again, Taylor's series expansion in the x direction (backward difference), keeping t constant. Therefore, FDE of RHS of the equation 8 was obtained:

$$\frac{\partial^2 c}{\partial^2 x} = \frac{M_{i.-1} - 2M_{i,j+}M_{i+1,j}}{(\delta x)^2} \tag{15}$$

Governing equation was derived by equating equation (14) and (15)

$$\frac{M_{i.j+1} - M_{i,j}}{\delta t} = \frac{M_{i.-1} - 2M_{i,j+}M_{i+1,j}}{(\delta x)^2} \tag{16}$$

$$M_{i.j+1} - M_{i,j} = \frac{\delta t}{(\delta x)^2} M_{i.-1} - 2M_{i,j+}M_{i+1,j}$$

$$M_{i.j+1} = M_{i,j} + r\left[M_{i.-1} - 2M_{i,j+}M_{i+1,j}\right] \tag{17}$$

Where: $r = \frac{D_{eff\delta t}}{(\delta x)^2}$

At $x = 0, then, i = 0, M_{0.j+1} = M_{0,j} + r\left[M_{-1,j} - 2M_{0,j} + M_{+1,j}\right]$ (18)

Then, $M_{-1,j}$ (pseudo moisture concentration at external mesh point is assumed) in equation 18 is calculated:

To represent $\frac{\partial M}{\partial x}$ more accurately at x = 0 by central difference formula, it is necessary to introduce the pseudo concentration $M_{-1,j}$ at the external mesh point by imagining the sheet of the tissue is extended very slightly. Therefore, finite difference approximation at boundary x = 0 in terms of central difference representation:

$$\frac{M_{1,j} - M_{-1,j}}{2\delta x} = M_{0,j} \tag{19}$$

From equation 19, external mesh point becomes:

$$M_{-1,j} = M_{1,j} - 2\delta x M_{0,j} \tag{20}$$

Substitute equation 20 into equation 18 and it gives:

$$M_{0.j+1} = M_{0,j} + 2r\left[M_{1,j} - M_{0,j}(1 + \delta x)\right] \tag{21}$$

Equation 21 is the discretized equation of mass transfer equation for every node, and this algebraic relationship was used to obtain the transient moisture and oil content at each node.

2.6 Computer simulation

Codes were developed in MATLAB to implement solution and analysis of FDE at different frying conditions. Therefore, resulting equation from the FDT was implemented in MATLAB by developing codes in its command window so as to predict the moisture distribution during frying process. The criterion ($\frac{D\delta t}{\delta x} \leq \frac{1}{2}$, $\frac{D\delta t}{\delta y} \leq \frac{1}{2}$) for stability and convergence of the solution was satisfied during the simulation process in MATLAB environment. Then, correlation coefficient for simulated results with experimental data was performed, in

MATLAB environment, for the determination of degree of model predictability. The agreement between predicted and experimental results was further evaluated using the following statistical parameters: Mean square error (MSE), Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE) and Mean Absolute Deviation (MAD) (Hemmati and Kharrat, 2007). The above statistical parameters can be calculated as follows:

$$MSE = \frac{\sum_{t=1}^{n}(A_t - F_t)}{n} \tag{22}$$

$$RMSE = \sqrt{\frac{\sum_{t=1}^{n}(A_t - F_t)^2}{n}} \tag{23}$$

$$MAPE = \frac{\sum_{t=1}^{n}\left|\frac{A_t - F_t}{A_t}\right|}{n} \times 100 \tag{24}$$

$$MAD = \frac{\sum_{n}^{t=1}|A_t - F_t|}{n} \tag{25}$$

3. Results and Discussion

3.1 Predicted and experimental results for moisture loss from *dodo*

Figure 1 show curves of experimental and predicted moisture loss rate during frying of *dodo* at different temperatures (150, 160 170, 180 and 190 °C). It was noticed that the predicted result curves follow the exponential pattern as observed in experimental results. The predicted results for moisture loss during the frying process provide satisfactory prediction of experimental data. There was an insignificant error between predicted and experimental data at different frying temperature was observed from 2 - 4 minutes as indicated in Figure 1. This occurrence might be as a result of start-up operation mechanism of frying process. However, there was perfect match in the prediction of moisture removal during frying at this temperature little or no underestimation and overestimation was noticed between simulated and actual results at different frying temperature. The exponential nature of moisture loss curves revealed that moisture content decrease in *dodo* as frying time increases.

The statistical analysis (i.e. R^2, MSE, RMSE, MAD and MAPE calculated for frying of *dodo* ranged from 0.988 to 0.994, 0.0025 to 0.0093, 0.0238 to 0.0836, 0.0023 to 0.0095 and 0.7349 to 1.3480, respectively (Table 1). The model had the highest R^2 and MAPE values while the lowest values of MSE, RMSE and MAD was used as a basis for good predictability of the model. According to Azoubel and Murr (2002), value of MAD and MAPE less than or equal to 10% indicates good prediction of experimental data and the lower the percentage the better the model for predictive purpose. This indicates that the model, with the aid of FDM, for moisture transfer rate during the process predicts satisfactory. The closer the value to 1 the better the prediction and it was noticed that all the prediction produced in this work is very close to 1. The trend reported in this work is similar to earlier work on the kinetics of plantain and Gethi during DFF process (Mba *et al*., 2013; Manjunatha *et al*., 2014).

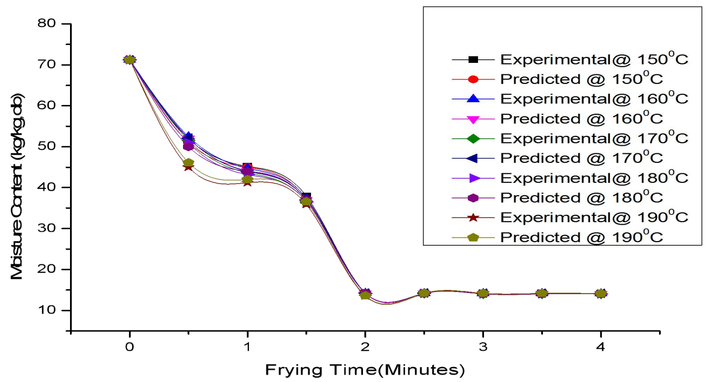

Figure 1: Predicted and experimental moisture loss in *dodo* during deep-fat frying

3.2 Predicted and experimental results for oil uptake from *dodo*

Figure 2 presents the comparison between predicted and experimental oil uptake results of *dodo* deep fried at 150, 160 170, 180 and 190 °C temperature. The predicted results of oil uptake during the frying process provide satisfactory prediction of experimental data (Fig. 2). It was observed that the predicted result curves follow the parabolic pattern as observed in experimental results. Statistical parameters such as R^2, MSE, RMSE, MAD and MAPE calculated at different frying temperature were varied from 0.958 to 0.978, 0.0006 to 0.0202, 0.0078 to 0.1420, 0.0069 to 0.0194 and 0.5716 to 1.3214, respectively, as displayed in Table 2.

It could be seen that the prediction showed good representation of experimental data with the value of R^2, MSE, RMSE, MAD and MAPE obtained between experimental and predicted results. The correlation coefficients are near one which indicates positive correlation. The deviation between predicted and experimental value in this work might be due to the error in the experimental measurement and the assumptions made in the present analysis as indicated earlier. The parabolic nature of oil uptake curves revealed that oil content increased in *dodo* as frying time increased. The trend reported in this work is similar to an earlier work on plantain slices (Troncoso and Pedreschi, 2009; Mba *et al.*, 2013).

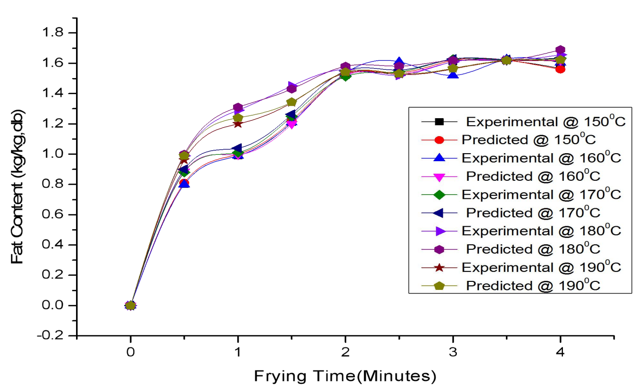

Figure 2: Predicted and experimental oil uptake in *dodo* during deep-fat frying

Table 1: Statistical index of predicted and experimental results of moisture content

Temperature (°C)	R^2	MSE	RMSE	MAD	MAPE
150	0.992	0.0078	0.0253	0.0023	0.7340
160	0.994	0.0025	0.0536	0.0095	0.9731
170	0.989	0.0093	0.0312	0.0036	1.2530
180	0.988	0.0083	0.0836	0.0025	1.3480
190	0.992	0.0032	0.0238	0.0032	1.1452

3.3 Prediction of moisture content distribution at different positions

The simulated moisture profile at different axial positions of plantain samples from top to the centre at 170 °C are presented in Figure 3. It was observed that moisture rate removal was proportional to axial distance from the centre of plantain sample. It was further noticed from the curve that the distance of X_5 = 0.005 m is far from the centre of the plantain and highest moisture removal was achieved as depicted in Figure 3. On the contrary, at the beginning of the moisture removal distribution during the frying process it was observed that maximum residual moisture content was found at X_1 = 0.0025 m location and the centre of *dodo* witnessed a slower moisture removal rate (Fig. 3). High rate of moisture removal was observed at the plantain surface relative to inner surfaces. This could be explained in terms of the moisture transfer resulting from direct interaction with the frying medium (Kassama and Ngadi, 2005).

Table 2: Statistical index of predicted and experimental results of oil content

Temperature (°C)	R^2	MSE	RMSE	MAD	MAPE
150	0.978	0.0006	0.0078	0.0069	0.5716
160	0.973	0.0024	0.0499	0.0346	1.0648
170	0.969	0.0003	0.0182	0.0135	1.1233
180	0.968	0.0201	0.1420	0.0194	1.3214
190	0.958	0.0003	0.0173	0.0114	0.9589

The predicted results from this study show that axial positions, within the plantain sample, have effect on the moisture removal rate during frying process. As revealed in Figure 3, moisture removal equilibrium (no net moisture transfer from plantain slices) was reached between 100 - 120 seconds period of time. Moisture content distribution during *dodo* frying in this work predicted equilibrium moisture removal point. The predicted results obtained from this work are similar to previous works reported in the literature (Garayo and Moreira, 2002; Kassama and Ngadi, 2005). This suggests that the moisture transfer model could predict shut down and startup operations of plantain frying process and this will be useful for industrial application of the process.

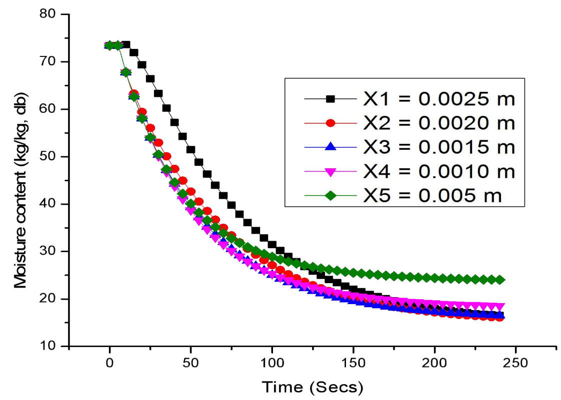

Figure 3: Predicted moisture loss distribution during DFF of *dodo* at different positions

3.4 Prediction of oil uptake distribution at different positions

The simulated oil uptake profile at different axial positions of plantain samples during frying process of *dodo* at 170 °C are shown in Figure 4. It was observed that the rate of oil absorption was proportional to axial distance from the centre of plantain sample. It was further noticed from the curve that distance of X_5 = 0.005 m is far from the centre of the plantain and least oil uptake was achieved as depicted in Figure 4. There was a slower moisture removal rate at the centre of *dodo* (Fig. 4). In contrast, high rate of oil uptake was observed at the plantain surface relative to inner surfaces. This could be explained in terms of the oil transfer resulting from direct interaction with the frying medium (Moyano and Pedreschi, 2006). The predicted results from this study show that axial positions, within the plantain sample have effect on the oil uptake rate during frying process. Oil uptake distribution during plantain frying in this work predicted equilibrium point. Figure 4 revealed that oil uptake equilibrium was reached between 120 - 220 seconds period of time. The predicted results obtained from this work are similar to previous works reported in the literature (Krokida *et al*., 2000).

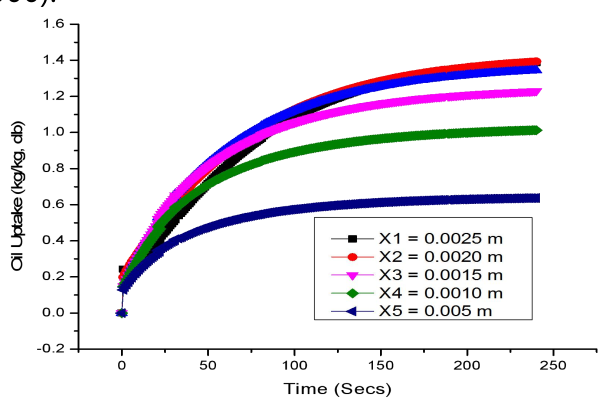

Figure 4: Predicted oil uptake distribution during DFF of *dodo* at different positions

4. Conclusion

In the present study, the moisture loss and oil uptake during deep-fat frying of *dodo* is modeled. It was established that FDM solution technique is a better tool for solving partial differential equation related to moisture and oil transfer. There is a close agreement between the experimental and predicted result for this study. The correlation coefficients between the predicted and experimental values of moisture and oil transfer models ranged from 0.988 to 0.994 and 0.958 to 0.978, respectively. The results show that the model is consistent and it may be used to predict moisture and oil transfer during DFF of *dodo*.

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