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Research Article

Description of Guava Osmotic Dehydration Using a Three-Dimensional Analytical Diffusion Model

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The mass migrations during osmotic dehydration of guava were studied. Parallelepiped shaped slices were dipping in syrup of distilled water and sucrose with two concentrations and two temperatures. It was supposed that a three-dimensional diffusion model with boundary condition of the first kind satisfactorily describes the mass migrations and that the volume and effective mass diffusivities can be assumed constant during the process. The effective mass diffusivities were determined by coupling the three-dimensional analytical solution of the diffusion equation with an optimizer based on the inverse method. The proposed model well described the kinetics of water and sucrose migrations and enabled determining the mass distributions (water and sucrose) within the product at any instant.

1. Introduction

In order to prolong the shelf life of fruits, an alternative is the water removal from these agricultural products. In this sense, one of the methods of partial water removal is the osmotic dehydration. For fruits, generally dipping of pieces of the product in a solution of distilled water and sucrose is used, at given concentration and temperature. As examples, the following processes involving osmotic dehydration of fruits through dipping of the product in syrup can be cited: apples [1], mango [2], acerola [3], melon [4], papaya [5], banana [6], pumpkin, kiwi and pear [7], coconut [8], and pineapple [9]. According to Yadav and Singh [10], many advantages of water removal by the use of osmotic dehydration can be cited. Among them is (1) a low temperature water removal process and hence the minimum loss of color and flavor take place. (2) Flavor retention is more when sugar syrup is used as osmotic agent. (3) Energy consumption is less when no phase change is involved. (4) It increases solid density due to solid uptake and helps in getting better quality product in freeze drying. (5) The textural quality of product is better after reconstitution. (6) The storage life of product is greatly enhanced. (7) Simple equipment is required for the process.

In order to extract the major quantity of information on the osmotic dehydration process of a fruit, generally a mathematical model is used to describe the water removal and sucrose uptake. Although empirical models are used to describe osmotic dehydration [4, 6, 7], the most frequent in the literature is diffusion model [1–3, 8, 9, 11]. According to Da Silva et al. [9], the main advantage of diffusion models is the possibility to predict the distributions of mass content (water and sucrose) within the product at any instant, and this allows the analysis of stresses that can damage the product.

In order to describe osmotic dehydration through a diffusion model, normally the geometry of the fruit pieces is simplified reducing the problem to the one-dimensional case [3, 11–16]. However, if the exact distribution of water and sucrose along the time is required, the real geometry must be used in the description of the process [8, 9]. In the case of water removal from guava pieces, some works are found in the literature [17–19], but none of them consider the three-dimensional nature of the pieces of pulp. In this sense, the objective of this paper is defined below.

In this paper, osmotic dehydration of guava pieces was described through three-dimensional diffusion model. The analytical solution of the diffusion equation was coupled with an optimizer, which enabled calculating the effective mass diffusivities for a given experimental data set. Consequently, the simulation of the water quantity and sucrose gain kinetics can be performed, and information related to the process can be obtained. In particular, the adequacy of the proposed model in the description of the process can be analyzed, and the distributions of water and sucrose within the sample at any given instant previously stipulated can be also known.

2. Material and Methods

In this paper, a diffusion model with boundary condition of the first kind was used in order to describe the water and sucrose migrations during osmotic dehydration of guava. In this sense, the three-dimensional analytical solution of the diffusion equation will be presented below.

2.1. Diffusion Equation. The diffusion equation, used to describe mass transport in porous media many times, can be written as [20]

$$\frac{\partial \Phi}{\partial t} = \nabla \cdot (D \nabla \Phi), \quad (1)$$

where Φ is a generic variable that represents the relative water quantity, W, or relative sucrose gain, S, t is the time, and D is the effective mass diffusivity (D_w for water and D_s for sucrose). In Cartesian coordinates, (1) for the three-dimensional case is written in the following way:

$$\frac{\partial \Phi}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial \Phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(D\frac{\partial \Phi}{\partial y}\right) + \frac{\partial}{\partial z}\left(D\frac{\partial \Phi}{\partial z}\right). \quad (2)$$

In order to solve (2), some assumptions should be established: (1) diffusion is the only transport mechanism of mass within the guava slices; (2) the initial mass distributions should be uniform; (3) the dimensions of the slices do not vary significantly during the mass diffusion; (4) the effective mass diffusivities do not vary during the diffusion; (5) the boundary condition of the diffusion equation is of the first kind (i.e., at the edges of the slices, the relative water content and relative sucrose gain are known and have fixed values); (6) each guava slice is considered homogeneous and isotropic.

The solution to be presented below takes into account the parallelepiped shown in Figure 1.

The analytical solution at instant t in a position (x, y, z) within the parallelepiped is given by [20, 21]

$$\begin{aligned}\Phi(x, y, z, t) &= \Phi_{eq} + \left(\Phi_0 - \Phi_{eq}\right)\sum_{n=1}^{\infty}\sum_{m=1}^{\infty}\sum_{k=1}^{\infty} A_n A_m A_k \\ &\quad \times \cos\left(\mu_n \frac{x}{L_1/2}\right)\cos\left(\mu_m \frac{y}{L_2/2}\right) \times \cos\left(\mu_k \frac{z}{L_3/2}\right) \\ &\quad \times \exp\left[-\left(\frac{\mu_n^2}{(L_1/2)^2} + \frac{\mu_m^2}{(L_2/2)^2} + \frac{\mu_k^2}{(L_3/2)^2}\right)Dt\right],\end{aligned} \quad (3)$$

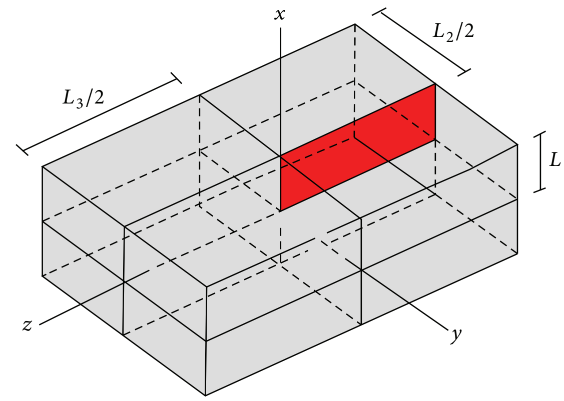

Figure 1: Parallelepiped, highlighting a vertical plane xz, at position $y = 0$, where the distributions of water quantity and sucrose gain were examined.

in which A_j and μ_j are given by

$$A_j = \frac{2(-1)^{j+1}}{\mu_j}, \quad (4a)$$

$$\mu_j = \frac{(2j-1)\pi}{2}, \quad (4b)$$

with j equal to indexes n, m, and k.

In (3), Φ_0 and Φ_{eq} are the initial and equilibrium value of Φ. The average value of $\Phi(x, y, z, t)$, at any instant t, is given in the following way:

$$\begin{aligned}\overline{\Phi}(t) &= \Phi_{eq} + \left(\Phi_0 - \Phi_{eq}\right)\sum_{n=1}^{\infty}\sum_{m=1}^{\infty}\sum_{k=1}^{\infty} B_n B_m B_k \\ &\quad \times \exp\left[-\left(\frac{\mu_n^2}{(L_1/2)^2} + \frac{\mu_m^2}{(L_2/2)^2} + \frac{\mu_k^2}{(L_3/2)^2}\right)Dt\right],\end{aligned} \quad (5)$$

with B_j (j equal to n, m, and k) given by

$$B_j = \frac{2}{\mu_j^{\,2}}. \quad (6)$$

2.2. Optimization. For the boundary condition of the first kind, the average value of Φ at instant t only depends on the value of the effective mass diffusivity D, since the convective mass transfer coefficient is known (and it tends to infinity). Then, for a given experimental data set, the chi-square is defined in the following way [22, 23]:

$$\chi^2 = \sum_{i=1}^{N_p}\left[\overline{\Phi}_i^{\exp} - \overline{\Phi}_i^{\text{ana}}(D)\right]^2 \frac{1}{\sigma_i^2}, \quad (7)$$

where $\overline{\Phi}_i^{\exp}$ represents the average water quantity $\overline{W}$ or sucrose gain $\overline{S}$ of the ith experimental point; $\overline{\Phi}_i^{\text{ana}}(D)$ is the average value of Φ as a function of D at the same point, calculated through (5); σ_i is the standard deviation of the experimental value of Φ at the point i; and N_p is the number of experimental points. An optimum value of D can be determined for each set of experimental data by minimizing (7). If σ_i was not obtained from the experiment and is therefore unknown, a common value, for example, $\sigma_i = 1$, should be attributed to all experimental points. da Silva et al. [23] proposed an algorithm to determine D in spheres, and this algorithm can be adapted for parallelepipeds. Such algorithm consists essentially of the following steps.

(i) An initial value close to zero (1×10^{-20}) is attributed to D and replaced into (5), approximated by a certain number of terms, for instance, 25 terms for each summation. Thus, $\overline{\Phi}_i^{ana}(D)$ can be calculated for a given time by (5) and, consequently, χ^2 can be determined for a set of experimental data through (7). Then, the value of D is doubled, and a new χ^2 is calculated. The new χ^2 is compared with the former value. If the new value is lower than the foregoing, D is again doubled and the corresponding value of χ^2 is calculated and compared with the former one. This procedure is repeated until the last calculated χ^2 is greater than the anterior value. Thereby, the antepenultimate and ultimate values of D, denoted as D_a and D_b, respectively, define a region which contains the minimal value of χ^2. The penultimate value of the effective mass diffusivity corresponds to the smallest value of χ^2 obtained in this interval.

(ii) The latter procedure can be refined between D_a and D_b, subdividing this interval in nv values of D uniformly distributed. Then, a more refined interval can be obtained, and this procedure can be repeated until a convergence criterion is satisfied.

According to da Silva et al. [23], the described algorithm needs neither the input of an initial value, nor the definition of a search interval for the determination of an optimum "D." This is a very comfortable characteristic of the optimization procedure since the user of the algorithm only needs to inform the set of experimental data, once the guesses of values defining the interval which contains the optimal value are not necessary. Due to the advantages presented above, this algorithm was adapted to the three-dimensional geometry to be analyzed in this paper. On the other hand, the criterion of convergence was stipulated in this paper as 1×10^{-16}.

Since the diffusivities are determined by optimization, (3) can be used to calculate the water quantity and sucrose gain distributions as a function of the position at given time t.

2.3. Experimental Data. Mature guavas (*Psidium guajava* L.) were peeled and the seeds were removed. Its pulp was cut into parallelepiped shaped pieces with the following average dimensions, measured with a caliper rule: $L_1 = 9.56$; $L_2 = 20.03$; and $L_3 = 30.29$ mm (Figure 1).

Guava slices with initial moisture content of $5.34\,\mathrm{kg_{water}\,kg_{dry\ matter}^{-1}}$ were submitted to osmotic dehydration, and two experiments were carried out: one of them at 40°Brix and 30°C and other at 50°Brix and 40°C. The ratio of the volume of the guava pieces to that of the medium was maintained at 1 : 15.

The quantities analyzed in the experiments were the relative water quantity within the sample during the process, $\overline{W}$, and relative sucrose gain, $\overline{S}$. In each osmotic dehydration experiment, ten samples with about 15 g were weighted and immersed in syrup, and one sample was weighted and placed in a kiln at 105°C during 24 h to determine its initial water mass and dry matter. This procedure permits to determine the mass of water and dry matter of all samples at initial instant. After that, in each instant t previously stipulated, one sample was removed from the syrup and its weight was measured. Then, the mass of water and its dry matter was also determined as described above. This procedure enables to determine the mass of water and dry matter at instant t of each sample that continues to be immersed in the solution. In each removal, the sample was washed in tap water and the external moisture was removed with paper towel. The equations used to determine $\overline{W}$ and $\overline{S}$ in each instant t are given, respectively, by

$$\overline{W}(t) = \frac{m_W(t)}{m_W(0)} \times 100,$$
$$\overline{S}(t) = \frac{m_S(t)}{m_{d0}} \times 100, \tag{8}$$

where $m_W(t)$ and $m_W(0)$ represent the mass of water within the sample at instants t and zero, respectively; $m_S(t)$ is the mass of sucrose transferred to the sample up to the instant t; and m_{d0} is its initial dry matter.

The initial and equilibrium sucrose gain were, respectively, $S_0 = 0$ and $S_{eq} = 72.0\%$ (40°Brix, 30°C) and $S_0 = 0$ and $S_{eq} = 74.2\%$ (50°Brix, 40°C). The initial and equilibrium water quantity within the samples were, respectively, $W_0 = 100\%$ and $W_{eq} = 33.8\%$ (40°Brix, 30°C) and $W_0 = 100\%$ and $W_{eq} = 25.0\%$ (50°Brix, 40°C).

3. Results and Discussion

The experimental data were processed as described above, and the results will be presented in the following.

3.1. Results. Equation (5) was coupled with the optimizer described herein and the values presented in Table 1 were obtained for the effective mass diffusivities. This table also presents the statistical indicators for each optimization process.

Performing the simulations using the effective water diffusivities determined by optimization, the water migration kinetics is given through Figure 2 for two experiments carried out.

As additional information, the graphs of Figure 2 were drawn by the own software developed to obtain the effective mass diffusivities by optimization. On the other hand, the simulations related to the sucrose uptake kinetics are shown in Figure 3. As is realized, an advantage of the diffusion model used to represent the experiments (Figures 2 and 3) is the possibility to describe the whole process by simulation, once

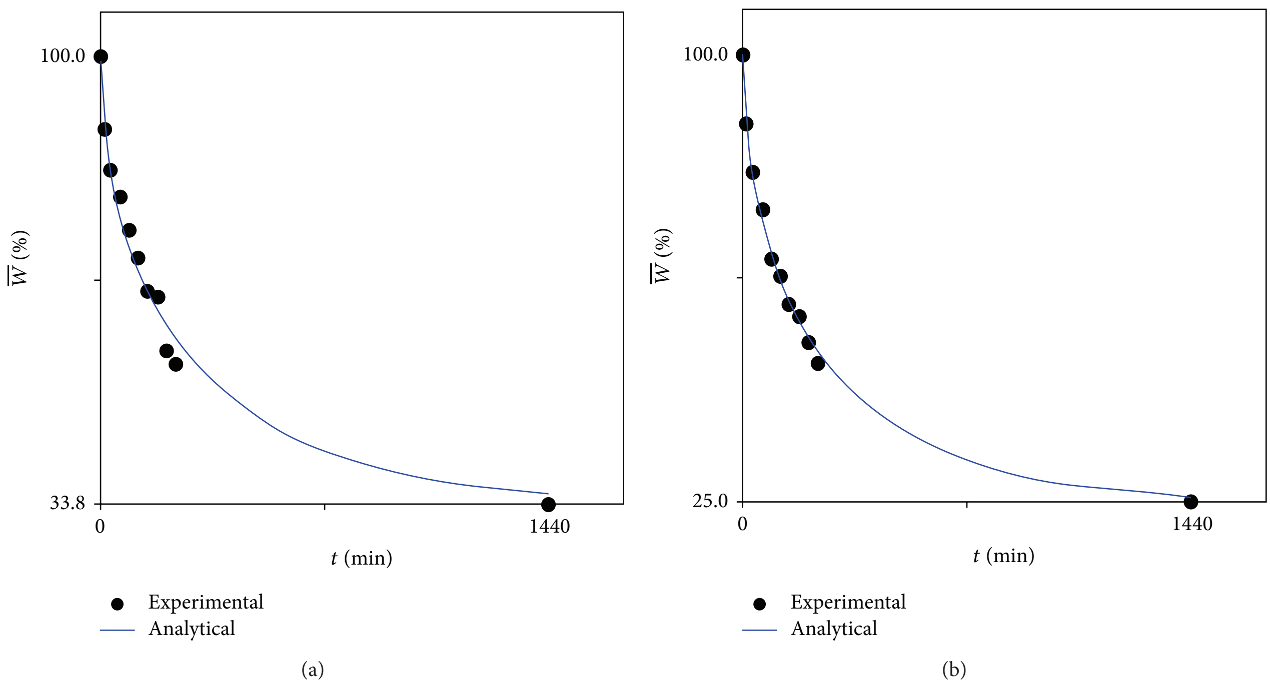

Figure 2: Water quantity at (a) 40°Brix and 30°C; (b) 50°Brix and 40°C.

Table 1: Effective mass diffusivities and statistical indicators for three-dimensional model.

Experiment at		D ($m^2\ min^{-1}$)	R^2	χ^2
40°Brix, 30°C	Water	1.52×10^{-8}	0.9857	55.04
50°Brix, 40°C	Water	1.74×10^{-8}	0.9973	16.48
40°Brix, 30°C	Sucrose	3.55×10^{-8}	0.9869	67.61
50°Brix, 40°C	Sucrose	4.11×10^{-8}	0.9926	38.20

the experimental points are known at beginning the process (first 4 or 5 h) and also the equilibrium point (for the guava slices used in the experiments, about 24 h). Such information is enough to determine D, enabling the simulation of the whole process.

The contour plots showing the distributions of water quantity and sucrose gain within the guava slices at any instant can be obtained using (3). These distributions in the vertical plane xz in $y = 0$ (Figure 1) were determined for 50°Brix and 40°C, at instant of 144 min, and the obtained results are shown in Figure 4.

3.2. Discussion. An inspection of Table 1 (and also an observation of Figures 2 and 3) enables affirming that three-dimensional diffusion model with boundary condition of the first kind well describes the osmotic dehydration of the parallelepiped shaped slices of guava. For example, the determination coefficient was greater than 0.9850 for all analyzed migrations. From Figure 3 it is realized that the difference between the experimental results is very little when sucrose uptake is analyzed (72% and 74.2%). On the other hand, comparing the experiments at 40°Brix and 30°C and 50°Brix and 40°C, shown in Figure 2, the water removal in the second experiment is almost 9% greater than in the first one. Thus, in order to remove a major quantity of water, it is recommendable to perform osmotic dehydration at 50°Brix and 40°C.

Boundary condition of the first kind is used with success by several researchers in the description of osmotic dehydration of many fruits [3, 11]. However, in order to describe osmotic dehydration of some agricultural products in a rigorous way, in many occasions the boundary condition of the third kind must be used [8, 9]. As was observed by Da Silva et al. [9], the appropriate boundary condition to describe an osmotic dehydration process depends on the type of studied product, shape, dimensions, and experimental conditions. In the guava case, it was observed that the boundary condition of the first kind well describes the process.

An observation of Figure 4 enables to realize that the water quantity, for instance, at $t = 144$ min, is greater in the central region than in the extremities. On the other hand, the sucrose concentration is greater in the extremities than in the central region. Obviously, these results are foreseeable, but all of them were obtained by proposed model.

As was observed in this study, the obtained results indicated that the boundary condition of the first kind is appropriate to describe the mass migrations. For that, each summation of (3) and (5) varied from 1 to 25 (instead of "infinite terms"). According to Da Silva et al. [24], for the boundary condition of the first kind, 25 terms in each summation are enough to maintain the maximum cut-off error in 1.3%, at $t = 0$. On the other hand, as was commented by Da Silva et al. [20], it should be observed that, due to some heterogeneity and anisotropy, the diffusion process in a given

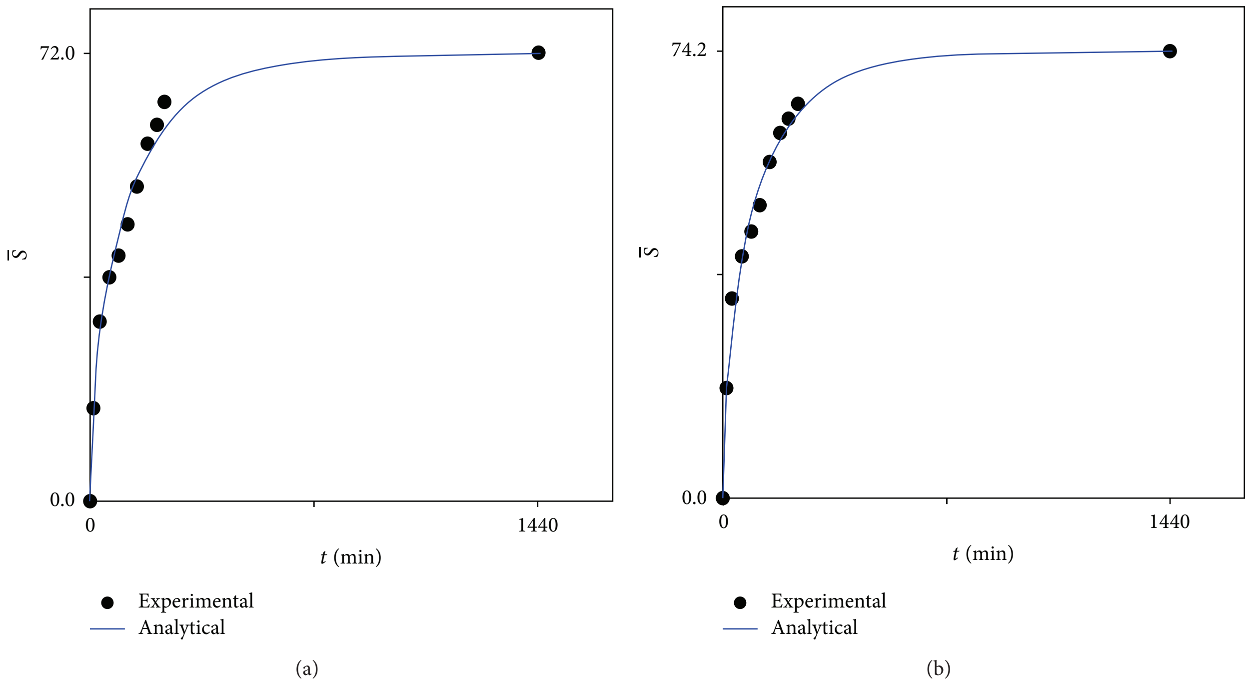

FIGURE 3: Sucrose gain at (a) 40°Brix and 30°C; (b) 50°Brix and 40°C.

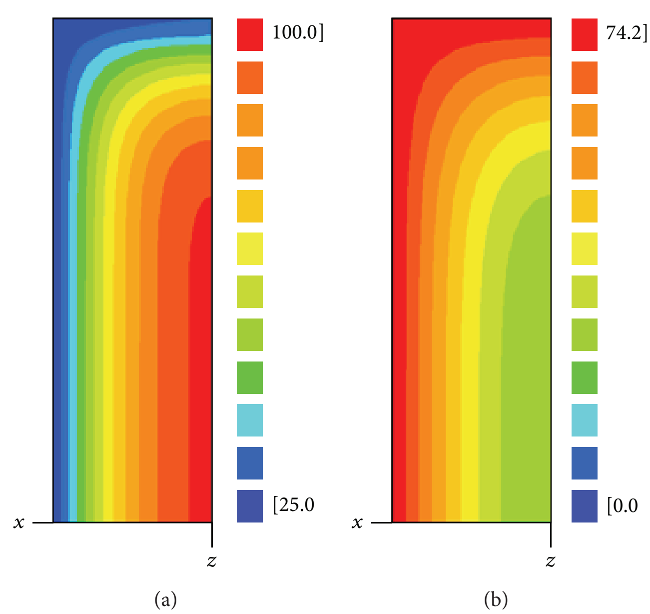

FIGURE 4: Distributions at 50°Brix and 40°C, at instant t = 144 min: (a) water; (b) sucrose.

direction can be a little different from the diffusion in other directions. Then, in this paper, the values of the diffusivities determined by optimization really should be interpreted as effective values.

According to Luikov [21], a question must be asked on the results, due to water loss during the process. If there is a considerable shrinkage during water loss, and this shrinkage was not included in the proposed model, why are the obtained results so good? da Silva et al. [25] explain that during the process, shrinkage occurs and, together with this phenomenon, the effective mass diffusivities vary because of the modifications in the internal structure of the product, due to shrinkage, loss water, and sucrose gain. As these two phenomena (variable volume and diffusivities) were not considered in the assumptions made for the mathematical modeling, it is possible that their effects are mutually canceled. Due to the good results, models considering constant volume and diffusivities are very common in the literature

[1–3, 8, 9, 11–16]. On the other hand, in order to consider the effects above-mentioned, an analytical solution is not appropriate to describe the process, which may best be described by numerical solutions. However, even in these cases, the study presented in this paper is useful because, through the proposed model, the obtained results serve as initial values for other optimization processes involving, for instance, a numerical solution of the diffusion equation.

4. Conclusion

The statistical indicators related with the kinetics of mass migrations can be considered good. Particularly, the determination coefficients were greater than 0.9850. In addition, the use of proposed three-dimensional model enables obtaining information as, for instance, the local value of the water quantity and sucrose gain, at any point within the parallelepiped that represents the slices of guava.

The final sucrose gain was practically the same for two experiments carried out in this study. However, the final water quantity was significantly lesser for 50°Brix and 40°C (about 25%) than for 40°Brix and 30°C (about 34%). Thus, in order to remove a major quantity of water, the experiment at 50°Brix and 40°C should be preferred when compared with the experiment at 40°Brix and 30°C.

The model analyzed in this paper presupposes restrictive assumptions such as constant volume and diffusivities. However, even if the obtained results were not considered completely satisfactory, these results could be used as initial values in other optimization processes that use numerical solutions. Such solutions would take into account the mentioned restrictions.

Practical Applications

In order to prolong the shelf life of fruits and vegetables, an alternative is the water removal. In this sense, this paper presents a study on the guava osmotic dehydration using sucrose solutions at two concentrations and two temperatures. Therefore, the results of this research can be used in food processing industry in order to partially remove water of guava.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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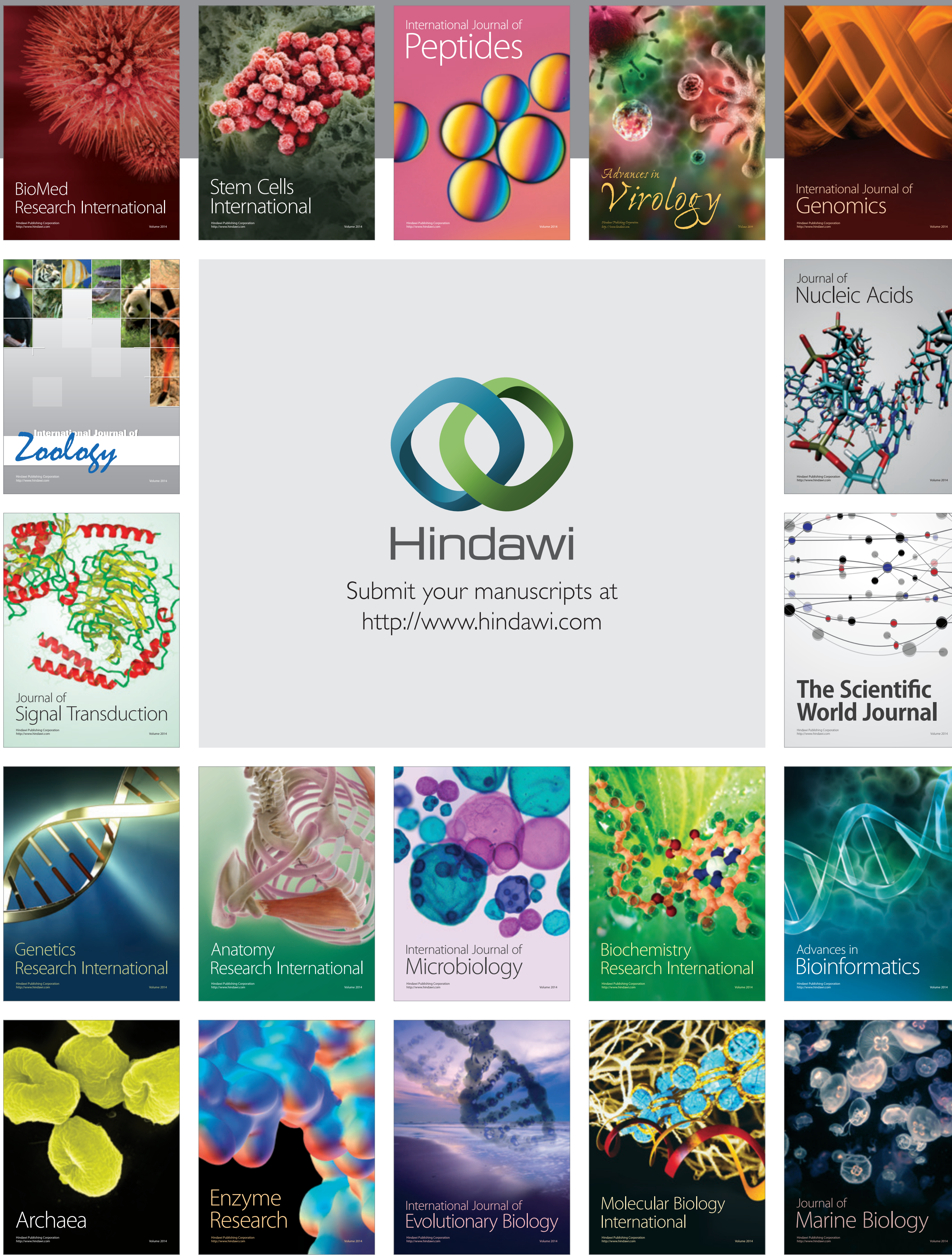
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