



## **Modelling the Transport of Lactic Acid, Sodium Chloride and Reducing Sugars in Carrot Slices Submerged in Brines — Part I. Univariate Approach**

Regina M. Nabais,<sup>1</sup> Madalena C. Vieira & F. Xavier Malcata\*

Escola Superior de Biotecnologia, Universidade Católica Portuguesa, Rua Dr. António Bernardino de Almeida, 4200 Porto, Portugal

(Received 13 June 1994; accepted 6 May 1995)

### *ABSTRACT*

*The transport phenomena pertaining to the independent diffusion of lactic acid and sodium chloride from a brine into carrot slices submerged therein, and of reducing sugars in the opposite direction, were experimentally studied at various temperatures and initial concentrations of salt and acid in the brine. The data sets obtained at each combination of temperature and initial concentration of the brine were independently fit to three analytical models derived from first principles on three alternative mechanisms postulated for the time-variation of the diffusivity. Incremental sum of squares analyses have shown that the diffusion of acid and salt into the carrots is well described by a constant diffusivity, whereas the diffusion of reducing sugars out of the carrots is well described by a diffusivity undergoing a sigmoidal variation with time. This sigmoidal variation may be explained by the assumption that the bursting of the carrot cells is simultaneously proportional to the fraction of intact cells and the fraction of burst cells of the carrot material. The analysis developed is relevant because it allows an approximate prediction of the rates of acid and salt intake, as well as the release rates of reducing sugars, pertaining to brined carrot slices, the basic processes that occur during manufacture of lactic acid carrot pickles. Copyright © 1996 Elsevier Science Limited.*

### NOTATION

$A_c$  Area of each exposed surface of the carrot slice (cm<sup>2</sup>)  
 $C_{c,a}$  Concentration of acid in the carrot material (% w/v)

<sup>1</sup>Current address: Escola Superior Agrária, S. Martinho do Bispo, 3000 Coimbra, Portugal.

\* Author to whom correspondence should be addressed.

$\hat{C}_{c,a}$	Volume-averaged concentrations of acid (% w/v)
$C_{c,a,\infty}$	Volume-averaged concentration of acid in carrot material in equilibrium with the brine (% w/v)
$C_{c,r,\infty}$	Constant concentration of reducing sugars in carrot material (% w/v)
$C_{c,s}$	Concentration of salt in the carrot material (% w/v)
$\hat{C}_{c,s}$	Volume-averaged concentrations of salt (% w/v)
$C_{c,s,\infty}$	Volume-averaged concentrations of salt in carrot material in equilibrium with the brine (% w/v)
$C_{1,a,0}$	Initial concentration of acid in brine (% w/v)
$C_{1,a,\infty}$	Constant concentration of acid in carrot material (% w/v)
$C_{1,s,0}$	Initial concentration of salt in brine (% w/v)
$C_{1,s,\infty}$	Constant concentrations of salt in carrot material (% w/v)
$C_{1,r}$	Concentration of reducing sugars in brine (% w/v)
$C_{1,r,\infty}$	Concentration of reducing sugars in brine in equilibrium with carrot material (% w/v)
$C_X$	Concentration of intact carrot cells ( $\text{g}/\text{cm}^3$ )
$C_{X,0}$	Concentration of intact carrot cells at start-up of experiment ( $\text{g}/\text{cm}^3$ )
$C_{X,\text{tot}}$	Total concentration of carrot cells in carrot material ( $\text{g}/\text{cm}^3$ )
$D_{\text{ap},c,a}$	Apparent diffusivity of acid in the carrot ( $\text{m}^2/\text{s}$ )
$D_{\text{ap},f,a}$	Apparent diffusivity of acid in the fluid imbedded within the carrot ( $\text{m}^2/\text{s}$ )
$D_{\text{ap},c,r}$	Apparent diffusivity of reducing sugars in the carrot ( $\text{m}^2/\text{s}$ )
$D_{\text{ap},f,r}$	Apparent diffusivity of reducing sugars in the fluid imbedded within the carrot ( $\text{m}^2/\text{s}$ )
$D_{\text{ap},c,s}$	Apparent diffusivity of salt in the carrot ( $\text{m}^2/\text{s}$ )
$D_{\text{ap},f,s}$	Apparent diffusivity of salt in the fluid embedded within the carrot ( $\text{m}^2/\text{s}$ )
$K_a$	Partition coefficient of acid between the brine and the carrot material defined as $C_{c,a,\infty}/C_{1,a,\infty}$ (% w/v/% w/v)
$k_r$	Second-order rate constant for bursting of carrot cells ( $\text{cm}^3/\text{g}/\text{h}$ )
$K_r$	Partition coefficient of reducing sugar between brine and carrot material defined as $C_{c,r,\infty}/C_{1,r,\infty}$ (% w/v/% w/v)
$K_s$	Partition coefficient of salt between brine and carrot material defined as $C_{c,s,\infty}/C_{1,s,\infty}$ (% w/v/% w/v)
$L_c$	Half-thickness of the slice (cm)
$q_{a,n}$	Non-negative eigenvalues of $\tan(q_{a,n}) + \alpha_a q_{a,n} = 0$
$q_{r,n}$	Non-negative eigenvalues of $\tan(q_{r,n}) + \alpha_r q_{r,n} = 0$
$q_{s,n}$	Non-negative eigenvalues of $\tan(q_{s,n}) + \alpha_s q_{s,n} = 0$
$t$	Time elapsed after submersion of carrot slices in brine (h)
$\bar{t}$	Time corrected for initial lag time (h)
$V_c$	Volume occupied by carrot ( $\text{cm}^3$ )
$V_l$	Volume of brine ( $\text{cm}^3$ )
$x$	Coordinate along the direction of diffusional flow (cm)
$\alpha_a$	Auxiliary parameter, defined as $V_l/(2A_c L_c K_a)$
$\alpha_r$	Auxiliary parameter, defined as $V_l/(2A_c L_c K_r)$
$\alpha_s$	Auxiliary parameter, defined as $V_l/(2A_c L_c K_s)$
$\Phi_{c,a}$	Time integral of the apparent diffusivity of acid in the carrot material ( $\text{m}^2$ )
$\Phi_{c,r}$	Time integral of the apparent diffusivity of reducing sugars in the carrot material ( $\text{m}^2$ )
$\Phi_{c,s}$	Time integral of the apparent diffusivity of salt in the carrot material ( $\text{m}^2$ )

## INTRODUCTION

Vegetables can be temporarily preserved by submerging them in aqueous solutions with high concentrations of salt and/or acid (brines), in a process called pickling; the high acid content may in turn be obtained by direct addition or through microbial fermentation, which can be spontaneous or induced (Fleming, 1982; Anderson *et al.*, 1990). The prevention of undesirable microbial degradation and texture change of the vegetable material through pickling with time can be mainly attributed to the osmotic and antiseptic actions of the brine once inside the tissue (Fleming, 1982). Therefore, the ability to predict the rate of transport of salt or acid solutes from the brine into the vegetable material (or fermentable sugars from the vegetable material to the brine in the case where microbial fermentation plays a role) for various operating temperatures is a particularly important challenge in the design of any pickling process.

The final composition of the brine (i.e. the composition that the final consumer will experience) and the composition of the intercellular juice of the vegetable material is a function of chemical and osmotic equilibria (Bell *et al.*, 1972; Schwartz & Carnoad, 1979); such composition (together with the ability of varying the temperature) can be taken advantage of in the creation of a programmed environment for the preferential growth of beneficial micro-organisms (Fabian & Wadsworth, 1939; Etchels *et al.*, 1950; Fleming *et al.*, 1983; Anderson, 1984; Adams & Hall, 1988; Tuncan & Martin, 1990). The water and solutes transported to and from the vegetable material during immersion in aqueous solutions will also have an effect on the final weight (Selman & Rolfe, 1979; Kincan & Kaymak, 1987; Oliveira, 1988), flavour and texture (Etchels & Moore, 1971; Bell *et al.*, 1972), and nutrient content (Schwartzberg & Chao, 1982; Steinkraus, 1983), and are decisive in controlling enzyme activity within the food material (Schwimmer, 1980).

The mechanisms of transport of solutes from/to vegetables and to/from a brine have been extensively studied for high and moderate temperature conditions (Pflug *et al.*, 1967; Stahl & Loncin, 1979; Selman & Rolfe, 1979; Selman *et al.*, 1983; Potts *et al.*, 1986; Kincan & Kaymak, 1987; Oliveira, 1988; Biswall & Maguer, 1989; Beristain *et al.*, 1990; Liu, 1992; Moreira *et al.*, 1992). There is a general consensus that the transport of small solutes between the outer brine and the fluid between the cell membrane and the cell wall, or solutes of any size from the brine to the vegetable material, can be accurately modelled by Fick's law of diffusion using apparent diffusivities (which are a result of the anisotropic structure of the vegetable material). However, at low temperatures (say, below 50°C) the observed rate of transport of large solutes (e.g. reducing sugars) from the vegetable material to the brine does not follow Fick's law because the cell membrane needs to burst before the solute becomes available for molecular transport. Various models have been proposed for this latter situation which take into account the process direction (leaching or infusion), the electrostatic behavior of the solute, the inorganic or organic nature of the solute, the concentration and distribution of the solute between the two phases, the molecular size of the solute, the integrity and structural arrangement of the solid matrix, and the histological state of the system (Soddu & Gioia, 1979; Schwartzberg & Chao, 1982; Toupin *et al.*, 1989; Oliveira & Silva, 1992; Moreira *et al.*, 1992). In studying the behaviour at low temperatures, Pflug *et al.* (1967) have proposed a graphical method for the fitting of their experimental data, whereas Potts *et al.* (1986) used an empirical equilibration-prediction approach; in

the case of Soddu & Gioia (1979), such an empirical approach took the form of a Langmuir isotherm. In this communication another approach is proposed, which is based on a combination of a process of molecular transport with a process of release following bursting of the carrot cells according to first-order processes.

Since carrots are one of the most common vegetables which have been traditionally used in pickling processes in southern Europe and northern Africa, an impetus exists for detailed studies on the quantitative evaluation of the combined effects of temperature and salt concentration of the brine on the rates of transport of native sugars from, and added acid to, the carrot material. Carrots possess a strong flavour, and their major components are gluten, starch, sugars, malic and pectic acids, fluor, mannitol and resin (Alabran & Mabrouk, 1973; Phan & Hsu, 1973; Andersson *et al.*, 1990). As with other plants, two main tissues can be considered: (i) the parenchima (or cortex), which is a storage tissue rich in starch and sucrose; and (ii) the vascular system, which encompasses the xylem (upward direction, inner portion of the core), which is rich in salts, and the phloem (downward direction, outer portion of the core), which is rich in glucose and fructose. The parenchima cells are regularly shaped, and have thin walls and vacuoles; the vascular system cells, on the other hand, have walls richer in lignin and their vacuoles increase in size giving place to tubular-shaped cells, which can remain alive and keep their tops (phloem) or die and hence lose their ends (xylem) (Meyer *et al.*, 1965; Goris, 1969; Phan & Hsu, 1973; Richardson, 1975; Salisbury & Ross, 1978; Soddu & Gioia, 1979; Oliveira, 1988). In order to parallel the conditions more likely to be of interest at the industrial processing level, the following ranges for the operating parameters were selected in our studies: salt concentration from 5 to 20% (w/v) and lactic acid concentrations from 0.5 to 2% (w/v). Since the initial content of reducing sugars of the carrots cannot be artificially manipulated, it was decided to study the rates of diffusion of such sugars under various concentrations of salt in the brine ranging from 0 to 20% (w/v).

## EXPERIMENTAL WORK

### Materials

Fresh carrots were bought at random at local markets (main cultivar: Nantes). Sodium chloride, sodium hydroxide, potassium dichromate, copper sulphate, potassium permanganate, silver nitrate and lactic acid were purchased from Merck (Germany). Dinitrosalicilic acid was obtained from BDH (UK).

### Equipment

Centrifugations were performed with a Universal centrifuge from Hettich (Germany). Measurements of pH were made with a pH-meter from Crisson, model 2002 (Spain) coupled with a standard Ingold combined pH electrode (Switzerland). Isothermal conditions and stirring were achieved using a thermostatted shaker water bath Kotterman 3047 from Labortechnik (Germany). Spectrophotometric measurements were performed with a visible spectrophotometer model 350 from Pye Unicam (UK). Sterilization was accomplished using a laboratory retort Austester 437G from Selecta (Spain).

## Methods

### *Preparation of brines*

Brines were prepared at 25°C using a thermostatted bath with the required amounts of sodium chloride (previously dried overnight at 60°C) or of lactic solution (90% pure), as appropriate, and diluting them to the desired volume with deionized water. The solutions thus prepared were distributed into flasks and sterilized for 15 min in a laboratory retort.

### *Diffusion experiments*

Before the experiments, the carrots had both tops cut off, were thoroughly washed with tap water, submerged for 15 min in a 0.2% (w/v) solution of copper sulphate, and were finally submerged for 15 min in a 0.2% (w/v) solution of potassium permanganate. The carrots were then sliced in pieces 1 cm-high and the diameters were measured using a micrometer. Each slice was, at this time, stuck on a sterilized stainless steel pin, submerged in a beaker containing 50 ml of an aqueous brine with the desired salt concentration and gently stirred in an uniform fashion using the orbital shaker (orbital velocity setting: 5) set at the temperature required.

### *Analysis of sodium chloride*

After removal from the brine, the carrot slices were quickly rinsed with deionized water, slightly dried with tissue paper, cut into very small pieces, submerged in 50 ml of deionized water in a stoppered flask and heated for 30 min in a laboratory retort (McKnee, 1985). After cooking the carrots pieces, together with the aqueous extract, were homogenized in a mixer and centrifuged for 10 min at 5000 rpm. Finally, 2 ml of the clarified supernatant were titrated with 0.05 N solution of silver nitrate using potassium dichromate as indicator.

### *Analysis of reducing sugars*

Aliquots of the brines were periodically taken, diluted with deionized water and analysed using the dinitrosalicilic acid method (Miller, 1959). The results were expressed as glucose equivalent. Residual reducing sugars in the carrot slices were obtained by analysing, using the same method, the clarified extract obtained as described in the section 'Analysis of sodium chloride'.

## Analysis of lactic acid

The total acidity of the solutions was measured and expressed as lactic acid equivalent. For this purpose, an aliquot of 2 ml of the clarified extract was titrated with a 0.01 N solution of sodium hydroxide until pH 8.2 was reached and remained for at least 1 min; the titre of the blank (which consisted of the solution obtained when a second carrot slice was submerged in deionized water) was deducted in an appropriate fashion.

## Measurement of partition coefficients

The partition coefficients for salt, acid and reducing sugars was obtained as the ratio of the per cent concentration (w/v) in the crushed carrot material to the brine counterpart after equilibrium conditions were reached.

TABLE 1

Geometrical and physical characteristics (and associated standard deviations) of the carrot slices utilized in the experiments (approximate diameter, 3 cm; approximate height, 1 cm)

Location	Volume ( $10^6 \text{ m}^3$ )	Mass (kg)	Density ( $\text{kg/m}^3$ )	Total reducing (% (w/w))
Core	$0.670 \pm 0.043$	$0.00073 \pm 0.00040$	$1048 \pm 277$	$1.32 \pm 0.65$
Cortex	$5.9 \pm 3.4$	$0.0067 \pm 0.0036$	$1128 \pm 378$	$0.73 \pm 0.29$
Total	$6.7 \pm 3.8$	$0.0079 \pm 0.0039$	$1112 \pm 349$	$1.28 \pm 0.53$

## EXPERIMENTAL RESULTS

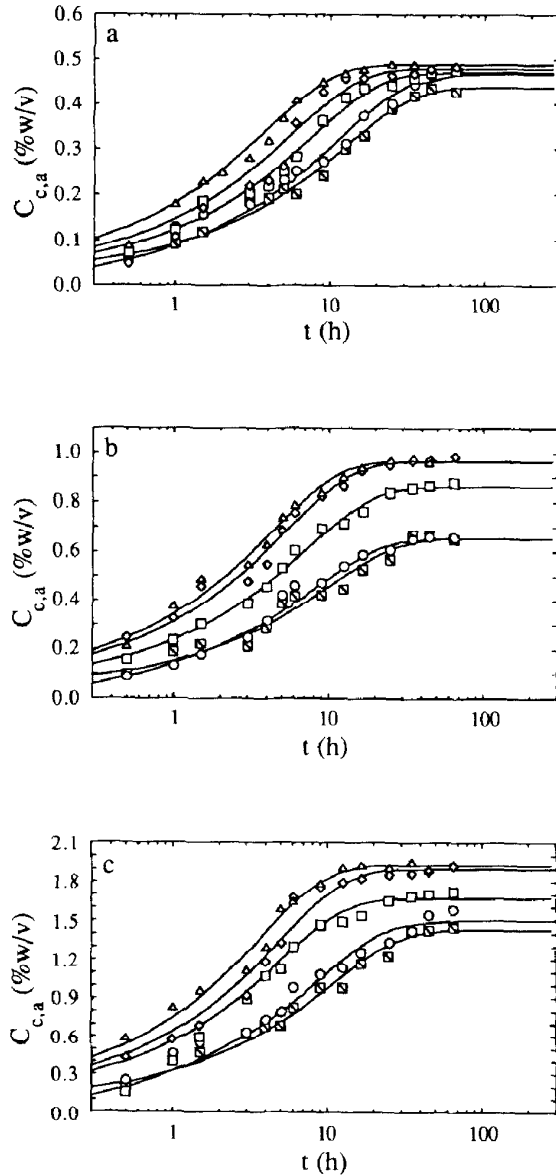
Geometrical characteristics and physico-chemical properties of the carrot slices are listed in Table 1. The effect of the lactic acid concentration in the brine and the temperature on the observed rates of transport of acid from the brines to the carrot slices was studied for acid levels of 0.5, 1 and 2% (w/v) and temperatures of 15, 20, 30, 40 and 50°C, and the experimental results thus obtained are depicted in Fig. 1. The effect of the salt concentration in the brine and the temperature on the observed rates of transport of salt from the brines to the carrot slice was studied for salt levels of 5, 7.5, 10, 15 and 20% (w/v) and temperatures of 15, 20, 30, 40 and 50°C, and the experimental results thus obtained are depicted in Fig. 2. The effect of the salt concentration in the brine and the temperature on the observed rates of transport of reducing sugars from the carrot slices to the brine was studied for salt levels of 0, 5, 7.5, 10, 15 and 20% (w/v) and temperatures of 15, 20, 30, 40 and 50°C, and the experimental results thus obtained are depicted in Fig. 3.

## MATHEMATICAL ANALYSIS

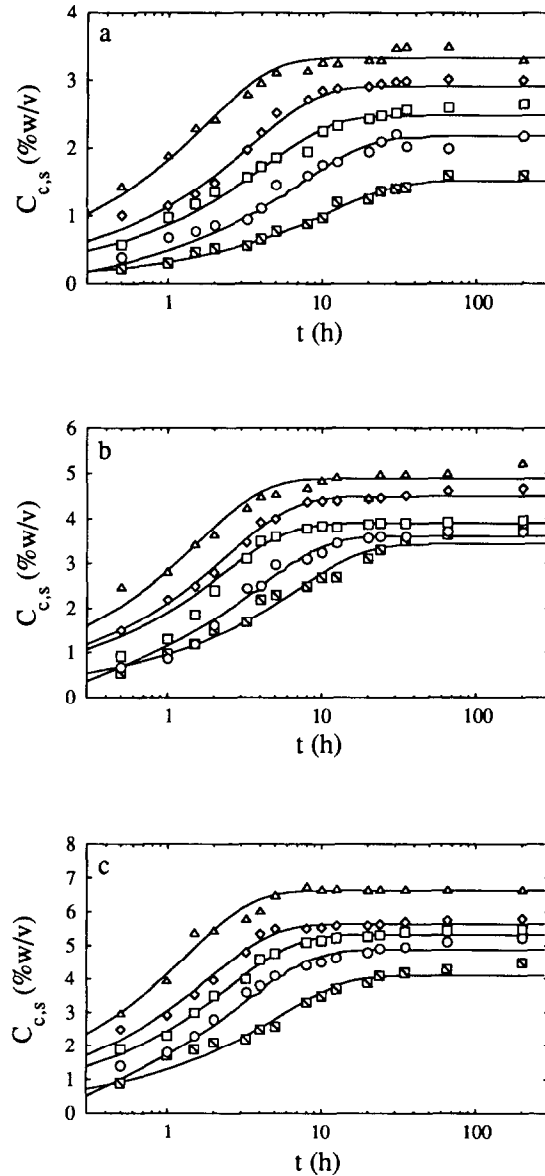
Assume that the carrot slice behaves as an infinite slab of uniform carrot material of thickness  $2L_c$  submerged in a well-stirred solution. The mass balances to solute within the carrot material can be written as:

$$\left( \frac{\partial C_{c,i}}{\partial \bar{t}} \right)_x = \frac{\partial}{\partial x} \left( D_{\text{ap},c,i} \{ \bar{t} \} \left( \frac{\partial C_{c,i}}{\partial x} \right)_{\bar{t}} \right); \quad i \equiv r, s, a \quad (1)$$

where  $C_{c,i}$  is the concentration of solute  $i$  in the carrot material, i.e. reducing sugars ( $i=r$ ), salt ( $i=s$ ) or lactic acid ( $i=a$ ),  $D_{\text{ap},c,i} \{ \bar{t} \}$  is the apparent diffusivity of solute  $i$  in the carrot material (assumed to be, in general, a function of time) and  $x$  is the coordinate along the direction of diffusional flow ( $x=0$  at the centre of the carrot slice). In eqn (1),  $\bar{t}$  is the time elapsed according to a predefined scale (i.e.  $\bar{t}=t-t_0$ ) where the lag time,  $t_0$ , is the time at which the transport of the species under consideration is assumed to essentially start; the value of  $t_0$  may tentatively be set equal to 0 (i.e. the time at which the carrot slice is submerged in the brine) or be left as an adjustable parameter. Equation (1) can be rearranged to read (Crank, 1975):



**Fig. 1.** Plot of the concentration of lactic acid in the carrot material,  $C_{c,a}$ , vs the time elapsed after submersion,  $t$ : experimental values ( $\square$ , 15°C;  $\circ$ , 20°C;  $\square$ , 30°C;  $\diamond$ , 40°C; and  $\Delta$ , -50°C) and fit of model A (—) for (a) 0.5%, (b) 1% and (c) 2% (w/v) total acid in the brine.



**Fig. 2.** Plot of the concentration of sodium chloride in the carrot material,  $C_{c,s}$ , vs the time elapsed after submersion,  $t$ : experimental values ( $\square$ , 15°C;  $\circ$ , 20°C;  $\square$ , 30°C;  $\diamond$ , 40°C; and  $\triangle$ , -50°C) and fit of model A (—) for (a) 5.0%, (b) 7.5%, (c) 10.0%, (d) 15.0% and (e) 20% (w/v) total salt in the brine.



$$\left( \frac{\partial C_{c,i}}{\partial \Phi_{c,i}\{\bar{t}\}} \right)_x = \left( \frac{\partial^2 C_{c,i}}{\partial x^2} \right)_t; \quad i \equiv r, s, a \quad (2)$$

where

$$\Phi_{c,i}\{\bar{t}\} = \int_{t_0}^{\bar{t}} D_{ap,c,i}\{\zeta\} d\zeta; \quad i \equiv r, s, a \quad (3)$$

Equation (2), which is a form of Fick's second law, is subject to one of the following initial conditions:

$$\begin{aligned} C_{c,i} &= C_{c,i,0}, \quad -L_c \leq x \leq L_c, \quad \Phi_{c,i}\{\bar{t}\} = 0; \quad i \equiv r \\ C_{c,i} &= 0, \quad -L_c \leq x \leq L_c, \quad \Phi_{c,i}\{\bar{t}\} = 0; \quad i \equiv s, a \end{aligned} \quad (4)$$

where  $C_{c,i,0}$  is the initial concentration of solute  $i$  in the carrot material and  $L_c$  is the half-thickness of the carrot slab. Equation (1) is also subject to the following two boundary conditions:

$$\frac{V_1}{2A_c K_i} \left( \frac{dC_{l,i}}{d\Phi_{c,i}\{\bar{t}\}} \right) = \left( \frac{\partial C_{c,i}}{\partial x} \right)_t, \quad x = -L_c, \quad \Phi_{c,i}\{\bar{t}\} > 0; \quad i \equiv r, s, a \quad (5)$$

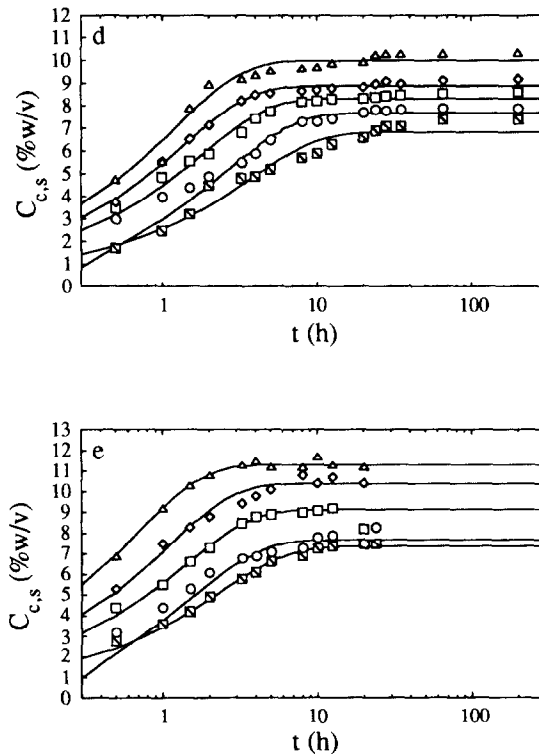
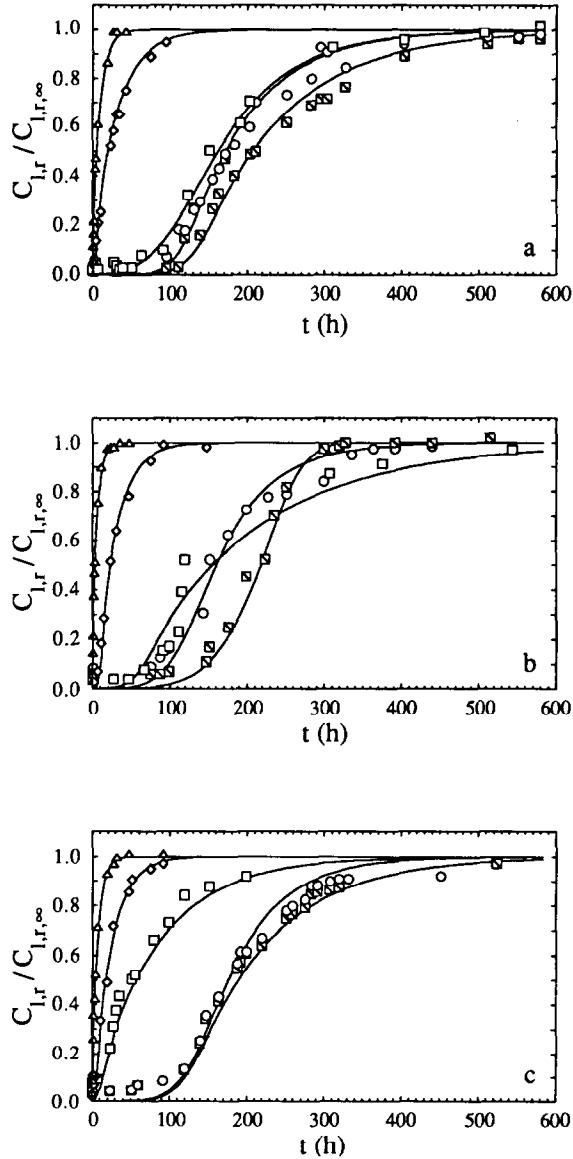


Fig. 2. continued.



**Fig. 3.** Plot of the concentration of reducing sugars in the brine,  $C_{1,r}$ , normalized by the equilibrium estimated concentration,  $C_{1,r,\infty}$ , vs the time elapsed after submersion,  $t$ : experimental values ( $\nabla$ , 15°C;  $\circ$ , 20°C;  $\square$ , 30°C;  $\diamond$ , 40°C; and  $\triangle$ , 50°C) and fit of model  $C(\_)$  for (a) 0.0%, (b) 5.0%, (c) 7.5%, (d) 10.0%, (e) 15.0% and (f) 20% (w/v) total salt in the brine.

$$\frac{V_1}{2A_c K_i} \left( \frac{dC_{l,i}}{d\Phi_{c,i}\{t\}} \right) = - \left( \frac{\partial C_{c,i}}{\partial x} \right)_t, \quad x=L_c, \quad \Phi_{c,i}\{t\} > 0; \quad i \equiv r, s, a$$

where  $V_1$  is the volume of brine,  $C_{l,i}$  is the concentration of solute  $i$  in the brine,  $K_i$  is the partition coefficient of solute  $i$  between the brine and the carrot material, i.e.  $C_{c,i}/C_{l,i,\infty}$  (where  $C_{l,i,\infty}$  is the concentration of solute  $i$  in the brine in equilibrium

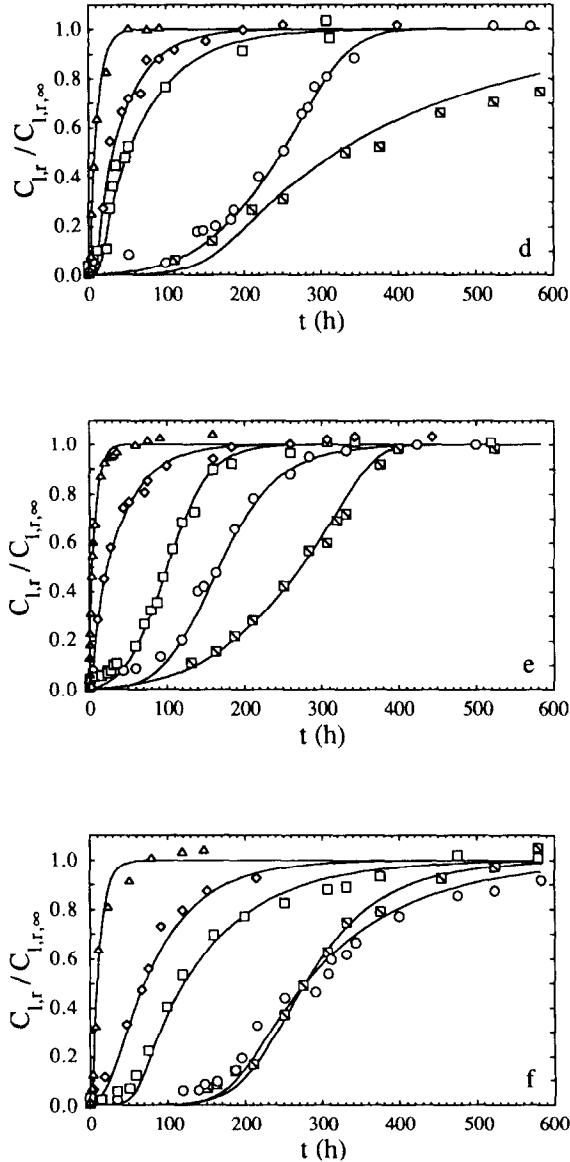


Fig. 3. continued.

with the carrot material and  $C_{c,i,\infty}$  is the concentration of solute  $i$  in the carrot material in equilibrium with the brine) and  $A_c$  is the area of each exposed surface of the carrot slice (assuming a semi-infinite geometry).

Combining eqn (2)–eqn (5), the concentration of species  $i$  within the carrot slice is given by (Crank, 1975):

$$C_{c,i}\{x,t\} = C_{c,i,0} - (C_{c,i,0} - C_{c,i,\infty}) \left( 1 + \sum_{n=1}^{\infty} \frac{2(1+\alpha_i)\cos\{q_{i,n}x/L_c\}}{(1+\alpha_i+\alpha_i^2q_{i,n}^2)\cos\{q_{i,n}\}} \exp\left\{-\frac{q_{i,n}^2\Phi_{c,i}\{\bar{t}\}}{L_c^2}\right\} \right); \quad i \equiv r$$

$$C_{c,i}\{x,t\} = C_{c,i,\infty} \left( 1 + \sum_{n=1}^{\infty} \frac{2(1+\alpha_i)\cos\{q_{i,n}x/L_c\}}{(1+\alpha_i+\alpha_i^2q_{i,n}^2)\cos\{q_{i,n}\}} \exp\left\{-\frac{q_{i,n}^2\Phi_{c,i}\{\bar{t}\}}{L_c^2}\right\} \right); \quad i \equiv s, a$$
(6)

where  $C_{c,i,0}$  is the initial concentration of solute  $i$  in the carrot material, and where  $\alpha_i$  is a dimensionless parameter defined as:

$$\alpha_i \equiv \frac{V_l}{2A_c L_c K_i} \quad (7)$$

and  $q_n$  ( $n = 1, 2, \dots$ ) denotes every non-negative eigenvalue of

$$\tan\{q_{i,n}\} = -\alpha_i q_{i,n} \quad (8)$$

Integration of eqn (6) in the space variable and subsequent combination with eqn (8) yields:

$$\hat{C}_{c,i}\{\bar{t}\} \equiv \frac{\int_0^{L_c} C_{c,i}\{x,\bar{t}\} dx}{\int_0^{L_c} dx} = C_{c,i,0} - (C_{c,i,0} - C_{c,i,\infty}) \left( 1 - \sum_{n=1}^{\infty} \frac{2\alpha_i(1+\alpha_i)}{1+\alpha_i+\alpha_i^2q_{i,n}^2} \exp\left\{-\frac{q_{i,n}^2\Phi_{c,i}\{\bar{t}\}}{L_c^2}\right\} \right); \quad i \equiv r$$

$$\hat{C}_{c,i}\{\bar{t}\} \equiv \frac{\int_0^{L_c} C_{c,i}\{x,\bar{t}\} dx}{\int_0^{L_c} dx} = C_{c,i,\infty} \left( 1 - \sum_{n=1}^{\infty} \frac{2\alpha_i(1+\alpha_i)}{1+\alpha_i+\alpha_i^2q_{i,n}^2} \exp\left\{-\frac{q_{i,n}^2\Phi_{c,i}\{\bar{t}\}}{L_c^2}\right\} \right); \quad i \equiv s, a$$
(9)

for the carrot material, where  $\hat{C}_{c,i}$  is the volume-averaged concentration of solute  $i$  in the carrot material, and  $\hat{C}_{c,i,\infty}$  is the volume-averaged concentration of solute  $i$  in the carrot material in equilibrium with the brine.

The constancy of the total amount of solute in the brine and carrot slice combined allows one to write:

$$\begin{aligned}\alpha_i C_{l,i}\{\bar{t}\} + \hat{C}_{c,i}\{\bar{t}\} &= C_{c,i,0}; \quad i \equiv r \\ \alpha_i C_{l,i}\{\bar{t}\} + \hat{C}_{c,i}\{\bar{t}\} &= \alpha_i C_{l,i,0}; \quad i \equiv s, a\end{aligned}\quad (10)$$

as well as

$$\begin{aligned}\alpha_i C_{l,i,\infty}\{\bar{t}\} + C_{c,i,\infty}\{\bar{t}\} &= C_{c,i,0}; \quad i \equiv r \\ \alpha_i C_{l,i,\infty}\{\bar{t}\} + \hat{C}_{c,i,\infty}\{\bar{t}\} &= \alpha_i C_{l,i,0}; \quad i \equiv s, a\end{aligned}\quad (11)$$

Combination of eqn (9)–eqn (11) yields

$$\begin{aligned}C_{l,i}\{\bar{t}\} &= C_{l,i,\infty} \left( 1 - \sum_{n=1}^{\infty} \frac{2\alpha_i(1+\alpha_i)}{(1+\alpha_i+\alpha_i^2q_{i,n}^2)} \exp\left\{-\frac{q_{i,n}^2\Phi_{c,i}\{\bar{t}\}}{L_c^2}\right\} \right); \quad i \equiv r \\ C_{l,i}\{\bar{t}\} &= C_{l,i,\infty} + (C_{l,i,0} - C_{l,i,\infty}) \left( 1 - \sum_{n=1}^{\infty} \frac{2\alpha_i(1+\alpha_i)}{1+\alpha_i+\alpha_i^2q_{i,n}^2} \exp\left\{-\frac{q_{i,n}^2\Phi_{c,i}\{\bar{t}\}}{L_c^2}\right\} \right); \quad i \equiv s, a\end{aligned}\quad (12)$$

The decision whether to use eqn (9) or eqn (12) to fit the experimental data depends on the type of experimental measurements possible. The measurement of the amount of reducing sugars leached from the carrot slice is more accurately achieved via measurement of the variation in the concentration of these species in the brine (because the initial concentration here is negligible), and hence eqn (12) should be employed (in this case,  $C_{l,r,\infty}$  plays the role of an adjustable parameter); by the same token, the measurement of the amount of salt and lactic acid absorbed by the carrot slice is more accurately achieved via measurement of the variation in the concentration of these species in the carrot material (because the initial concentration here is negligible), and hence eqn (9) should be employed (in this case,  $C_{c,i,\infty}$  plays the role of an adjustable parameter).

Concerning the functional form of  $\Phi\{\bar{t}\}$ , three situations will be considered, giving rise to as many different models (see below). All such models assume that, before submersion of the carrots in the brine, a fraction of the plant cells have died and hence their cytoplasm membranes have burst; for such cells (in a concentration denoted by  $C_{X,\text{tot}} - C_{X,0}$ , where  $C_{X,\text{tot}}$  is the total amount of plant cells and  $C_{X,0}$  is the concentration of cells that were initially intact), the intracellular fluid is not essentially different from the intercellular fluid for transport of the solutes. The cells that were initially intact will burst owing to the osmotic pressure of the solutes in the brine at rates that show different time dependencies depending on the model considered. The diffusivity should then, in its simplest form, be given by:

$$\frac{D_{\text{ap},c,i}\{\bar{t}\}}{D_{\text{ap},f,i}} = \frac{C_{X,\text{tot}} - C_X\{\bar{t}\}}{C_{X,\text{tot}} - C_{X,0}} \quad (13)$$

where  $D_{\text{ap},f,i}$  denotes the apparent diffusivity if all intracellular fluid were available

for molecular transport and where  $C_X\{\bar{t}\}$  is the concentration of cells still left intact at time  $\bar{t}$ .

### Model A

At the moment of submersion (or a short time thereafter) virtually all plant cells have already burst (i.e.  $0 \leq C_X\{\bar{t}\} \leq C_{X,0} = 0$ ); hence, the diffusivity of solutes within the carrot material is essentially a constant, and eqn (13) becomes:

$$D_{ap,c,i}\{\bar{t}\} = D_{ap,f,i} \quad (14)$$

where  $D_{ap,f,i}$  is an adjustable parameter. Recalling eqn (3), one finally obtains:

$$\Phi_{c,i}\{\bar{t}\} \equiv D_{ap,c,i}(t-t_0); \quad i \equiv r, s, a \quad (15)$$

where  $D_{ap,c,i}$  and  $t_0$  are the adjustable parameters.

### Model B

At the time of submersion of the carrots in the brine, some of the cells have already burst (i.e.  $C_{X,tot} > C_{X,0} \geq 0$ ), and the remaining intact cells will burst at a rate that is proportional to the number of cells still left intact. Mathematically, this corresponds to a first-order process, viz.:

$$-\frac{dC_X}{dt} = k_i C_X; \quad @t=0, \quad C_X = C_{X_0} \quad (16)$$

where  $k_i$  is a constant. Upon integration, eqn (16) yields:

$$C_X = C_{X,0} \exp\{-k_i \bar{t}\} \quad (17)$$

Combination of eqn (13) and eqn (17) gives, following some algebraic rearrangement,

$$D_{ap,c,i}\{\bar{t}\} = D_{ap,f,i} \left( \frac{1}{1 - C_{X_0}/C_{X,tot}} - \frac{C_{X_0}/C_{X,tot}}{1 - C_{X_0}/C_{X,tot}} \exp\{-k_i(t-t_0)\} \right) \quad (18)$$

where  $D_{ap,f,i}$ ,  $t_0$ ,  $(C_{X,0}/C_{X,tot})$  and  $k_i$  are the three statistically independent adjustable parameters. Recalling eqn (3), one finally obtains:

$$\Phi_{c,i}(\bar{t}) = \frac{D_{ap,f,i}}{1 - C_{X_0}/C_{X,tot}} \left( t - t_0 - \frac{C_{X_0}/C_{X,tot}(1 - \exp\{-k_i(t-t_0)\})}{k_i} \right) \quad (19)$$

### Model C

At the time of submersion of the carrots in the brine, some of the cells have already burst (i.e.  $C_{X,tot} > C_{X,0} \geq 0$ ), and the remaining intact cells will burst at a rate that is proportional to the number of cells still left intact, on one hand, and that is proportional to the number of cells that have already burst, on the other (this latter behaviour may be explained by the fact that a cell will more easily burst if it is surrounded by plain intercellular fluid rather than by cells with intact membranes). Mathematically, this corresponds to the combination of a first-order process with first-order inhibition, viz.

$$-\frac{dC_X}{dt} = k_i C_X (C_{X,\text{tot}} - C_X); \quad @t=0, \quad C_X = C_{X_0} \quad (20)$$

where  $k_i$  is a constant. Equation (20) is a Riccati equation which, upon integration, yields the logistic curve (Bailey & Ollis, 1986), *viz.*

$$C_X = \frac{C_{X,0} C_{X,\text{tot}} \exp\{-k_i C_{X,\text{tot}} t\}}{C_{X,\text{tot}} - C_{X,0} (1 - \exp\{-k_i C_{X,\text{tot}} t\})} \quad (21)$$

Combination of eqn (13) and eqn (21) gives, following some algebraic rearrangement:

$$D_{\text{ap},\text{c},\text{i}}\{\bar{t}\} = \frac{D_{\text{ap},\text{f},\text{i}}}{1 - C_{X,0}/C_{X,\text{tot}} (1 - \exp\{-k_i C_{X,\text{tot}} t\})} \quad (22)$$

where  $D_{\text{ap},\text{f},\text{i}}$ ,  $(C_{X,0}/C_{X,\text{tot}})$  and  $k_i \cdot C_{X,\text{tot}}$  are the three statistically independent adjustable parameters. Recalling eqn (3), one finally obtains:

$$\Phi_{\text{c},\text{i}}\{\bar{t}\} = \frac{D_{\text{ap},\text{f},\text{i}}}{k_i C_{X,\text{tot}} (1 - C_{X,0}/C_{X,\text{tot}})} \ln \left\{ \frac{C_{X,0}}{C_{X,\text{tot}}} + \left( 1 - \frac{C_{X,0}}{C_{X,\text{tot}}} \right) \exp\{k_i C_{X,\text{tot}} t\} \right\} \quad (23)$$

From inspection of the aforementioned models, it is apparent that Model A is nested in either Model B or C since eqn (18) and eqn (22), respectively, reduce, in both cases, to an analogue of eqn (14) when the two parameters  $k_i$  and  $t_0$  tend to zero.

## STATISTICAL ANALYSIS

The non-linear regression of the experimental data on the transport of lactic acid and sodium chloride to the carrots, and transport of reducing sugars to the brine were made by unweighted least squares using a software package, GREG (Caracotsios *et al.*, 1985). Initial guesses of the relevant parameters, *viz.* the diffusivities and the equilibrium concentrations, were obtained from the order of magnitude of similar diffusivities in liquid phases (say,  $10^{-10}$  m<sup>2</sup>/s) and observation of the asymptotic values of concentrations in the brine or in the carrot obtained after long-term (constrained by the perishable nature of the carrot material) experiments, respectively. The lag times were estimated by extrapolation of the linear increasing portion of the concentration curves at (relatively) short times to zero concentration. Trial and error guesses had to be made for the remaining parameters.

The statistical adequacies of the base (partial) models with respect to the two alternative (full) models were tested via extra sum of squares analyses. These analyses are depicted in Tables 2–4, and are based on a rationale available elsewhere (Bates & Watts, 1980). The parameter estimates obtained from the non-linear regression fits using the statistically best models for the transport of acid, salt and reducing sugars are listed in Tables 5–7, and the corresponding theoretical curves are plotted in Figs 1–3, respectively.

TABLE 2  
Extra Residual Sum of Squares Analyses Involving Models A and B, or Models A and C, for the Transport of Acid from the Brine into the Carrots

Nested models	Source	15°C			20°C			30°C			40°C			50°C		
		SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>	SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>	SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>	SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>	SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>
A-B (0.5% (w/v) acid)	extra parameters	0.00001	2	0.0207	0.00001	2	0.0121	0.00001	2	0.0143	0.00008	2	0.0560	0.00047	2	1.3202
	rate expression B	0.00242	10	P>5%	0.00414	10	P>5%	0.00350	10	P>5%	0.00714	10	P>5%	0.00178	10	P>5%
	rate expression A	0.00243	12	0.00415	12	0.00415	12	0.00351	12	2.9386	0.00722	12	3.7896	0.00225	12	0.0987
A-C (0.5% (w/v) acid)	extra parameters	0.00002	1	0.0913	0.00001	1	0.0266	0.00074	1	2.9386	0.00185	1	P>5%	0.00002	1	0.0987
	rate expression C	0.00241	11	P>5%	0.00414	11	P>5%	0.00277	11	P>5%	0.00537	11	P>5%	0.00223	11	P>5%
	rate expression A	0.00243	12	0.00415	12	0.00351	12	0.00530	12	0.00722	12	0.00722	12	0.00225	12	0.0987
A-B (1.0% (w/v) acid)	extra parameters	0.00010	2	0.0286	0.00400	2	2.7027	0.00010	2	0.0962	0.00010	2	0.0292	0.00010	2	0.0439
	rate expression B	0.01750	10	P>5%	0.00740	10	P>5%	0.00520	10	P>5%	0.01710	10	P>5%	0.01140	10	P>5%
	rate expression A	0.01760	12	0.01140	12	0.01140	12	0.00530	12	0.01720	12	0.01720	12	0.01150	12	0.0965
A-C (1.0% (w/v) acid)	extra parameters	0.00020	1	0.1264	0.00010	1	0.0973	0.00100	1	2.5581	0.00010	1	0.0643	0.00010	1	0.0965
	rate expression C	0.01740	11	P>5%	0.01130	11	P>5%	0.00430	11	P>5%	0.01710	11	P>5%	0.01140	11	P>5%
	rate expression A	0.01760	12	0.01140	12	0.00503	12	0.00503	12	0.01720	12	0.01720	12	0.01150	12	0.0965
A-B (2.0% (w/v) acid)	extra parameters	0.00010	2	0.0137	0.00010	2	0.0089	0.00800	2	1.7621	0.00010	2	0.8306	0.00010	2	0.0101
	rate expression B	0.03640	10	P>5%	0.05590	10	P>5%	0.02270	10	P>5%	0.09090	10	P>5%	0.04970	10	P>5%
	rate expression A	0.03650	12	0.05600	12	0.03070	12	0.03070	12	0.10600	12	0.10600	12	0.04980	12	0.0101
A-C (2.0% (w/v) acid)	extra parameters	0.00010	1	0.0302	0.00010	1	0.0197	0.00020	1	0.0721	0.02730	1	3.8158	0.00010	1	0.0221
	rate expression C	0.03640	11	P>5%	0.05590	11	P>5%	0.03050	11	P>5%	0.07870	11	P>5%	0.04970	11	P>5%
	rate expression A	0.03650	12	0.05600	12	0.03070	12	0.03070	12	0.10600	12	0.10600	12	0.04980	12	0.0221

Note: F(1,1; 5%)=4.84; F(2,10; 5%)=4.10; SSR=sum of squares of residuals; DF=number of degrees of freedom; MSS=SSR/DF; F-ratio=(MSS associated with the extra parameters)/(MSS associated with the full model); P=probability that the given value of the F-ratio happens by pure chance.



TABLE 3  
Extra Residual Sum of Squares Analyses Involving Models A and B, or Models A and C, for the Transport of Salt from the Brine into the Carrots

Nested models	Source	15°C			20°C			30°C			40°C			50°C		
		SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>	SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>	SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>	SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>	SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>
A-B(5.0% (w/v) salt)	extra parameters	0.00010	2	0.0144	0.00010	2	0.0667	0.00100	2	0.0491	0.00700	2	0.1005	0.00100	2	0.0275
	rate expression B	0.03820	11	<i>P</i> > 5%	0.08180	11	<i>P</i> > 5%	0.11200	11	<i>P</i> > 5%	0.38300	11	<i>P</i> > 5%	0.20000	11	<i>P</i> > 5%
	rate expression A	0.03830	13		0.08190	13		0.11300	13		0.39000	13		0.20100	13	
A-C(5.0% (w/v) salt)	extra parameters	0.00030	1	0.0947	0.00010	1	0.0147	0.00100	1	0.1071	0.00010	1	0.0031	0.00060	1	0.0359
	rate expression C	0.03800	12	<i>P</i> > 5%	0.08180	12	<i>P</i> > 5%	0.11200	12	<i>P</i> > 5%	0.38990	12	<i>P</i> > 5%	0.20040	12	<i>P</i> > 5%
	rate expression A	0.03830	13		0.08190	13		0.11300	13		0.39000	13		0.20100	13	
A-B(7.5% (w/v) salt)	extra parameters	0.00300	2	0.0424	0.08400	2	2.1429	0.01810	2	1.0917	0.0012	2	0.0829	0.0280	2	0.3900
	rate expression B	0.35400	10	<i>P</i> > 5%	0.19600	10	<i>P</i> > 5%	0.08290	10	<i>P</i> > 5%	0.0724	10	<i>P</i> > 5%	0.3590	10	<i>P</i> > 5%
	rate expression A	0.35700	12		0.28000	12		0.10100	12		0.0736	12		0.3870	12	
A-C(7.5% (w/v) salt)	extra parameters	0.00200	1	0.0620	0.00500	1	0.2000	0.02430	1	3.4850	0.00120	1	0.1823	0.02700	1	0.8250
	rate expression C	0.35500	11	<i>P</i> > 5%	0.27500	11	<i>P</i> > 5%	0.07670	11	<i>P</i> > 5%	0.07240	11	<i>P</i> > 5%	0.36000	11	<i>P</i> > 5%
	rate expression A	0.35700	12		0.28000	12		0.10100	12		0.07360	12		0.38700	12	
A-B(10% (w/v) salt)	extra parameters	0.00800	2	0.0833	0.00300	2	0.0714	0.00300	2	0.1079	0.00200	2	0.0369	0.00400	2	0.0372
	rate expression B	0.4800	10	<i>P</i> > 5%	0.21000	10	<i>P</i> > 5%	0.13900	10	<i>P</i> > 5%	0.27100	10	<i>P</i> > 5%	0.53800	10	<i>P</i> > 5%
	rate expression A	0.48800	12		0.21300	12		0.14200	12		0.27300	12		0.54200	12	
A-C(10% (w/v) salt)	extra parameters	0.0001	1	0.0023	0.00100	1	0.0519	0.00400	1	0.3188	0.00200	1	0.0812	0.00400	1	0.0818
	rate expression C	0.4879	11	<i>P</i> > 5%	0.21200	11	<i>P</i> > 5%	0.13800	11	<i>P</i> > 5%	0.27100	11	<i>P</i> > 5%	0.53800	11	<i>P</i> > 5%
	rate expression A	0.4880	12		0.21300	12		0.14200	12		0.27300	12		0.54200	12	
A-B(15% (w/v) salt)	extra parameters	0.00010	2	0.0003	0.02000	2	0.0909	0.04400	2	0.3891	0.00500	2	0.1019	0.60000	2	2.5191
	rate expression B	2.07000	11	<i>P</i> > 5%	1.21000	11	<i>P</i> > 5%	0.62200	11	<i>P</i> > 5%	0.27000	11	<i>P</i> > 5%	1.31000	11	<i>P</i> > 5%
	rate expression A	2.47000	13		1.23000	13		0.66600	13		0.27500	13		1.91000	13	

TABLE 3 — contd.

Nested models	Source	15°C			20°C			30°C			40°C			50°C		
		SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>	SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>	SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>	SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>	SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>
A-C(15% (w/v) salt)	extra parameters	0.40000	1	2.3188	0.02000	1	0.1983	0.00300	1	0.0543	0.00010	1	0.0044	0.01000	1	0.0632
	rate expression C	2.07000	12	$P > 5\%$	1.21000	12	$P > 5\%$	0.66300	12	$P > 5\%$	0.27490	12	$P > 5\%$	1.90000	12	$P > 5\%$
	rate expression A	2.47000	13		1.23000	13		0.66600	13		0.27500	13		1.91000	13	
A-B(20% (w/v) salt)	extra parameters	0.00300	2	0.0451	0.00200	2	0.0099	0.00200	2	0.0379	0.01000	2	0.0396	0.00200	2	0.0235
	rate expression B	0.26600	8	$P > 5\%$	0.80600	8	$P > 5\%$	0.21100	8	$P > 5\%$	1.01000	8	$P > 5\%$	0.34100	8	$P > 5\%$
	rate expression A	0.26900	10		0.80800	10		0.21300	10		1.02000	10		0.34300	10	
A-C(20% (w/v) salt)	extra parameters	0.00300	1	0.1015	0.00100	1	0.0112	0.00200	1	0.0853	0.00100	1	0.0089	0.00400	1	0.1062
	rate expression C	0.26600	9	$P > 5\%$	0.80700	9	$P > 5\%$	0.21100	9	$P > 5\%$	1.01000	9	$P > 5\%$	0.33900	9	$P > 5\%$
	rate expression A	0.26900	10		0.80800	10		0.21300	10		1.02000	10		0.34300	10	

Note: F(1,11; 5%)=4.84; F(1,12; 5%)=4.75; F(2,10; 5%)=4.10; F(2,11; 5%)=3.98; SSR=sum of squares of residuals; DF=number of degrees of freedom; MSS=SSR/DF; F-ratio=(MSS associated with the extra parameters)/(MSS associated with the full model); P=probability that the given value of the F ratio happens by pure chance.

**TABLE 4**  
Extra Residual Sum of Squares Analyses Involving Models A and B, or Models A and C, for the Transport of Reducing Sugars from the Carrots into the Brine

Nested models	Source	15°C			20°C			30°C			40°C			50°C		
		SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>	SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>	SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>	SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>	SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>
A-B(0.0% (w/v) salt)	extra parameters	0.03600	2	3.7241	0.00980	2	0.9591	0.00154	2	4.2208	0.00057	2	0.4483	0.00033	2	0.8148
	rate expression B	0.08700	18	<i>P</i> > 5%	0.05620	11	<i>P</i> > 5%	0.00274	15	<i>P</i> < 5%	0.00445	7	<i>P</i> > 5%	0.00162	8	<i>P</i> > 5%
	rate expression A	0.12300	20		0.06600	13		0.00428	17		0.00502	9		0.00195	10	
A-C(0.0% (w/v) salt)	extra parameters	0.08280	1	39.1343	0.02990	1	9.9391	0.00141	1	7.8606	0.00370	1	22.4242	0.00129	1	17.5909
	rate expression C	0.04020	19	<i>P</i> < 5%	0.03610	12	<i>P</i> < 5%	0.00287	16	<i>P</i> < 5%	0.00132	8	<i>P</i> < 5%	0.00066	9	<i>P</i> < 5%
	rate expression A	0.12300	20		0.06600	13		0.00428	17		0.00502	9		0.00195	10	
A-B(5.0% (w/v) salt)	extra parameters	0.08520	2	20.2857	0.08570	2	8.9738	0.06604	2	40.1285	0.00502	2	16.1935	0.00096	2	5.7600
	rate expression B	0.03780	18	<i>P</i> < 5%	0.05730	12	<i>P</i> < 5%	0.00576	7	<i>P</i> < 5%	0.00093	6	<i>P</i> < 5%	0.00075	9	<i>P</i> < 5%
	rate expression A	0.12300	20	0.14300	14		0.07180	9	0.00595	8		0.00171	11			
A-C(5.0% (w/v) salt)	extra parameters	0.1123	1	199.4112	0.08570	1	19.4433	0.06713	1	114.9979	0.00533	1	60.1774	0.00098	1	13.4247
	rate expression C	0.01070	19	<i>P</i> < 5%	0.05730	13	<i>P</i> < 5%	0.00467	8	<i>P</i> < 5%	0.00062	7	<i>P</i> < 5%	0.00073	10	<i>P</i> < 5%
	rate expression A	0.12300	20		0.14300	14		0.07180	9		0.00595	8		0.00171	11	
A-B(7.5% (w/v) salt)	extra parameters	0.00216	2	5.3333	0.01251	2	16.4335	0.00289	2	1.9795	0.00140	2	0.2893	0.01650	2	12.2222
	rate expression B	0.00243	12	<i>P</i> < 5%	0.00609	16	<i>P</i> < 5%	0.00657	9	<i>P</i> > 5%	0.01210	5	<i>P</i> > 5%	0.00540	8	<i>P</i> < 5%
	rate expression A	0.00459	14		0.01860	18		0.00946	11		0.01350	7		0.02190	10	
A-C(7.5% (w/v) salt)	extra parameters	0.00409	1	106.3400	0.01194	1	30.4775	0.00318	1	5.0637	0.00672	1	5.9469	0.01961	1	77.0699
	rate expression C	0.00050	13	<i>P</i> < 5%	0.00666	17	<i>P</i> < 5%	0.00628	10	<i>P</i> < 5%	0.00678	6	<i>P</i> = 5%	0.00229	9	<i>P</i> < 5%
	rate expression A	0.00459	14		0.01860	18		0.00946	11		0.01350	7		0.02190	10	
A-B(10% (w/v) salt)	extra parameters	0.00849	2	3.2618	0.03230	2	8.0134	0.00010	2	8.9999	0.01286	2	6.0852	0.00456	2	0.9175
	rate expression B	0.00911	7	<i>P</i> > 5%	0.02620	13	<i>P</i> < 5%	0.03200	9	<i>P</i> < 5%	0.00634	6	<i>P</i> < 5%	0.00994	4	<i>P</i> > 5%
	rate expression A	0.01760	9		0.05850	15		0.03210	11		0.01920	8		0.01450	6	

TABLE 4 — contd.

Nested models	Source	15°C			20°C			30°C			40°C			50°C		
		SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>	SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>	SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>	SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>	SSR <sup>a</sup>	DF <sup>b</sup>	F-ratio <sup>c</sup>
A-C(10% (w/v) salt)	extra parameters	0.00943	1	9.2338	0.05423	1	177.8033	0.0159	1	9.8148	0.01280	1	14.0000	0.00955	1	9.6465
	rate expression C	0.00817	8	$P < 5\%$	0.00427	14	$P < 5\%$	0.01620	10	$P < 5\%$	0.00640	7	$P < 5\%$	0.00495	5	$P < 5\%$
	rate expression A	0.01760	9		0.05850	15		0.03210	11		0.01920	8		0.01450	6	
A-B(15% (w/v) salt)	extra parameters	0.07380	2	5.2578	0.04000	2	0.8392	0.00980	2	1.3555	0.00016	2	0.3982	0.00200	2	1.0833
	rate expression B	0.07720	11	$P < 5\%$	0.02860	12	$P > 5\%$	0.07230	20	$P > 5\%$	0.00221	11	$P > 5\%$	0.01200	13	$P > 5\%$
	rate expression A	0.15100	13		0.03260	14		0.08210	22		0.00237	13		0.01400	15	
A-C(15% (w/v) salt)	extra parameters	0.13870	1	135.3171	0.02220	1	27.7500	0.07510	1	225.3000	0.00102	1	9.0667	0.00510	1	8.0225
	rate expression C	0.01230	12	$P < 5\%$	0.01040	13	$P < 5\%$	0.00700	21	$P < 5\%$	0.00135	12	$P < 5\%$	0.00890	14	$P < 5\%$
	rate expression A	0.15100	13		0.03260	14		0.08210	22		0.00237	13		0.01400	15	
A-B(20% (w/v) salt)	extra parameters	0.0098	2	6.2222	0.0136	2	6.5385	0.00320	2	1.3968	0.00010	2	0.0120	0.00300	2	0.3846
	rate expression B	0.0063	8	$P < 5\%$	0.0156	15	$P < 5\%$	0.01260	11	$P > 5\%$	0.02080	5	$P > 5\%$	0.01950	5	$P > 5\%$
	rate expression A	0.0161	10		0.0292	17		0.01580	13		0.02090	7		0.02250	7	
A-C(20% (w/v) salt)	extra parameters	0.01480	1	102.4615	0.01670	1	21.3760	0.00790	1	12.0000	0.01310	1	10.0769	0.01520	1	12.4932
	rate expression C	0.00130	9	$P < 5\%$	0.01250	16	$P < 5\%$	0.00790	12	$P < 5\%$	0.00780	6	$P < 5\%$	0.00730	6	$P < 5\%$
	rate expression A	0.01610	10		0.02920	17		0.01580	13		0.02090	7		0.02250	7	

Note: F(1.5; 5%)=6.61; F(1.6; 5%)=5.99; F(1.7; 5%)=5.59; F(1.8; 5%)=5.32; F(1.9; 5%)=5.12; F(1.10; 5%)=4.96; F(1.12; 5%)=4.75; F(1.13; 5%)=4.67; F(1.14; 5%)=4.60; F(1.16; 5%)=4.49; F(1.17; 5%)=4.45; F(1.19; 5%)=4.38; F(1.21; 5%)=4.32; F(2.4; 5%)=6.94; F(2.5; 5%)=6.94; F(2.6; 5%)=5.14; F(2.7; 5%)=4.74; F(2.8; 5%)=4.46; F(2.9; 5%)=4.26; F(2.11; 5%)=3.98; F(2.12; 5%)=3.89; F(2.13; 5%)=3.81; F(2.15; 5%)=3.68; F(2.16; 5%)=3.63; F(2.18; 5%)=3.55; F(2.20; 5%)=3.49. SSR=sum of squares of residuals; DF=number of degrees of freedom; MSS=SSR/DF; F-ratio=(MSS associated with the extra parameters)/(MSS associated with the full model); P=probability that the given value of the F-ratio happens by pure chance.

**TABLE 5**

Results of the Regression Analysis of the Fit of the Data on Transport of Lactic Acid to the Model using Rate Expression A for Various Temperatures and Initial Concentrations of Lactic Acid

Temperature (°C)	ID	Units	0.5% (w/v) acid		1.0% (w/v) acid		2.0% (w/v) acid	
			Value	MII <sup>b</sup>	Value	MII <sup>b</sup>	Value	MII <sup>b</sup>
15	$pD_{ap,f,a}$	m <sup>2</sup> /s	9.720	0.066	9.61	0.11	9.620	0.048
	$t_0$	h	0.000	∞	0.000	∞	0.000	∞
	$C_{c,a,\infty}$	% (w/v)	0.439	0.011	0.655	0.045	1.430	0.040
20	$pD_{ap,f,a}$	m <sup>2</sup> /s	9.670	0.077	9.510	0.082	9.530	0.080
	$t_0$	h	0.000	∞	0.000	∞	0.000	∞
	$C_{c,a,\infty}$	% (w/v)	0.470	0.024	0.657	0.033	1.500	0.074
30	$pD_{ap,f,a}$	m <sup>2</sup> /s	9.490	0.077	9.450	0.041	9.270	0.048
	$t_0$	h	0.07	0.31	0.000	∞	0.426	0.079
	$C_{c,a,\infty}$	% (w/v)	0.472	0.019	0.861	0.021	1.671	0.040
40	$pD_{ap,f,a}$	m <sup>2</sup> /s	9.370	0.095	9.320	0.064	9.290	0.081
	$t_0$	h	0.41	0.18	0.000	∞	0.000	∞
	$C_{c,a,\infty}$	% (w/v)	0.481	0.024	0.962	0.034	1.900	0.084
50	$pD_{ap,f,a}$	m <sup>2</sup> /s	9.200	0.052	9.240	0.052	9.170	0.055
	$t_0$	h	0.18	0.15	0.000	∞	0.000	∞
	$C_{c,a,\infty}$	% (w/v)	0.490	0.011	0.965	0.026	1.930	0.053

<sup>a</sup>ID=identification; <sup>b</sup>MII=95% marginal inference interval.

**TABLE 6**

Results of the Regression Analysis of the Fit of the Data on Transport of Sodium Chloride to the Model using Rate Expression A for Various Temperatures and Initial Concentrations of Sodium Chloride

Temperature (°C)	ID	Units	5.0% (w/v) salt		7.5% (w/v) salt		10% (w/v) salt		15% (w/w) salt		20% (w/w) salt	
			Value	MII <sup>b</sup>	Value	MII <sup>b</sup>	Value	MII <sup>b</sup>	Value	MII <sup>b</sup>	Value	MII <sup>b</sup>
15	$pD_{ap,f,s}$	m <sup>2</sup> /s	9.640	0.073	9.420	0.089	9.300	0.085	9.160	0.091	8.950	0.039
	$t_0$	h	0.000	∞	0.000	∞	0.000	0.022	0.000	∞	0.000	∞
	$C_{c,s,z}$	% (w/v)	1.520	0.075	3.43	0.19	4.12	0.21	6.85	0.32	7.37	0.15
20	$pD_{ap,f,s}$	m <sup>2</sup> /s	9.440	0.062	9.170	0.085	9.080	0.064	9.020	0.063	8.790	0.065
	$t_0$	h	0.000	∞	0.35	0.17	0.06	0.19	0.000	∞	0.000	∞
	$C_{c,s,z}$	% (w/v)	2.180	0.082	3.6	1.4	4.88	0.11	7.69	0.22	7.70	0.23
30	$pD_{ap,f,s}$	m <sup>2</sup> /s	9.210	0.059	8.940	0.068	8.980	0.033	8.840	0.042	8.720	0.028
	$t_0$	h	0.000	∞	0.35	0.11	0.000	∞	0.000	∞	0.000	∞
	$C_{c,s,z}$	% (w/v)	2.480	0.077	3.90	0.10	5.333	0.084	8.35	0.15	9.14	0.11
40	$pD_{ap,f,s}$	m <sup>2</sup> /s	9.120	0.093	8.980	0.028	8.850	0.044	8.720	0.028	8.600	0.057
	$t_0$	h	0.000	∞	0.000	∞	0.000	∞	0.000	∞	0.000	∞
	$C_{c,s,z}$	% (w/v)	2.92	0.14	4.500	0.061	6.65	0.11	8.900	0.094	10.40	0.23
50	$pD_{ap,f,s}$	m <sup>2</sup> /s	8.820	0.061	8.770	0.059	8.700	0.055	8.67	0.13	8.400	0.081
	$t_0$	h	0.000	∞	0.000	∞	0.000	∞	0.02	0.25	0.01	0.12
	$C_{c,s,z}$	% (w/v)	3.330	0.083	4.89	0.12	6.63	0.14	10.00	0.26	11.30	0.13

<sup>a</sup>ID=identification; <sup>b</sup>MII=95% marginal inference interval.

**TABLE 7**  
**Results of the Regression Analysis of the Fit of the Data on Transport of Reducing Sugars Acid to the Model using Rate Expression C for Various Temperatures and Initial Concentrations of Sodium Chloride**

Temperature (°C)	ID	Units	0.0% (w/v)		5.0% (w/v)		7.5% (w/v)		10% (w/v)		15% (w/v)		20% (w/v)	
			Value	MII <sup>b</sup>	Value	MII <sup>b</sup>	Value	MII <sup>b</sup>	Value	MII <sup>b</sup>	Value	MII <sup>b</sup>	Value	MII <sup>b</sup>
15	$pD_{app,ir}$	$m^2/s$	14.80	0.11	13.6	1.6	14.6	1.5	14.0	1.9	12.80	0.32	14.90	0.76
	$C_{x,0}/C_{x,tot}$	/s	0.99953	0.00080	0.9994	0.0028	0.9999	0.0035	0.999	0.068	0.9999	0.0019	0.999960	0.000064
	$k_1 C_{x,tot}$	% (w/v)	0.0000179	0.0000012	0.000016	0.000010	0.0000189	0.0000080	0.0000104	0.0000080	0.0000050	0.0000011	0.0000117	0.0000025
	$pD_{app,ir}$	$m^2/s$	2.02	0.13	0.944	0.098	0.668	0.040	1.18	0.69	1.230	0.068	0.669	0.040
	$C_{x,0}/C_{x,tot}$	/s	0.99990	0.00021	0.9990	0.0021	0.9980	0.0053	0.9990	0.012	0.9980	0.0023	0.99996	0.00018
20	$k_1 C_{x,tot}$	% (w/v)	0.0000204	0.0000042	0.0000106	0.0000026	0.0000168	0.0000060	0.0000062	0.0000014	0.000012	0.0000038	0.0000136	0.0000054
	$C_{1,r,x}$	/s	1.750	0.036	1.310	0.040	0.718	0.081	0.644	0.37	0.849	0.039	0.97	0.11
	$pD_{app,ir}$	$m^2/s$	12.80	0.21	13.3	2.4	11.9	1.5	12.9	0.35	12.30	0.19	14.1	1.4
	$C_{x,0}/C_{x,tot}$	/s	0.9950	0.0020	0.9970	0.0014	0.96	0.13	0.997	0.023	0.9940	0.0021	0.9997	0.0012
	$k_1 C_{x,tot}$	/s	0.0000119	0.0000026	0.0000235	0.000019	0.000072	0.000069	0.000091	0.000014	0.0000146	0.0000021	0.000032	0.0000016
30	$C_{1,r,x}$	% (w/v)	0.409	0.026	0.573	0.064	0.679	0.095	0.960	0.097	0.965	0.019	0.951	0.040
	$pD_{app,ir}$	$m^2/s$	11.30	0.47	12.50	0.85	11.5	1.3	12.9	2.4	11.30	0.71	11.90	0.68
	$C_{x,0}/C_{x,tot}$	/s	0.940	0.062	0.9970	0.0058	0.971	0.088	0.998	0.010	0.92	0.12	0.968	0.044
	$k_1 C_{x,tot}$	/s	0.000165	0.000083	0.000136	0.000058	0.00014	0.00013	0.00014	0.00014	0.000149	0.000098	0.00023	0.000015
	$C_{1,r,x}$	% (w/v)	0.812	0.024	0.540	0.016	0.754	0.072	0.861	0.040	0.531	0.014	0.936	0.058
50	$pD_{app,ir}$	$m^2/s$	11.5	2.6	11.1	1.5	11.50	0.11	12.30	0.18	9.76	0.68	12.30	0.97
	$C_{x,0}/C_{x,tot}$	/s	0.988	0.064	0.981	0.065	0.991	0.060	0.998	0.072	0.48	0.39	0.998	0.014
	$k_1 C_{x,tot}$	/s	0.0021	0.0013	0.0038	0.0029	0.00209	0.00098	0.00060	0.00022	0.00069	0.00025	0.00040	0.00033
	$C_{1,r,x}$	% (w/v)	0.524	0.019	0.6100	0.0089	1.100	0.050	0.962	0.064	0.961	0.024	0.919	0.055

<sup>a</sup>ID=identification; <sup>b</sup>MII=95% marginal inference interval.

## DISCUSSION AND CONCLUSIONS

As explained above, Models A, B and C require rupture of the cell membrane prior to release of the sugars into the brine (although this rupture may follow different kinetics depending on the model in question); this assumption is confirmed by the observation that the weight of immersed carrot slices increased by 7–10% (w/w) during brining in plain water (data not shown), an increase which is most likely a result of the osmotic intake of water by the cells that will eventually degenerate into bursting thereof (or, at least, into expansion of the cell wall with concomitant increase in its porosity, which is equivalent for our purposes to bursting). The observation that  $V_c$  varies implies that parameter  $\alpha_i$ , as defined by eqn (7), is not a constant for each experiment, and it also implies that  $(dC_x/dt)$ , as utilized in eqn (16) and (20), should be replaced by  $(dC_x/dt) + C_x[d\ln(V_c)/dt]$ . However, the non-linear regression results were virtually insensitive to deliberate disturbances of up to 10% on  $V_c$ , i.e. the difference between the best parameter estimates obtained therewith and the original parameter estimates obtained under the assumption that bulk intake of water by the carrots is absent, was only a very small fraction of the listed parameter 95% inference intervals. It should also be noted here that, although  $\alpha_i$ ,  $\hat{C}_{c,i}$  and  $C_{c,i\infty}$  decrease, and  $C_{l,i}$  and  $C_{l,i\infty}$  increase as time of immersion elapses by virtue of such an osmotic intake of water by the carrots, such variations cancel out in the mass balances depicted as eqn (10) and eqn (11).

It is apparent from inspection of Tables 5 and 6 that the inference intervals associated with parameter  $t_0$  overlap the null hypothesis for virtually every data set. On the other hand, most parameters associated with Models B and C pertaining to the simulation of transport of acid and salt remain indeterminate after successful non-linear regression analyses (results not shown). Coupling these observations with the results of the extra sum of squares analyses tabulated in Tables 2 and 3, one is finally led to the conclusion that Model A is statistically sufficient to model every data set pertaining to the transport of acid and salt under the assumption that  $t_0=0$ . Most parameters associated with Model B for the simulation of transport of reducing sugars (results not shown) remain indeterminate after successful non-linear regression analysis. Although the 95% inference intervals of virtually all parameters associated with Models A (results not shown) and C (see Table 7) do not overlap zero, the sum of squares of residuals associated with the latter is sufficiently smaller than that of the former to be of statistical significance (see Table 4). Hence, from the set of three models postulated and tested, Model C should be elected as the best representation of the data generated for the transport of reducing sugars. The values for the diffusivities of salt are similar to those obtained by Bomben *et al.* (1974) in experiments pertaining to desalting of vegetable pickles; these authors also found increases in the diffusivities as temperature increases. For the higher temperatures, the apparent diffusion coefficients obtained for the transport of reducing sugars according to Model A (results not shown) are of the order of magnitude of those reported by Oliveira (1988).

The total concentration of the brines in terms of acid or salt was deliberately fixed, a situation that is in contrast with the total concentration of reducing sugars in the carrot which is a function of the maturation state, the variety, the size, the axial position, etc. (i.e. variables which are usually beyond one's control). Therefore, although the concentrations of acid and salt in the carrot approach equilibrium values which are close to the total initial concentration of the brine (and higher as

the temperature increases, as apparent from inspection of Figs 1 and 2), the concentrations of reducing sugars in the brine vary randomly between experiments performed at different temperatures and initial concentration of salt in the brine. Therefore, a much more informative picture of the situation is obtained if such concentrations are normalized by the equilibrium concentrations of reducing sugars for each data set (as done in Fig. 3). Using these transformed concentrations, it is apparent that high temperatures (say 40°C and above) lead to a behaviour which is consistent with the direct application of Fick's law, whereas low temperatures (say, 30°C and below) lead to a situation where full occurrence of the diffusional transport is slower as temperature is decreased. Recalling that the transport of acid and salt are well modelled by Model A and that transport of reducing sugars is well modelled by Model C, one can also conclude that increases in temperature lead to increases in  $D_{ap,f,i}$  or in both  $D_{ap,f,i}$  and  $k_i C_{X,tot}$  (as would be expected from the assumption of Arrhenius dependencies on temperature).

It is remarkable that the degree of integrity of the carrot cells at the start-up of the experiments, which is measured by parameter  $C_{X,0}/C_{X,tot}$ , was in all but one case very close to unity (i.e. above 0.99), which is an indication of the fact that the carrots were essentially intact (and were likely to have been harvested just prior to experimentation). It should be noted that the marginal inference intervals associated with this parameter were in all cases very narrow, which suggests that slight (say 0.1% or less) variations of this parameter about their best estimate lead to major distortions of the fit. The influence of the integrity of the cells on the rates of sugar transfer have been quantified previously by Soddu & Gioia (1979) and Oliveira (1988), although theoretical explanations for this fact followed alternative approaches.

For practical purposes, the production of lactic acid pickles by fermentation requires that a significant amount of fermentable sugars are available in the brine soon after submersion of the vegetable; our experiments indicate that high temperatures (say, above 30°C) should be employed in order to accelerate the process of sugar leaching (i.e. to have it virtually completed within 48 h). (The transport of salt into the carrots is much faster than that of sugar irrespective of the operating temperature utilized, so the operating temperature does not play an important role in this case.) On the other hand, owing to the low acid tolerance of the fermenting strains (according to Fleming (1982), the threshold is approximately 1.4%), the varieties commonly used in commercial pickling need not be those initially richer in sugar. Having lower initial contents of sugars is often related to higher contents of structural components, and this is also an advantage in the production of pickles where problems of final texture (which is considerably affected by the amount of acid produced (Bell *et al.*, 1972)) have to be addressed.

Given the significant variations of the various adjustable parameters with the operating conditions chosen, a logical sequence of this work would be to attempt to quantify these relationships. The results of that quantification are available in the following paper of this series.

#### ACKNOWLEDGEMENTS

The availability of Dr Fernanda A. Oliveira, c/o Escola Superior de Biotecnologia, for critical discussions relevant to the topic of this communication is hereby gratefully acknowledged.



## REFERENCES

- Adams, M. R. & Hall, C. J. (1988). Growth inhibition of food-borne pathogens by lactic and acetic acids and their mixtures. *Int. J. Food Sci. Technol.*, **23**, 287.
- Alabran, D. M. & Mabrouk, A. F. (1973). Sugars and free nitrogenous compounds in fresh carrots. *J. Agric. Food Chem.*, **21**, 205.
- Anderson, R. (1984). Characteristics of the bacterial flora isolated during spontaneous lactic acid fermentation of carrots and red beets. *Lebensmitt.-Wiss. Technol.*, **17**, 282.
- Anderson, R., Erikson, C. E., Salomonsson, A. C. & Theander, O. (1990). Lactic acid fermentation of fresh and stored carrot: chemical, microbial, and sensory evaluation of products. *Lebensmitt.-Wiss. Technol.*, **23**, 34.
- Bailey, J. E. & Ollis, D. F. (1986). *Biochemical Engineering Fundamentals*. McGraw-Hill, New York.
- Bates, D. M. & Watts, D. G. (1980). *Nonlinear Regression Analyses and Its Applications*. Wiley, New York.
- Bell, T. A., Turney, L. J. & Etchells, J. L. (1972). Influence of different organic acids on the firmness of fresh-pack pickles. *J. Food Sci.*, **37**, 446.
- Beristain, C. I., Azuara, E., Cortez, R. & Garcia, H. S. (1990). Mass transfer during osmotic dehydration of pineapple rings. *Int. J. Food Sci. Technol.*, **25**, 576.
- Biswall, R. N. & Maguer, M. (1989). Mass transfer in plant materials in contact with aqueous solutions of ethanol and sodium chloride: equilibrium data. *J. Food Proces. Engng*, **11**, 159.
- Bomben, J. L., Durkee, E. L., Lowe, E. & Secor, G. E. (1974). A laboratory study on counter current desalting of pickles. *J. Food Sci.*, **39**, 260.
- Caracotsios, M., Stewart, W. E. & Sørensen, J. P. (1985). *GREG User's Manual*. Department of Chemical Engineering of the University of Wisconsin, Madison.
- Crank, J. (1975). *The Mathematics of Diffusion*. Oxford University Press, Oxford.
- Etchells, J. L., Bell, T. A. & Jones, I. D. (1950). Softening of commercial cucumber salt-stock in relation to polygalacturonase activity. *Food Technol.*, **4**, 157.
- Etchells, J. L. & Moore, W. R. (1971). Factors influencing the brining of pickling cucumbers — questions and answers. *Pickle Pack Sci.*, **1**, 1.
- Fabian, F. W. & Wadsworth, C. K. (1939). Experimental work on lactic acid in preserving pickles and pickle products. 1. Rate of penetration of acetic and lactic acid in pickles. *Food Res.*, **4**, 499.
- Fleming, H. P. (1982). Fermented vegetables. In *Economic Microbiology, Fermented Foods*, ed. H. Rose. Academic Press, New York, p. 227.
- Fleming, H. P., McFeeters, R. L., Thompson, R. L. & Sanders, D. C. (1983). Storage stability of vegetables fermented with pH control. *J. Food Sci.*, **48**, 975.
- Goris, A. (1969). Carbohydrate metabolism of cultivated carrot roots (variety Nantaise demi longue) during the vegetative cycle of the plant. *Qual. Plant. Mater. Vegetab.*, **18**, 283.
- Kincan, N. S. & Kaymak, F. (1987). Modelling of dry matter losses from carrots during blanching. *J. Food Proc. Engng*, **9**, 201.
- Liu, H. (1992). A kinetic study of salt diffusion in potato at high temperature. *J. Food Sci. Technol.*, **27**, 443.
- McKnee, J. M. T. (1985). A single method for the extraction of reducing sugars and nonreducing sugars from carrots and other storage vegetables. *J. Sci. Food Agric.*, **36**, 55.
- Meyer, B. S., Anderson, D. B. & Bohning, R. (1965). *Introdução à Fisiologia Vegetal*. Fundação Calouste Gulbenkian, Lisbon.
- Miller, G. L. (1959). Use of dinitrosalicylic acid reagent for determination of reducing sugar. *Analyt. Chem.*, **31**, 426.
- Moreira, L. A., Oliveira, F. A. R. & Silva, T. R. (1992) Prediction of pH change in processed acidified turnips. *Int. J. Food Sci. Technol.*, **57**, 928.
- Oliveira, F. A. (1988). Mass transfer analysis for the leaching of water soluble components from food. Ph.D. thesis, Department of Food Science, University of Leeds, UK.

- Oliveira, F. A. R. & Silva, C. L. M. (1992) Freezing influences diffusion of reducing sugars in carrot cortex. *Int. J. Food Sci. Technol.*, **57**, 932.
- Phan, C. T. & Hsu, H. (1973). Physical and chemical changes occurring in the carrot root during growth. *Can. J. Plant Sci.* **53**, 629.
- Pflug, I. J., Fellers, P. J. & Gurevitz, D. (1967). Diffusion rates in the desalting of pickles. *Food Technol.*, **21**, 1634.
- Potts, E. A., Fleming, H. P., McFeeters, R. F. & Guinnup, D. E. (1986). Equilibration of solutes in nonfermenting, brined pickling cucumbers. *J. Food Sci.*, **51**, 434.
- Richardson, M. (1975). *Translocation in Plants*. Edward Arnold, London.
- Salisbury, F. & Ross, C. (1978). *Plant Physiology*. Wadsworth Publishers, Belmont, California.
- Schwartz, J. B. & Carnoad, P. A. (1979). Recycling water in vegetable blanching. *Food Technol.*, **33**, 54.
- Schwartzberg, H. B. and Chao, R. Y. (1982). Solute diffusivities in leaching processes. *Food Technol.* **36**, 73.
- Schwimmer, S. (1980). Influence of water activity on enzyme reactivity and stability. *Food Technol.*, **34**, 64.
- Selman, J. D. & Rolfe, E. J. (1979). Effects of water blanching on pea seeds. I. Fresh weight changes and solute loss. *J. Food Technol.*, **14**, 493.
- Selman, J. D., Rice, P. & Abdul-Rezzak, R. K. (1983). A study of apparent diffusion coefficients for solute losses from carrots during blanching in water. *J. Food Technol.*, **18**, 427.
- Soddu, A. & Gioia, F. (1979). Diffusion through living systems: sugar loss from sugar beets. *Chem. Engng Sci.*, **34**, 763.
- Stahl, R. & Loncin, M. (1979). Prediction of diffusion in solid foodstuffs. *J. Food Proc. Preserv.*, **3**, 213.
- Steinkraus, K. H. (1983). Acid fermented vegetables. In *Handbook of Indigenous Fermented Foods Involving an Acid Fermentation*. Marcel Dekker, New York.
- Toupin, C. J., Marcotte, M. & Maguer, M. (1989). Osmotically-induced mass transfer in plant storage tissues: a mathematical model. Part I. *J. Food Engng*, **10**, 13.
- Tuncan, E. U. & Martin, S. E. (1990). Combined effects of salts and temperature on the thermal destruction of *Staphylococcus aureus* MF-31. *J. Food Sci.*, **55**, 833.