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Modeling of solute transfer rate during osmotic dehydration of pretreated red bell pepper

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ABSTRACT

Osmotic dehydration process is a solid-liquid and mass transfer operation which is conducted with the aim of impregnating solute, from osmotic solution, into the tissue so as to reduce water content in red bell pepper. However, solute transfer rate during the process is relatively slow; the pepper was pretreated with pulsed electric field (PEF) process and membrane permeability was increased during the pretreatment process. In this study, a mathematical model was developed from fundamental law of mass diffusion with the aim of predicting solute transfer rate during osmotic dehydration of red bell pepper at different PEF- induced pore areas of the tissue. The model was solved analytically and numerically. Codes were developed in MATLAB environment for solute transfer into the tissue at different induced pore areas. The predicted results were compared with experimental results and gave high correlation coefficient ranging from 0.910 to 0.998 for numerical result and 0.920 to 0.970 for the analytical. These indicate that the predicted results were in good agreement with experimental results obtained from the literature.

Keywords: Solute Transfer, Induced Pore Area, Modeling, Pulsed electric field, Osmotic Dehydration

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INTRODUCTION

Red bell pepper is an important aspect of diet and is commonly consumed in almost every part of Nigeria. It is either eaten raw, cooked or used as a spice and flavor ingredients in food industries. However, it is usually in short supply during dry season because it is highly perishable because of moisture content of about 74 % (Ibrahim and Mehmet, 2002). This demand has prompted process researchers and engineers to explore osmotic dehydration method as pre-drying operation prior to conventional drying methods such as freezing, canning or thermal drying that rely on heating or cooling operations. Osmotic dehydration (OD) is not only used to reduce moisture content and air drying time but also to improve the product quality (Ade-Omowaye *et al*., 2002). Other advantages of osmotic dehydration over conventional air drying include limited heat damage, improved textural quality, vitamin retention and flavor enhancement (Karathanos *et al*., 1995).

Osmotic dehydration of bell pepper partially removes free surface water or intermediate moisture in the tissue. It involves immersion of red bell pepper in a solution (sugar/salt solution) for a given time, with water activities lower than that of the pepper (Le Mague, 1988). It gives rise to two major simultaneous counter-current flows: water flows into the solution and solute into the pepper, which are both due to the water and solute activity gradients across the interface of the tissue of the pepper and solution. This preservative technique allows the incorporation of certain

solutes, without modifying nutritional integrity of the pepper (Knorr and Angersbach, 1998). The water removal from bell pepper inhibits microbial activities in the pepper, besides, preventing a large part of biochemical reactions which occur in the presence of moisture (Krokida *et al*., 2000). Furthermore, dehydration is a means of reducing energy cost, packaging and storage (Park *et al*., 2002). However, rate of mass transfer during osmotic dehydration is relatively slow; and so, it takes longer time to reach equilibrium water loss.

Rate of mass transfer during OD of the pepper depends on concentration and temperature of osmotic solution, pretreatment of the material prior to osmosis and mass ratio of the solution to bell pepper, process time, agitation, size and shape of bell pepper, type of osmotic agent among others (Lazarides and Mavroudis, 1996). Pre-treatment process such as pulsed electric field (PEF) before osmotic dehydration has been reported to facilitate about 25% moisture removal during OD of the pepper and also improves nutritional quality of the pepper (Ade-Omowaye *et al*., 2002). The application of PEF appears promising for food processing due to its potential for continuous application with very little heating of medium, short treatment time, instant distribution of energy throughout the conductive tissue and low energy requirement. Among processing factors reported to influence the effectiveness of PEF treatment are field strength, pulsed number and impulse energy (Knorr and Angersbach, 1998). Therefore, vegetable tissue is pre-treated by pulsed electric field (PEF) which is related to non-thermal electroporation of cell membranes resulting to increase in cell permeability and leads to rapid water and solute transfer during osmotic dehydration process (Elez- Martinez *et al*., 2005). PEF pre-treatment involves disruption of cell membrane leading to formation of pores and pore has to be stable enough to allow interaction of the intra and extra cellular media.

This study targets mathematical modeling of rate of solute transfer during osmotic dehydration of bell pepper in the mixture of sucrose and sodium chloride solutions at different field strengths. Modeling of the process at different process conditions predicts optimal solute transfer during the process. The principle of modeling is based on having a set of mathematical equations, which adequately describes solute transfer rate in OD with appropriate initial and boundary conditions. The solution of these equations can predict solute concentration in the tissue at different operating conditions.

MATERIALS AND METHODS

2.0 MODEL DEVELOPMENT

2.1 GOVERNING EQUATION

Mathematical model for water and solute transfer rate during the process is developed from mass diffusion into and out of the tissue. Conservation of mass in differential element of the tissue is accomplished by identifying the simplifying assumptions, defining appropriate initial and boundary conditions. The pepper was cut into flat disc (flat sheet) with average dimensions of 35 mm diameter and 6.4 mm thickness (Ade-Omowaye *et al*., 2002). The following assumptions were made: Homogeneous tissue is assumed and one - dimensional diffusion occurs; and the osmotic dehydration is an isothermal process. The initial water and solute concentrations in tissue are uniform. Two simultaneous counter-current phenomena are assumed in modeling: water diffusion into the osmotic solution and the osmotic solutes into the bell pepper tissue. External resistance to mass transfer is neglected and diffusing mass enters through the plane faces and negligible amount through the edge. The governing equation was obtained from species balance for the control volume:

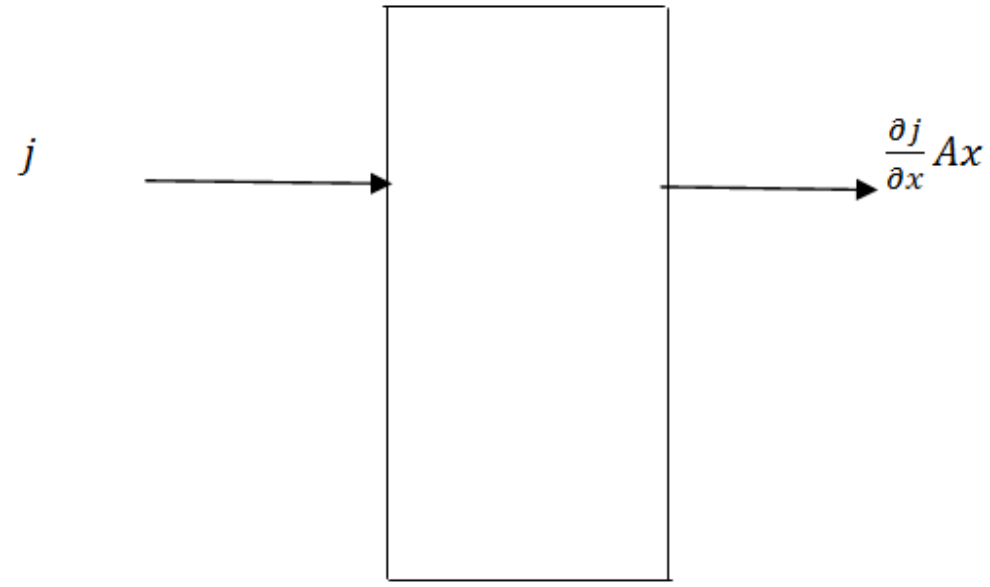

Figure2.1: species conservation in a differential volume (elemental tissue of the pepper)

Statement of species conservation is:

Time rate of change of water in the tissue

= Influx of water into the tissue – Out flux of Water from the tissue

Time rate of change of water in the tissue: $= \frac{\partial(c)Ax}{\partial t}$ 1

Influx of water into the tissue = j 2

Out flux of Water from the tissue $= j + \frac{\partial j}{\partial x}Ax$ 3

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

$$\frac{\partial(c)Ax}{\partial t} = j - \left(j + \frac{\partial j}{\partial x}Ax\right) \quad 4$$

$$\frac{\partial(c)Ax}{\partial t} = -\left(+\frac{\partial j}{\partial x}Ax\right) \quad 5$$

Divide equation (5) by Ax and gives:

$$\frac{\partial c}{\partial t} = -\frac{\partial j}{\partial x} \quad 6$$

Recall, Fick's first law:

$J = -D_{eff}\frac{\partial C}{\partial x}$. And $D_{eff} = D.\varepsilon$ 7

Where D_{eff} = Effective diffusion coefficient, ε = Open pore porosity of the tissue, D = Mass diffusion coefficient, x = tissue thickness (m) and j = flux of the mass relative to the tissue (number of species crossing unit plane per unit time).

Substitute 7 into 6 and obtain:

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\varepsilon . D \frac{\partial c}{\partial x} \quad 8$$

2.1.1 Determination of Open Pore Porosity (ε) **Induced by Pulsed Electric Field**
The overall volume of the tissue is expressed as the sum of three terms:

$$V_T = V_s + V_l + V_a \quad 9$$

Where V_s = Volume of solid in the tissue, V_l = Volume of liquid in the tissue and V_a =Volume of air in the tissue. Then, the total volume of air is considered as sum of two contributions:

$$V_a = V_{aop} + V_{acp} \quad 10$$

Where V_{aop} = Pore opened to the outside and V_{acp} = Pore closed to the outside. Then, particle density is defined as the ratio of the current weight of the sample and its overall volume diminished by pore open to outside:

$$\rho_p = \frac{M}{V_T - V_{aop}} \quad 11$$

Then, overall density of the tissue:

$$\rho_T = \frac{M}{V_T} \quad 12$$

Therefore, open pore porosity is the volume of pore open to outside and its overall volume:

$$\varepsilon = \frac{V_{aop}}{V_T} \quad 13$$

Therefore, equation 8 becomes:

$$\frac{\partial c}{\partial t} = \frac{V_{aop}}{V_T}\frac{\partial}{\partial x} . D \frac{\partial c}{\partial x} \quad 14$$

2.1.2 Initial and Boundary Conditions:

$$C(t = 0, x) = C_O, C(x = 0, t) = C_e, C(x = L, t) = C_e \quad 15$$

2.1.3 Method of Solution for Diffusion Model
The model for determining rate of water and solute transfer during osmotic dehydration of bell pepper is partial differential equation and initial-boundary value problem which was solved by method of separation of variables. Integral properties are adopted so as to calculate Fourier coefficient of the series. Then, finite difference method was also used as numerical approach.

Application of dimensionless quantity to space, time and concentration variable:

$$\eta = \frac{x}{L}, \ \tau = \frac{D_{eff} . t}{L^2}, C^* = \frac{C_t - C_e}{C_O - C_e},$$

Then, substitute dimensionless variables into equation 14:

$$\frac{\partial C^*}{\partial \tau} = \frac{\partial^2 C^*}{\partial \eta^2} \quad 16$$

2.2 ANALYTICAL PROCEDURE

Equation (16) was solved through separation of variables technique, which is, seeking a solution of the time variable (τ) is separated from space variable (η):

$$C^*(\tau,\eta) = \mathrm{W}(\tau).\ \mathrm{Y}(\eta) = Bsin(n\pi\eta)\left(Ce^{-\lambda^2\tau}\right) \quad 17$$

$$C^*{}_n(\tau,\eta) = \mathrm{W}(\tau).\mathrm{Y}(\eta) = B_n sin(n\pi\eta)\left(C_n e^{-(n\pi)^2\tau}\right)$$

Where $E_n = B_n C_n$ is arbitrarily constant, then, a series equation is formally formed:

$$C^*{}_n(\tau,\eta) = \sum_{n=0}^{\infty} E_n sin(n\pi\eta)\left(e^{-(n\pi)^2\tau}\right) \quad 18$$

Then, apply initial condition: $C^*{}_n(0,\eta) = \sum_{n=0}^{\infty} E_n sin(n\pi\eta)\left(e^{-(n\pi)^2(0)}\right)$

$$But\ \left(e^{-(n\pi)^2(0)}\right) = 1$$

Therefore, $C^*{}_n(0,\eta) = \sum_{n=0}^{\infty} E_n sin(n\pi\eta)(1) = 1 \quad 19$

Now, integral properties are applied so as to determineE_n:

$$\int_0^1 \sin(n\pi x)\sin(m\pi x)\,dx = 0, \quad n\ and\ m\ are\ integers\ and\ n \neq m \quad 20$$

$$\int_0^1 \sin(n\pi x)\sin(m\pi x)\,dx = \frac{1}{2}, \quad n\ and\ m\ are\ integers\ and\ n = m \quad 21$$

Using above properties in equation 20 and 21 to determine the coefficient of the series

Then, multiply both sides of equation (19) by $\sin(n\pi\eta)$ and integrate the function across the domain. Therefore:

$$E_n = \frac{2(1-cosn\pi)}{n\pi} \quad 22$$

Substitute equation 22 into 18 with original variables, then, the solution of diffusion equation 10 is:

$$\frac{C_t - C_e}{C_O - C_e} = 2\sum_{n=0}^{\infty} \frac{(1-cosn\pi)}{n\pi}(sinn\pi)\left(\frac{x}{L}\right).\left(e^{-\left(\frac{n\pi}{L}\right)^2\frac{D\varepsilon t}{L^2}}\right) \quad 23$$

$$C_t = C_e + 2(C_O - C_e)\sum_{n=0}^{\infty} \frac{(1-cosn\pi)}{n\pi}\left(\sin(n\pi)\left(\frac{x}{L}\right)\right)\left(e^{-\left(\frac{n\pi}{L}\right)^2\frac{D\varepsilon t}{L^2}}\right) \quad 24$$

Then, determine concentration of water and solute in the tissue at different operating conditions and gives:

$$C_{st} = C_{se} + 2(C_{sO} - C_{se})\sum_{n=0}^{\infty} \frac{(1-cosn\pi)}{n\pi}(sinn\pi\eta)\left(e^{-\left(\frac{n\pi}{L}\right)^2\frac{D\varepsilon t}{L^2}}\right) \quad 25$$

2.3 NUMERICAL SOLUTION TECHNIQUE

Approximate technique of solution is used to solve the equation. The method used in this study is the explicit finite difference method and the equation is transformed into difference 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.The finite difference representations of various derivatives that appear in the governing equation are derived from Taylor's series expansion where δx and δt represent grid sizes in the x and t directions respectively:

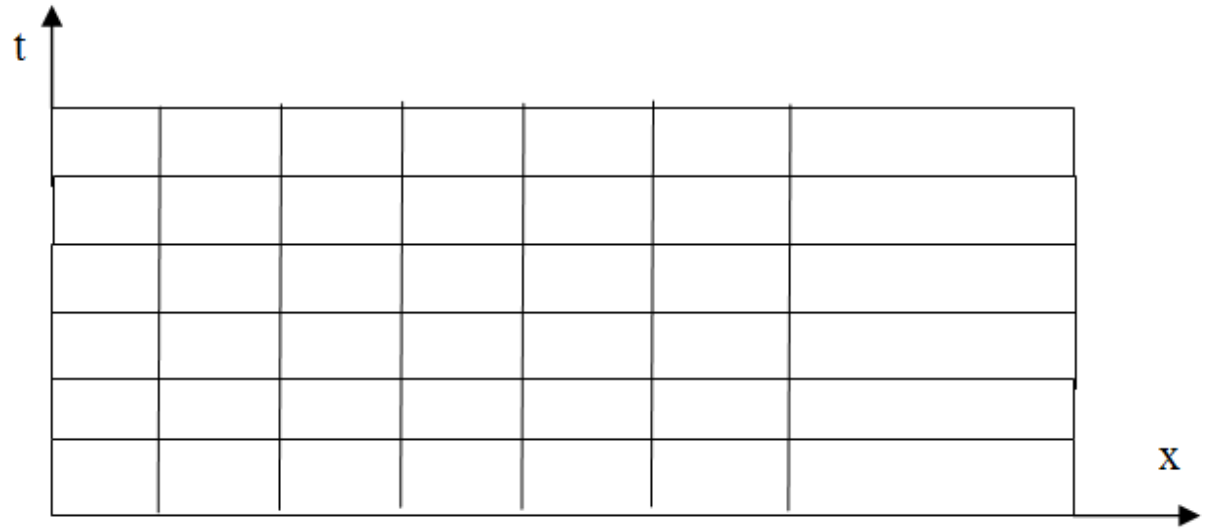

Fig 2.2: Numerical grid for a slab of bell pepper.

$$\frac{\partial c}{\partial t} = \frac{C_{i,j+1} - C_{i,j}}{\delta t} \quad (26)$$

$$\frac{\partial^2 c}{\partial x^2} = \frac{C_{i,-1} - 2\,C_{i,j} + C_{i+1,j}}{(\delta x)^2} \quad (27)$$

Equate (26) and (27) to represent governing equation:

$$C_{i,j+1} = C_{i,j} + r\left[C_{i-1,j} - 2C_{i\,j} + C_{i+1,j}\right] \quad (28)$$

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

At $x = 0, then, i = 0,\ C_{0,j+1} = C_{0,j} + r\left[C_{-1,j} - 2C_{0,j} + C_{+1,j}\right]$

Then, calculate $C_{-1,j}$ (pseudo concentration at external mesh point) using finite difference approximation at boundary x=0 in terms of central difference representation:

$$\frac{C_{1,j} - C_{-1,j}}{2\delta x} = C_{0,j}$$

$$C_{0,j+1} = C_{0,j} + r\left[C_{1,j} - 2\delta x\, C_{0\,j} - 2\,C_{0\,,j} + C_{1\,,j}\right]$$

$$C_{0,j+1} = C_{0,j} + r\left[-2\delta x\, C_{0\,j} - 2\,C_{0\,,j} + 2C_{1\,,j}\right]$$

$$C_{0,j+1} = C_{0,j} + 2r\left[C_{1,j} - C_{0\,j}\,(1 + \delta x)\right] \quad (29)$$

Therefore, equation 29 gives one extra equation for $C_{0,j}$ at any time step, to be used in explicit finite difference instead of a given value (initial concentration value) of $C_{0,j}$. Similarly at x = L (for other side of the tissue) the concentration at any time step becomes:

$$C_{10,j+1} = C_{10,j} + 2r\left[C_{9,j} - (1+\delta x)C_{10,j}\right] \quad 30$$

Therefore, equation 29 and 30 predict concentration of water and solute in the tissue at any process time for different operating conditions.

Then, equation 31 estimate solute gain ($\frac{Kg\ solute}{Kg\ initial\ product}$) during the process:

$$\text{Solute gain } (\Delta M_s) = \frac{M_t C_{st} - M_o C_{so}}{M_o} \quad 31$$

Where M_o = Mass of the tissue at time (t) = 0, M_t = Mass of the tissue at time (t) = t, C_{st} = Concentration of solute in the tissue at time (t) = t,C_{s0} = Concentration of solute in the tissue at time (t) = 0, C_{se} = Concentration of solute in the tissue at equilibrium.

2.3 Computer Simulation

MATLAB was used as simulation tool to solve the corresponding equations. Therefore, resulting equations from analytical approaches were implemented in MATLAB by developing codes in it so as to obtain weight reduction during the process at different PEF-induced pore areas in two osmotic solutions. Then, correlation coefficient for predicted results and experimental data was carried out in standard program in excel Microsoft spreadsheet. The agreement between predicted and experimental results was further evaluated using the mean relative deviation modulus (%E) as indicated in equation 32.

$$\%E = \frac{1}{n}\sum\left|\frac{V_E - V_P}{V_E}\right| \quad 32$$

Where: V_E = Experimental value
V_p = Predicted value

Table 2.1: properties of flat sheet of the pepper used in the simulation

Parameters	Value
Temperature	30
Characteristic length (L)	0.0064m
Initial solute concentration in the tissue for binary solution	0.07486
Initial water concentration in the tissue for ternary solution.	0.89564
Initial water concentration in the tissue for binary solution.	0.91448
Initial solute concentration in the tissue for ternary solution	0.09328

Source: Ade-Omowaye et al., 2002

Table 2.2: Pulsed electric field pretreatment conditions and diffusivities at 400μS pulse number

Field strength (kv/cm)	Osmotic solution	Diffusivity (m/s)	Open pore porosity (ε)
Untreated tissue	Ternary solution	$2.32\ X\ 10^{-10}$	0
1.0	Ternary solution	$6.79\ X\ 10^{-10}$	0.001
1.5	Ternary solution	$7.01\ X\ 10^{-10}$	0.007
2.0	Ternary solution	$7.01\ X\ 10^{-10}$	0.014
Untreated tissue	Binary solution	$1.35\ X\ 10^{-10}$	0
1.0	Binary solution	$3.3\ X\ 10^{-10}$	0.001
1.5	Binary solution	$3.44\ X\ 10^{-10}$	0.007
2.0	Binary solution	$3.57\ X\ 10^{-10}$	0.014

Source: Ade- Omowaye et al., 2002

RESULTS AND DISCUSSION

3.1 RESULTS

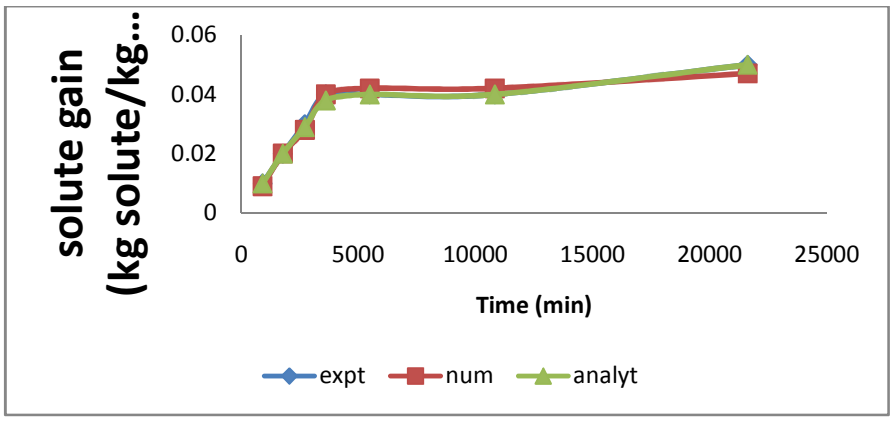

Figure 4.1: Solid gain rate into untreated tissue in sucrose solution

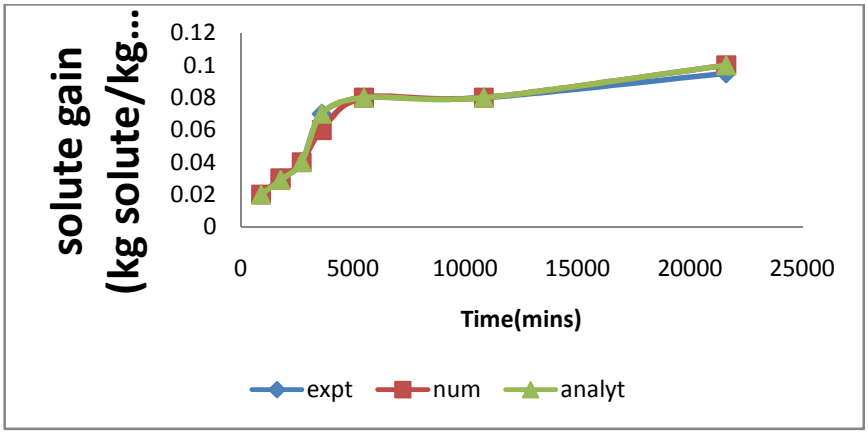

Figure 4.2: Solid gain rate into pretreated tissue with field strength of 1.0 kv/ cm in sucrose solution

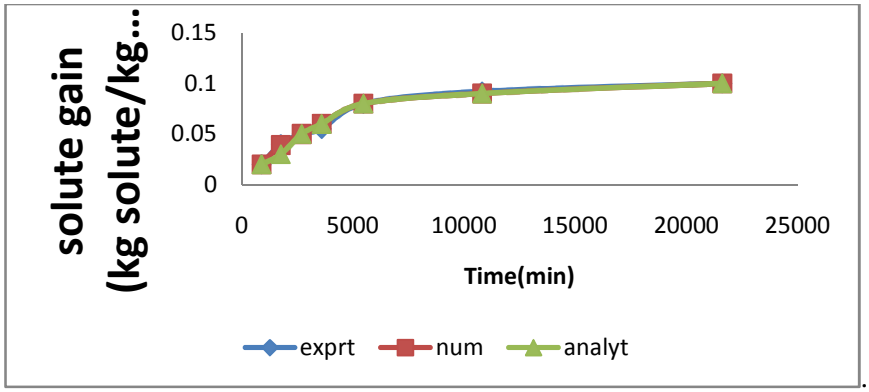

Figure 4.3: Solid gain rate into pretreated tissue with field strength of 1.5 kv/ cm in sucrose solution

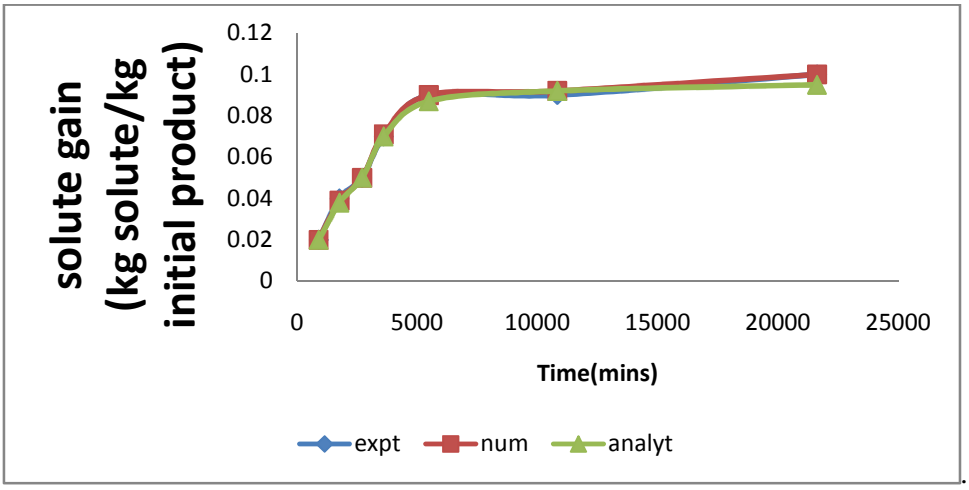

Figure 4.4: Solid gain rate into pretreated tissue with field strength of 2.0 kv/ cm in sucrose solution

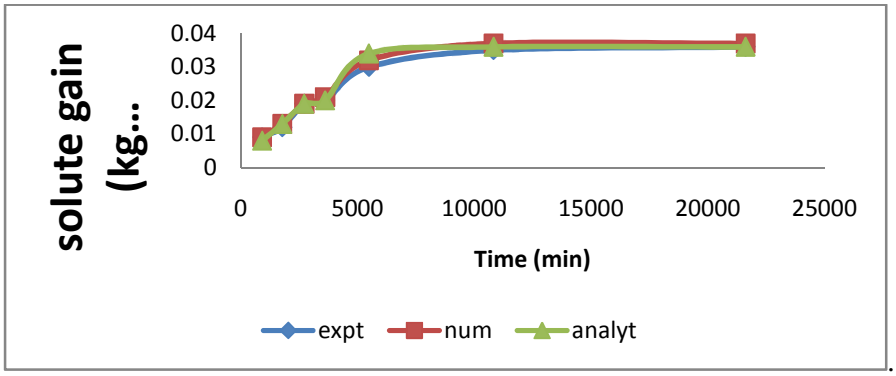

Figure 4.5: Solid gain rate into untreated tissue in sucrose/Nacl solution

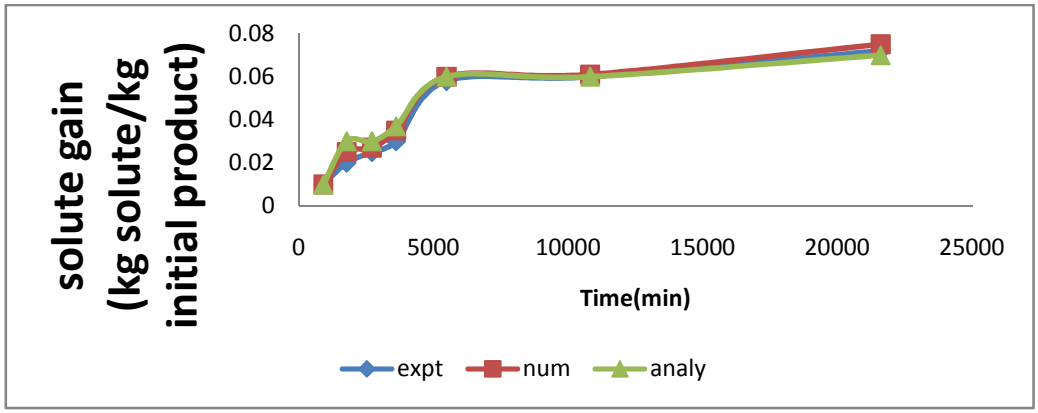

Figure 4.6: Solid gain rate into pretreated tissue with field strength of 1.0 kv/ cm in sucrose/salt solution

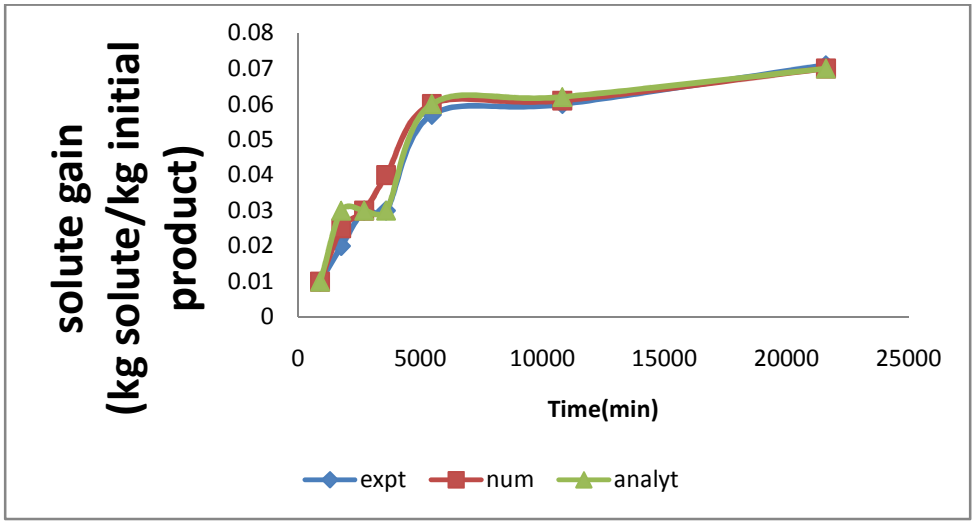

Figure 4.7: Solid gain rate into pretreated tissue with field strength of 1.5 kv/ cm in sucrose/salt solution

Table 2.3: Solid gain into untreated tissue in sucrose solution

Treatment time	Osmotic solution	Field strength	Solid gain value			MRDM % Error		Correlation coefficient	
			Analytical	Numerical	Experimental	Analytical	Numerical	Analytical	Numerical
t_1	Sucrose solution	zero field strength	0.01	0.01	0.01	0.0	0.0	0.981	0.991
t_2	Sucrose solution	zero field strength	0.03	0.025	0.025	0.02	0.0	0.984	0.995
t_3	Sucrose solution	zero field strength	0.05	0.03	0.03	0.06	0.0	0.974	0.981
t_4	Sucrose solution	zero field strength	0.06	0.05	0.05	0.09	0.0	0.986	0.971
t_5	Sucrose solution	zero field strength	0.08	0.06	0.06	0.0	0.0	0.988	0.992
t_6	Sucrose solution	zero field strength	0.08	0.065	0.06	0.03	0.0	0.976	0.996
t_7	Sucrose solution	zero field strength	0.08	0.07	0.07	0.09	0.0	0.986	0.993

Table 4.4: Solid gain into Pretreated Tissue with field Strength of 1.0kv/cm in Sucrose Solution

Treatment time	Osmotic solution	Field strength	Solid gain value			MRDM % Error		Correlation coefficient	
			Analytical	Numerical	Experimental	Analytical	Numerical	Analytical	Numerical
t_1	Sucrose solution	1kv/cm	0.02	0.02	0.02	0.0	0.0	0.980	0.981
t_2	Sucrose solution	1kv/cm	0.029	0.03	0.03	0.03	0.0	0.946	0.941
t_3	Sucrose solution	1kv/cm	0.04	0.04	0.04	0.0	0.0	0.966	0.994
t_4	Sucrose solution	1kv/cm	0.07	0.06	0.07	0.0	0.01	0.982	0.996
t_5	Sucrose solution	1kv/cm	0.08	0.08	0.08	0.0	0.0	0.906	0.971
t_6	Sucrose solution	1kv/cm	0.10	0.10	0.09	0.0	0.08	0.976	0.981
t_7	Sucrose solution	1kv/cm	0.10	0.10	0.10	0.0	0.0	0.989	0.993

Table 4.5: Solid gain into Pretreated Tissue with field Strength of 1.5kv/cm in Sucrose Solution

Treatment time	Osmotic solution	Field strength	Solid gain value			MRDM % Error		Correlation coefficient	
			Analytical	Numerical	Experimental	Analytical	Numerical	Analytical	Numerical
t_1	Sucrose solution	1.5kv/cm	0.02	0.02	0.02	0.0	0.0	0.956	0.994
t_2	Sucrose solution	1.5kv/cm	0.039	0.03	0.04	0.02	0.02	0.976	0.951
t_3	Sucrose solution	1.5kv/cm	0.05	0.05	0.05	0.0	0.0	0.986	0.982
t_4	Sucrose solution	1.5kv/cm	0.06	0.06	0.055	0.0	0.09	0.989	0.997
t_5	Sucrose solution	1.5kv/cm	0.08	0.08	0.08	0.0	0.0	0.986	0.996
t_6	Sucrose solution	1.5kv/cm	0.09	0.09	0.08	0.0	0.1	0.976	0.961
t_7	Sucrose solution	1.5kv/cm	0.10	0.10	0.10	0.0	0.0	0.946	0.991

Table 4.6: Solid gain into Pretreated Tissue with field Strength of 2.0kv/cm in Sucrose Solution

Treatment time	Osmotic solution	Field strength	Solid gain value			MRDM % Error		Correlation coefficient	
			Analytical	Numerical	Experimental	Analytical	Numerical	Analytical	Numerical
t_1	Sucrose solution	2.0kv/cm	0.02	0.02	0.02	0.0	0.0	0.988	0.995
t_2	Sucrose solution	2.0kv/cm	0.039	0.039	0.04	0.05	0.02	0.989	0.941
t_3	Sucrose solution	2.0kv/cm	0.05	0.05	0.05	0.0	0.0	0.926	0.971
t_4	Sucrose solution	2.0kv/cm	0.07	0.071	0.07	0.0	0.01	0.996	0.934
t_5	Sucrose solution	2.0kv/cm	0.087	0.09	0.09	0.03	0.0	0.989	0.925
t_6	Sucrose solution	2.0kv/cm	0.092	0.092	0.09	0.0	0.02	0.982	0.991
t_7	Sucrose solution	2.0kv/cm	0.10	0.10	0.10	0.0	0.0	0.985	0.996

Table 4.7: Solid gain into untreated tissue in sucrose solution

Treatment time	Osmotic solution	Field strength	Solid gain value			MRDM % Error		Correlation coefficient	
			Analytical	Numerical	Experimental	Analytical	Numerical	Analytical	Numerical
t_1	Sucrose/salt solution	Zero field strength	0.008	0.009	0.009	0.1	0.0	0.983	0.990
t_2	Sucrose/salt solution	Zero field strength	0.0017	0.018	0.019	0.05	0.1	0.996	0.957
t_3	Sucrose/salt solution	Zero field strength	0.019	0.019	0.02	0.0	0.05	0.976	0.963
t_4	Sucrose/salt solution	Zero field strength	0.021	0.02	0.022	0.04	0.09	0.969	0.972
t_5	Sucrose/salt solution	Zero field strength	0.032	0.03	0.034	0.05	0.06	0.943	0.989
t_6	Sucrose/salt solution	Zero field strength	0.033	0.03	0.036	0.08	0.08	0.972	0.986
t_7	Sucrose/salt solution	Zero field strength	0.038	0.036	0.038	0.0	0.05	0.976	0.991

Table 4.8: Solid gain into Pretreated Tissue with field Strength of 1.0kv/cm in Sucrose/salt Solution

Treatment time	Osmotic solution	Field strength	Solid gain value			MRDM % Error		Correlation coefficient	
			Analytical	Numerical	Experimental	Analytical	Numerical	Analytical	Numerical
t_1	Sucrose/salt solution	1.0kv/cm	0.01	0.01	0.01	0.0	0.0	0.946	0.997
t_2	Sucrose/salt solution	1.0kv/cm	0.026	0.025	0.024	0.08	0.04	0.957	0.978
t_3	Sucrose/salt solution	1.0kv/cm	0.027	0.027	0.025	0.08	0.08	0.978	0.996
t_4	Sucrose/salt solution	1.0kv/cm	0.034	0.035	0.032	0.06	0.1	0.905	0.989
t_5	Sucrose/salt solution	1.0kv/cm	0.07	0.065	0.065	0.07	0.0	0.981	0.954
t_6	Sucrose/salt solution	1.0kv/cm	0.08	0.07	0.067	0.1	0.04	0.943	0.953
t_7	Sucrose/salt solution	1.0kv/cm	0.08	0.075	0.07	0.1	0.07	0.981	0.931

Table 4.9: Solid gain into Pretreated Tissue with field Strength of 1.5kv/cm in Sucrose/salt Solution

Treatment time	Osmotic solution	Field strength	Solid gain value			MRDM % Error		Correlation coefficient	
			Analytical	Numerical	Experimental	Analytical	Numerical	Analytical	Numerical
t_1	Sucrose/salt solution	1.5kv/cm	0.01	0.01	0.01	0.0	0.01	0.981	0.990
t_2	Sucrose/salt solution	1.5kv/cm	0.03	0.025	0.026	0.1	0.025	0.967	0.993
t_3	Sucrose/salt solution	1.5kv/cm	0.035	0.03	0.03	0.1	0.03	0.984	0.995
t_4	Sucrose/salt solution	1.5kv/cm	0.05	0.05	0.04	0.06	0.05	0.979	0.956
t_5	Sucrose/salt solution	1.5kv/cm	0.07	0.07	0.063	0.01	0.07	0.942	0.989
t_6	Sucrose/salt solution	1.5kv/cm	0.072	0.07	0.065	0.1	0.07	0.986	0.978
t_7	Sucrose/salt solution	1.5kv/cm	0.078	0.075	0.07	0.1	0.02	0.981	0.994

Table 4.10: Solid gain into Pretreated Tissue with field Strength of 2.0kv/cm in Sucrose/salt Solution

Treatment time	Osmotic solution	Field strength	Solid gain value			MRDM % Error		Correlation coefficient	
			Analytical	Numerical	Experimental	Analytical	Numerical	Analytical	Numerical
t_1	Sucrose/salt solution	1.5kv/cm	0.01	0.01	0.01	0.0	0.01	0.946	0.981
t_2	Sucrose/salt solution	1.5kv/cm	0.03	0.025	0.026	0.1	0.025	0.967	0.951
t_3	Sucrose/salt solution	1.5kv/cm	0.035	0.03	0.03	0.1	0.03	0.976	0.996
t_4	Sucrose/salt solution	1.5kv/cm	0.05	0.05	0.04	0.06	0.05	0.948	0.981
t_5	Sucrose/salt solution	1.5kv/cm	0.07	0.07	0.063	0.01	0.07	0.988	0.964
t_6	Sucrose/salt solution	1.5kv/cm	0.072	0.07	0.065	0.1	0.07	0.992	0.971
t_7	Sucrose/salt solution	1.5kv/cm	0.078	0.075	0.07	0.1	0.02	0.986	0.996

DISCUSSION

Figures 4.1 to 4.7 show curves of experimental and predicted solid gain rate during osmotic dehydration of red bell pepper at different operating conditions i.e. at different field strengths and osmotic solutions. The predicted curves exhibit parabolic trend like experimental data and this is similar to earlier work by Carmo, 2007. The predicted

results for solute gain during the process provide satisfactory prediction of experimental data, as indicated in Tables 2.3 to 2.10, with mean relative deviation modulus less than 1%. It could be seen that numerical prediction show good representation of experimental data with less value of MRDM. The obtained values for correlation coefficient for the predicted data are summarized in Table 2.3 – 2.10 ranging from 0.939 to 0.996 for analytical and numerical results. The parabolic nature of solid gain curves revealed that osmotic solute increases in the tissue as dehydration time increases; the trend reported in this work is similar to earlier work on the kinetics of osmotic dehydration of red bell pepper as influenced by pulsed electric field pretreatment (Ade-Omowaye *et al*.,2002). However, this is contrary to Ade-Omowaye *et al. (2002)* that show exponential decrease of water in the tissue during the process i.e. as the dehydration time increases rate of water loss increases and this conforms to earlier work by Chiang (1998).

Figures 4.15 to 4.24 present predicted and experimental results for weight reduction of the tissue. The predicted curves follow the same trend with experimental results and the results exhibit parabolic nature. It was observed that as independent variable (process time) increases during the process, the rate of weight reduction increases. Both numerical and analytical results gave high correlation coefficients ranging from 0.925 to 0.957 for the analytical and 0.920 to 0.945 for numerical prediction. The correlation coefficients are near one which indicates positive correlation; however, correlation coefficients for weight reduction values are less than that of water loss and solid gain. It was also noticed that much difference in predicted value of weight reduction compared to the experimental might be due to the sum of the deviation in water loss and solid gain. 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.

CONCLUSION

Numerical and analytical methods of solution of diffusion equation were developed and applied to weight reduction rate during osmotic dehydration of red bell pepper tissue. Satisfactory prediction, with less than 10% of mean relative deviation modulus, of weight reduction at different osmotic solutions and field strengths with corresponding open pore porosity was obtained. Both numerical and analytical approaches satisfactorily predicted experimental data with high correlation coefficients ranging from 0.955 to 0.997 for the analytical and 0.991 to 0.999 for numerical prediction numerical. Better rate of weight reduction was obtained for predicted value of pretreated tissue compared to the untreated tissue. It could be concluded that combined PEF and osmotic dehydration would yield satisfactory weight reduction in bell pepper during the process

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