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Modelling the kinetics of osmotic dehydration of mango: Optimizing process conditions and pre-treatment for health aspects

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ABSTRACT

The kinetics of mass transfer and vitamin C loss in mango during osmotic dehydration (OD) were described by mathematical models. Water loss (WL) and weight reduction (WR) was modelled by Weibull's model, soluble solid gain (SSG) was better described by Peleg's model. Vitamin C loss was described by a multiresponse model incorporating both degradation and leaching processes into the OD-solution. Effects of vacuum impregnation (VI) and pectin methylesterase (PME) addition on the model parameters were evaluated. VI increases SSG indicated by a 55% lower value of k_2 in the Peleg model ($P < 0.05$). PME addition showed no significant effect on the mass transfer kinetics. The major mechanism of vitamin C loss during OD was degradation. The pre-treatments have no significant effect on degradation and leaching rate constants of vitamin C. The combination of modelling the mass transfer and vitamin C retention was shown to be valuable in optimizing the OD process design to enhance the health-promoting value of OD mango (sugar content, vitamin C) and processing time.

1. Introduction

Mango (*Mangifera indica* L.) ranks second among tropical fruits in global market after banana (Altendorf, 2017). The fruit is an important source of vitamin C (between 9.79 and 186 mg/100 g edible portion due to different varieties, and growing conditions) and it is rich in various phytochemicals, including carotenoids and phenolic compounds (Ribeiro et al., 2010). Along with fresh mango's trade expansion, the global demand for minimally processed mango products has been increasing (Hanemann et al., 2017). These mild treated products feature an extended shelf-life with fresh-like characteristics, while maintain a high nutritional and health-promoting value (Ciurzyńska et al., 2016).

New product design of dehydrated fruit range from the direct consumption as snacks to its use as ingredients in various foods such as dairy, breakfast cereals and confectionery products, e.g., Betoret et al. (2003); Talens et al. (2012); Threlfall et al. (2007). Different dehydration technologies like vacuum impregnation and osmotic dehydration (OD) can be tailored to obtain these products. Over recent years, OD has received much appraisal from researchers as a minimal processing operation (Ahmed et al., 2016; Ciurzyńska et al., 2016; Ramya and Jain, 2017). OD is a mass transfer process involving immersion of fruit pieces in an OD-solution, which is a hyperosmotic solution inducing partial water removal from the tissue and soluble solid uptake in the tissue (Torreggiani, 1993), as illustrated in Fig. 1. Its application can precede drying or freezing and contributes to creating new and less perishable fruit products with health-promoting, nutritional and sensory properties (Ciurzyńska et al., 2016). Therefore, OD application should aim for a healthier OD fruit with a low soluble solid uptake and a high retention of nutrients. However, with a given fruit material, health quality of the products can be affected by the setting of OD process variables, e.g., pretreatments, temperature, additives, and time (Ahmed et al., 2016).

Due to a complex microstructure of a plant tissue, the OD should be explained as a process where several other mechanisms influence mass transfer (Chiralt and Fito, 2003). Right after a fruit tissue is immersed in OD-solution, the initial capillary pressure induced a flux of OD-solution into voids in the tissue (Seguí et al., 2012). During OD, three other mechanisms simultaneously occur: (i) cell dehydration caused by aw gradients; both (ii) soluble solid diffusion and (iii) deformed cell impregnation caused by cellular volume changes. In addition to the mass transfer, due to the viscoelastic properties of the cells, a structural shrinkage and relaxation also occur simultaneously; however, they have different rates (Oliver et al., 2012). Application of vacuum impregnation (VI) prior to OD, hereafter called OD-VI shows mass transfer kinetics (Fito and Chiralt, 1995; Fito et al., 2001). During OD-VI, the capillary

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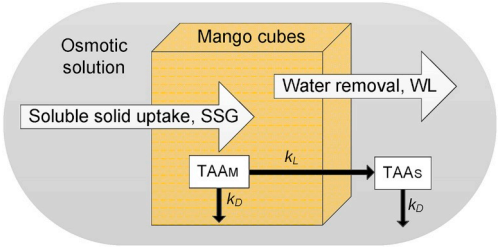

Fig. 1. Mass transfer of fruit during osmotic dehydration, e.g., mango cubes. TAA_M – Total Ascorbic Acid content in mango, TAA_S – Total Ascorbic Acid content in the OD-solution, k_D - degradation rate constant, k_L - leaching rate constant.

Table 1
Characteristics of mango samples.

Characteristics	Ripe mango batch 1	Ripe mango batch 2
Average weight (g)[a]	678.2 ± 71.3	482 ± 25.2
Firmness (kg)[a]	2.9 ± 0.6	2.6 ± 0.5
Total soluble solid (°Brix)[b]	13.0 ± 0.9	12.4 ± 3.9
Titratable acidity (% citric acid)[b]	0.69 ± 0.08	0.69 ± 0.08
Moisture (%)[b]	85.8 ± 1.8	83.6 ± 1.82
pH	4.67 ± 0.7	3.97 ± 0.1
Number of mangoes used	88	95

All physicochemical analyses were carried out based on Sulistyawati et al. (2018).
[a] Values represent mean ± SD of all selected mango within the same ripeness.
[b] Values represent mean ± SD of two batches per pretreatment that were each analyzed in duplicate.

impregnation and vacuum-induced impregnation concurrently occur. Both impregnations expand internal gas in pores triggering the gas partially flowing out of the pores (when vacuum is applied) and followed by compression sucking in the OD-solution into the pores (Chiralt and Fito, 2003).

A mild temperature (30–50 °C) applied during OD result in tissue modification without damaging the fruit structure (Shi and Xue, 2009) and low thermal degradation of nutrients (Ciurzyńska et al., 2016). Previous studies has been reported that application of texturizing agents during OD can enhance product firmness, e.g. calcium salts (Silva et al., 2014) or pectin methylesterase (PME) (Guillemin et al., 2008), or both agents (Sirijariyawat et al., 2012). The firmness enhancement by these agents can be augmented by OD-VI (Sirijariyawat et al., 2012). Nevertheless, during immersion of the fruit in OD-solution, water-soluble nutrients will partially leach from the tissue, such as vitamin C, and phenolic compounds (Nowacka et al., 2018; Peiró et al., 2006).

Retention of nutrients in dehydrated plant material, e.g., by OD is generally inferred from the extent of vitamin C retention (Nowacka et al. (2018); Nuñez-Mancilla et al. (2013); Oladejo et al. (2017)). In literature conflicting results on leaching of vitamin C into the OD-solution have been reported; it has been considered as not relevant since some authors found it as a minor cause of vitamin C loss (Alam et al., 2010). Meanwhile other studies report significant amounts of vitamin C appear in the reuse of OD-solutions, e.g., Germer et al. (2016); Moraga et al. (2011); Peiró et al. (2006)). Most OD studies addressed vitamin C degradation kinetics without including the leaching mechanism, e.g., Alam et al. (2010); Dermesonlouoglou et al. (2016). This study aims to model the kinetics of mass transfer and vitamin C loss during osmotic dehydration of mango and the effect of vacuum impregnation as pre-treatment and addition of PME on the model parameters, to contribute to optimizing process design towards maintaining health-promoting value of OD mango (i.e., optimum sugar content and vitamin C).

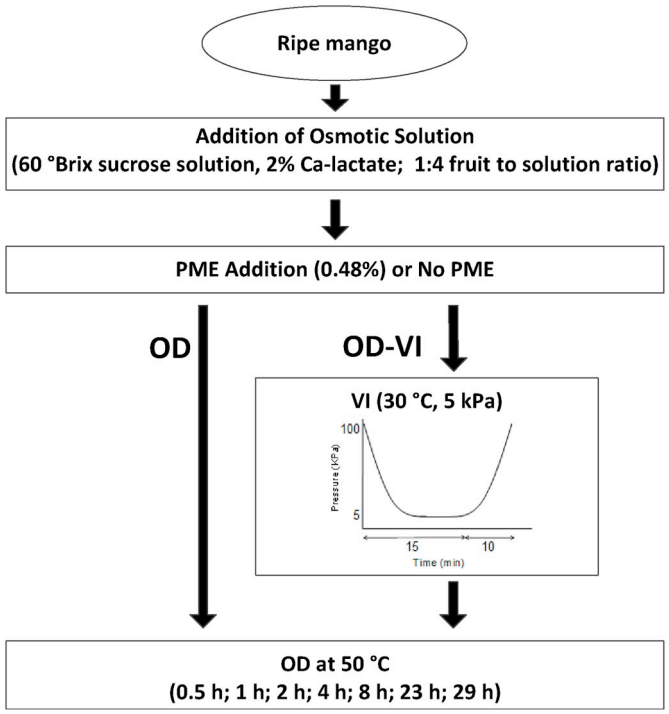

Fig. 2. Experimental setup for osmotic dehydration treatment (OD) of mango cubes treated with vacuum impregnation (VI) and pectin methylesterase (PME) (Sulistyawati et al., 2018).

2. Materials and methods

2.1. Fruit material

Ripe mango (*Mangifera indica* L. cv. Kent) fruit originated from Brazil was purchased from Bakker Barendrecht B.V. (Ridderkerk, The Netherlands), stored at 11 °C - to prolong mango's shelf life (Tharanathan et al., 2006) - and used within four days after arrival. Mango was selected based on firmness (Table 1), then cut into cubes approximately 1.2 cm × 1.2 cm x 1.2 cm (Sulistyawati et al., 2018), mixed and kept on ice prior to treatment.

Pectin methylesterase (PME) from a recombinant *Aspergillus oryzae* (Novoshape® Novozymes, Denmark) and calcium-L-lactate pentahydrate (Merck KGaA, Darmstadt, Germany) were used. OD-solutions were prepared with commercial sucrose in demineralized water.

2.2. Pretreatment and osmotic dehydration

Osmotic dehydration (OD) was carried out at atmospheric pressure and in combination with a vacuum impregnation (OD-VI) according to Sulistyawati et al. (2018). Mango cubes (250 g) were immersed in 1 L OD-solution of 60 °Brix sucrose, 2% calcium lactate and 0 or 0.48% PME at 50 °C for 0–29 h under continuous stirring.

VI was carried out at 30 °C in a vacuum chamber at 5 kPa for 15 min and 10 min pressure recovery (Fito and Chiralt, 1995). Samples for water and soluble solid analyses were kept at 4 °C, and samples for vitamin C analysis were frozen into liquid nitrogen and kept at −20 °C prior to analysis (Olivares-Tenorio et al., 2017). The experimental setup of this study is shown in Fig. 2, in which each treatment was done with two independent batches.

Weight reduction (WR), water loss (WL) and soluble solids gain at time t (SSG) were determined according to Sulistyawati et al. (2018) and were described using the equations:

$$\Delta M_t = \frac{(M_t - M_0)}{M_0} \quad (1)$$

$$\Delta M_t^W = \frac{(M_t)(x_t^W) - (M_0)(x_0^W)}{M_0} \quad (2)$$

$$\Delta M_t^{SSG} = \frac{(M_t)(x_t^{SSG}) - (M_0)(x_0^{SSG})}{M_0} \quad (3)$$

where Δ is the weight difference of component at time t, M *is* the weight of sample (g) and x *is* the initial mass fraction of component (g/g), subscript t refers to time and 0 to $t = 0$ and superscript W to water and SSG to soluble solids.

2.3. Vitamin C analysis

2.3.1. Sample preparation

Frozen mango and OD-solution samples were freeze dried (GRI Vriesdroger, GR Instruments B·V., Wijk bij Duurstede, the Netherlands) connected to a two-stages vacuum pump (E2M18, Edward®, Crawley, UK) to a constant weight. Thereafter, samples were milled in liquid nitrogen (IKA A11 basic; IKA-Werke GmbH, Staufen, Germany) and kept at −20 °C for vitamin C analysis.

2.3.2. Measurement of vitamin C

Vitamin C was expressed as the Total Ascorbic Acid (TAA) content - includes two biologically active forms, which are ascorbic acid and its oxidized form, dehydroascorbic acid - and was determined according to Hernández et al. (2006) with modifications, using an HPLC system (a thermo separation products model with P-2000 Binary Gradient Pump and UV, 2000 detector), see Supplementary data 1. Each sample was measured in duplicate – for mango and OD-solution samples - and then was averaged to get one data set per batch (Olivares-Tenorio et al., 2017). Results were expressed in mg total ascorbic acid 100 g^{-1} fresh weight (FW).

2.4. Kinetics modelling

2.4.1. Modelling of mass transfer

In literature mainly empirical models have been applied on modelling the mass transfer in OD, the most widely applied models are the Peleg, Azuara, Page and Weibull model (Assis et al., 2017). These existing models are briefly described as the following.

Peleg Model. Peleg (1988) proposed a two-parameter sorption equation that can describe water loss (WL) and soluble solid gain (SSG) kinetics during OD:

$$x_t^W - x_0^W = -\frac{t}{k_1^W + k_2^W \cdot t} \quad (4)$$

$$x_t^{SSG} - x_0^{SSG} = +\frac{t}{k_1^{SSG} + k_2^{SSG} \cdot t} \quad (5)$$

with x_0^W is the initial mass fraction of water (g/g), x_t^W is the mass fraction of water at time t (g/g), x_0^{SSG} is the initial mass fraction of soluble solids (g/g) and x_t^{SSG} is the mass fraction of soluble solids at time t (g/g).

The water reduction (WR) kinetics was rewritten from the same Peleg's equation in the form:

$$M_t - M_0 = -\frac{t}{k_1 + k_2 \cdot t} \quad (6)$$

where M_0 is the initial weight of sample (g), $M_t$is the weight of sample at time t (g).

The constant k_1 relates to the reciprocal of the rate of mass transfer and constant k_2 relates to the reciprocal of the equilibrium composition.

Azuara Model. Azuara et al. (1992) proposed a two-parameter model to estimate mass transfer coefficients and the equilibrium values:

$$Y = \frac{s.t.Y_\infty}{1 + s.t} \quad (7)$$

where Y could be respectively: WL or SSG or WR. Y_∞ indicates the respective Y at equilibrium. s is the rate parameter of the respective Y.

Weibull Model. The Weibull's model has been used to describe mass transfer coefficients and equilibrium values during OD (Cunha et al., 2001) by three parameters:

$$Y = Y_\infty \left(1 - exp\left[-\left(\frac{t}{\tau}\right)^\beta\right]\right) \quad (8)$$

where Y could be respectively: WL or SSG or WR. Y_∞ indicates the respective Y at equilibrium. τ is the scale parameter related to the process rate, and β is the shape parameter.

Page Model. Page (1949) proposed an empirical three-parameter model based on an exponential equation for mass transfer:

$$Y = Y_\infty \left(1 - exp\left(-A.t^B\right)\right) \quad (9)$$

A (h^{-1}) and B are the Page's constants.

Although in literature these four models have been used to model OD, it is important to realize that the Peleg and Azuara model and the Page and Weibull model are mathematically identical. Therefore, the parameters of these models can be transformed into one another. In the Azuara model the Peleg's parameters can be expressed as: $k_1 = 1/(s.Y_\infty)$ and $k_2 = (1/Y_\infty)$. While in the Page's model the Weibull's parameters can be expressed as: $\tau = 1/A^{-\beta}$ and $\beta = B$. Therefore, in this study, only the Peleg and Weibull models were considered for mass transfer.

2.4.2. Modelling of vitamin C loss

Vitamin C concentrations during OD was described by two mechanisms (1) leaching from mango cubes into the OD-solution; and (2) degradation of vitamin C (see Fig. 1).

In this study it was assumed that the leaching rate rL is proportional to the vitamin C concentration difference between mango TAA_M and the OD-solution TAA_S (Sarvan et al., 2012):

$$r_L = k_L \cdot (TAA_M - TAA_S) \quad (10)$$

The degradation rate of vitamin C in mango and in the OS r_D is described by a first order reaction (Dermesonlouoglou et al., 2016; Katsoufi et al., 2017):

$$r_D = k_D \cdot TAA \quad (11)$$

Vitamin C concentrations in time are described by combining the rate of leaching and that of degradation:

$$\frac{dTAA_M}{dt} = -r_L - r_D \quad (12)$$

$$\frac{dTAA_S}{dt} = +r_L \cdot \frac{M_M}{M_S} - r_D \quad (13)$$

Euler's method was used for the numerical integration of the two differential equations (12) and (13) (Butcher, 2016).

For all models the parameters were estimated by minimizing the weighted residual sum of squares SS_{res} between the data and model predictions (GRG Nonlinear algorithm) using Microsoft Excel 2010 Solver®.

2.5. Statistical analysis

Differences between the model parameters for the four OD treatments were evaluated using a two-way ANOVA (IBM SPSS Statistics version 23, Chicago, USA) with a confidence level of 95%. Effects of VI and PME were evaluated by independent sample T-test. Statistical analysis of the model fits (SD values and correlation matrices of the parameter estimates) was done by using the 'SolverAid' macro (De

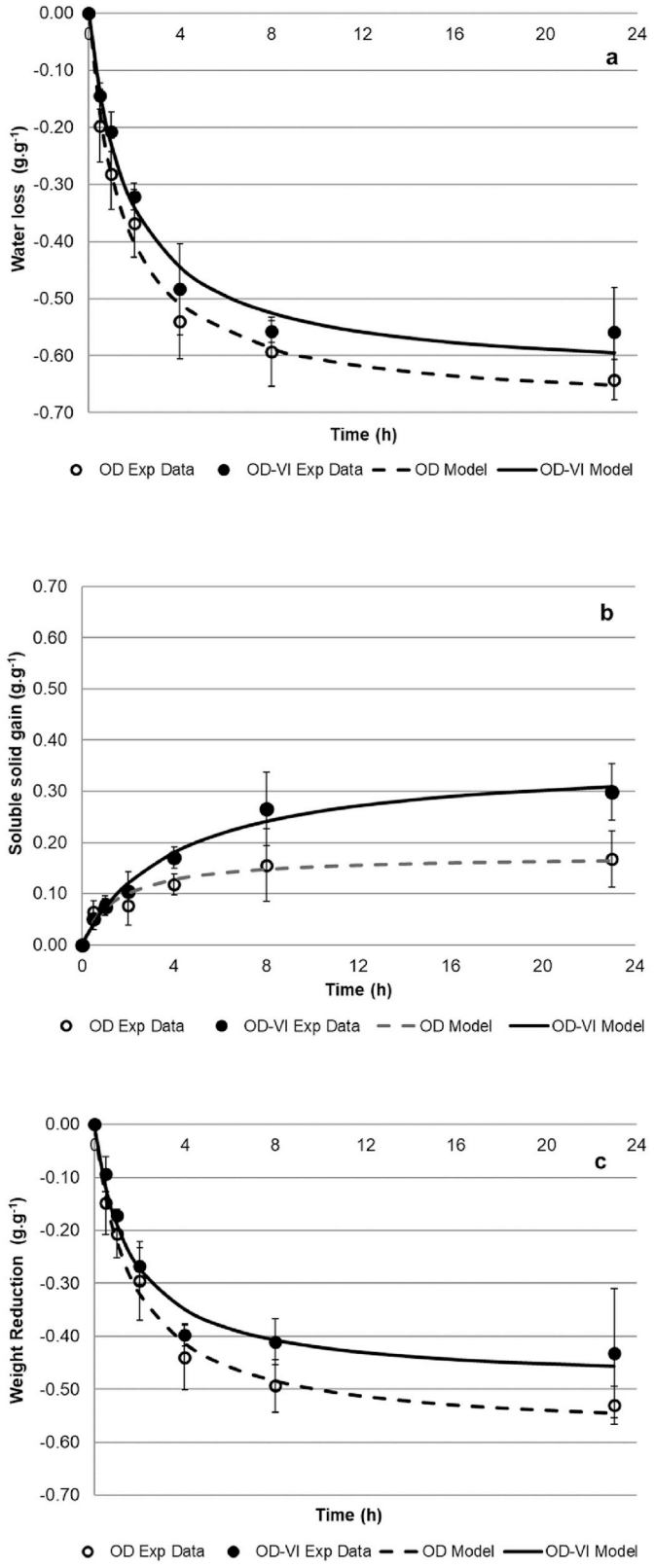

Fig. 3. Mass transfer of mango with different pretreatments during osmotic dehydration: (a) water loss, (b) soluble solid gain; (c) weight reduction.

Levie, 2004). Model discrimination was done by the corrected Akaike Information Criterion (AIC_C) value (Hurvich and Tsai, 1995):

$$AIC_C = n\ln(\hat{\sigma}^2) + 2(p+1)\frac{n}{n-p} \quad (14)$$

where n = the number of data, p = the number of parameters, $\hat{\sigma}^2 = (SS_{res}/n)$ with SS_{res} the residual sum of squares.

3. Results and discussion

3.1. Mass transfer kinetics

The observed WL, SSG, and WR for all treatments increased along with the osmotic dehydration time (Fig. 3). The Peleg and Weibull model showed a good fit of the data. Parameter standard deviations and parameter correlation coefficients were acceptable (<0.9). Since the two models had similar good fitting performances on mass transfer variables, a quantitative comparison using the Akaike Information Criterion (AIC_C) was done (Table 2). The Weibull model was superior for WL and WR data while the Peleg model was better for the SSG.

Table 3 presents parameter values of the selected models for the OD mass transfer variables. A two-way ANOVA on the parameters of the mass transfer resulted in a significant effect of VI on k_2 values for SSG ($P < 0.05$) but no effect of PME or the interaction between VI and PME. The lacking effect of PME might be due to low pectin concentration of ripe mango – because of progressive depolymerization of pectin during ripening causing a significant decrease of pectin concentration (Prasanna et al., 2003; Yashoda et al., 2006) - which did not create sufficient calcium-pectin gels to affect the mass transfer kinetics. This result differed from Van Buggenhout et al. (2008) for OD strawberries who found that PME addition slightly decreased WR, which was correlated to a small increase of the SSG, although they did not model their data.

For WL and WR, applying VI resulted in an increase of shape-parameter β – associated with the mechanism of OD mass transfer -, but this increase was not significant ($P > 0.05$). In this study, the increasing β-values for WL by VI is in line with Assis et al. (2017) for OD of apple. However, Deng and Zhao (2008) found that pulse vacuum treatment reduced the β-value of WL for apple (0.46 vs 0.57). β-values for WL of OD-treated mango are in agreement with what was found by Khan et al. (2008). VI application did not change τ values for WL and WR ($P > 0.05$). For WL, the estimated τ-values - associated with the process rate - are similar to the values found in other OD studies, *e.g.*, for mango and apple (Assis et al., 2017; Khan et al., 2008).

The equilibrium water loss (WL_∞) and weight reduction (WR_∞) values were similar in all treatments. The WL_∞ of this study are in between those of Ganjloo et al. (2012) for OD of guava (0.40–0.49 g g^{-1}) and that of Mokhtarian et al. (2014) for pumpkin (0.71–0.86 g g^{-1}).

The k_1 values for SSG tends to increase by VI although they were not significantly different ($P > 0.05$) (Table 3), so VI did not significantly affect the initial mass transfer rate. These results could be explained by the fact that ripe mango has both a small pore size, porosity and number of pores (Cantre et al., 2014) which may cause no distinct effect of the imposed vacuum pressure in modifying the pore characteristics impregnating OD-solution into the tissue. The observed OD-VI results on SSG in this study differed from Lin et al. (2016) and Assis et al. (2017) who both found that VI significantly increased the initial rate of SSG in ripe mango and apple.

VI significantly increased the equilibrium of SSG ($1/k_2$) two-fold, P > 0.05 (Fig. 4). In the case of VI-treated mango, upon removal of some water the protoplast shrinks. This shrinkage causes retraction of protoplasm from the peripheral layers of the cell and/or detachment from the cell wall. Yet, deformation of the cell wall is scarce due to weaker interaction between cell wall and protoplast than that of OD-treated sample (Oliver et al., 2012). Consequently, cell filling (SSG) due to relaxation of cells and subsequent increase in total volume occurs at longer times throughout the equilibration time (Barat et al., 1999; Lin et al., 2016). This effect of VI on k_2 is also reported by Assis et al. (2017) for OD of apple.

Table 2
Model discrimination of Peleg and Weibull models fitted to mass transfer (n = 14 for each data set).

Model	Sum of squares of residuals (SS_{res})			AIC_C		
	Water Loss	Soluble Solid Gain	Weight Reduction	Water Loss	Soluble Solid Gain	Weight Reduction
Peleg ($p = 2$)	0.004	0.001	0.003	−91.51	−107.43	−95.26
Weibull ($p = 3$)	0.001	0.001	0.001	−94.49	−105.07	−102.86
Δ AIC_C	–	–	–	2.98	2.36	7.60

Better AIC_C values for each mass transfer variable are presented in bold.

Table 3
Parameter values of the mass transfer kinetic models during osmotic dehydration of mango.

Pretreatment		Water Loss[b]			Soluble Solid Gain[c]		Weight Reduction[b,a]		
		τ(h)	β	WL_∞(g.g^{-1})	k_1(h.g.g^{-1})	k_2(g.g^{-1})	τ(h)	β	WR_∞(g.g^{-1})>
OD	No PME	2.29 ± 0.07	0.74 ± 0.09	−0.65 ± 0.04	9.11 ± 0.62	4.95 ± 0.51[a]	2.50 ± 0.26	0.85 ± 0.18	−0.51 ± 0.05
	PME	1.96 ± 0.32	0.78 ± 0.22	−0.64 ± 0.08	7.97 ± 3.07	7.36 ± 2.63[a]	2.04 ± 0.37	0.84 ± 0.26	−0.55 ± 0.05
OD-VI	No PME	2.18 ± 0.80	0.87 ± 0.07	−0.54 ± 0.02	11.77 ± 2.99	2.99 ± 0.24[b]	1.39[a]	0.99[a]	−0.35[a]
	PME	2.54 ± 0.96	1.04 ± 0.23	−0.62 ± 0.05	10.54 ± 4.89	2.60 ± 1.05[b]	2.53 ± 1.32	1.11 ± 0.38	−0.49 ± 0.09

Values represent means ± SD of two batches that was each analyzed in duplicate. Means with the same lower case did not differ significantly at P < 0.05.
[a] One batch analyzed in duplicate.
[b] For Weibull model.
[c] For Peleg model.

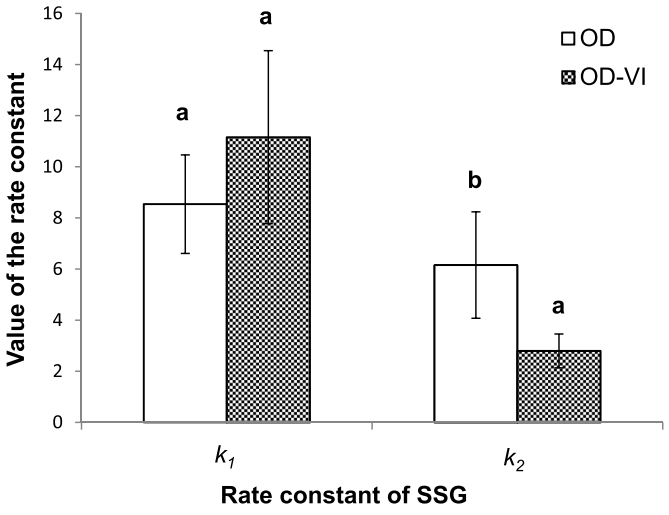

Fig. 4. Peleg parameters of soluble solid gain of mango during osmotic dehydration (different letters indicate significant differences ($P < 0.05$) for the parameter between pretreatments).

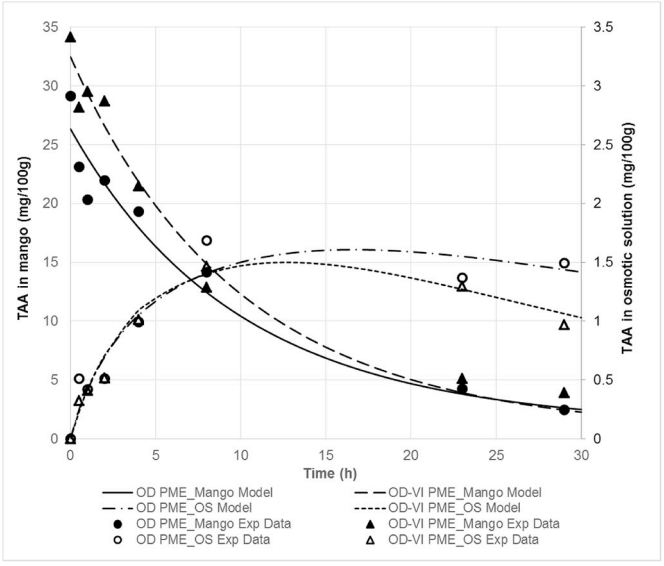

Fig. 5. Multiresponse modelling results of the total ascorbic acid loss in mango and OD-solution during osmotic dehydration: illustrated for OD with PME and OD-VI with PME.

3.2. Kinetics of vitamin C loss

Applying Eqs. (10) and (11) for degradation and leaching of vitamin C results in a continuous decrease of vitamin C in mango and an initial increase in OD-solution followed by a decrease when degradation becomes more dominant than leaching (Fig. 5).

For all treatments, the multiresponse model fitted the observed data of mango and the OD-solution well (Fig. 5). Parameter standard deviations for some of the estimates were quite high, but parameter correlation coefficients were acceptable (<0.9). See Table 4.

Two way ANOVA showed no significant effects of VI, PME and their interaction on bothk_L and k_D (P > 0.05). Although an effect of VI on OD during processing was not investigated, an OD study on frozen lotus root reported that applying VI gave higher vitamin C retention during storage at −18 °C (Song et al., 2017). Insignificant effect of adding PME in the presence of calcium on vitamin C loss was also found in an OD study on papaya (Germer et al., 2014).

Table 4
Parameter values of vitamin C loss during osmotic dehydration of mango with different treatments.

Pretreatment		Vitamin C (h^{-1}.10^{-3})	
		k_L	k_D
OD	No PME	77.5 ± 2.9	16.0 ± 9.1
	PME	48.2 ± 37.9	30.3 ± 13.6
OD-VI	No PME	41.6 ± 24.7	41.4 ± 12.8
	PME	52.2 ± 5.0	32.8 ± 13.2

Values represent means ± SD of two batches.

The average leaching rate constants (54.9 ± 15.7) are significantly higher than the degradation rate constants (30.1 ± 10.6), $P = 0.04$, $t_{crit} = 2.617$. However the degradation mechanism is causing a higher loss of

Table 5
Scenario analysis of osmo-dehydrated mango and its effect to the mass transfer variables and vitamin C content.

Pretreatment		Weight reduction[b]	Water loss[b]	Soluble solid gain[b]	Time[c]	Vitamin C[b]	
		(g.100 g^{-1})	(g.100 g^{-1})	(g.100 g^{-1})	(h)	(mg.100 g^{-1})	
						in mango (TAA_M)	in OD-solution (TAA_M)
Scenario (1): target is 35% WR of initial mango weight							
OD	No PME	−35.00[a]	−45.31 ± 4.32	12.33 ± 0.84[a]	2.9	20.2 ± 0.8	1.5 ± 0.1[a]
	PME		−41.38 ± 8.99	9.10 ± 2.40[a]	2.1	23.1 ± 2.3	0.7 ± 0.5[ab]
OD-VI	No PME		−50.74 ± 3.20	24.19 ± 2.24[b]	6.9	11.8 ± 5.3	2.0 ± 1.2[ab]
	PME		−41.72 ± 7.40	17.97 ± 4.48[ab]	2.6	21.5 ± 1.0	0.9 ± 0.1[b]
Scenario (2): 50% WL of initial mango weight							
OD	No PME	−39.29 ± 7.10	−50.00[a]	13.61 ± 0.99[a]	3.8	17.8 ± 1.0	2.0 ± 0.1[a]
	PME	−42.95 ± 9.14		10.29 ± 2.95[a]	3.4	20.3 ± 3.8	1.1 ± 0.9[ab]
OD-VI	No PME	−34.86		20.55 ± 2.24[b]	6.3	13.2 ± 4.8	1.8 ± 1.1[ab]
	PME	−41.59 ± 11.04		18.64 ± 5.76[ab]	3.8	18.7 ± 1.5	1.4 ± 0.1[b]

[a] Target setting for each scenario.
[b] Values present calculated value ± SD, the calculation was based on averaged values of the experimental data of fresh mango: 85.79 g.100 g^{-1} water, 12.97 g.100 g^{-1} sucrose and 27.6 mg.100 g^{-1}. SD was calculated by the error propagation using the SD values of all parameters (as given in Table 3). Statistical significance between two means is based on the square root of the sum of squares of the SD using an α of 5%. Different letters within the same column and scenario indicate significant differences ($P < 0.05$).
[c] Calculated by the Weibull equation for the target variable with parameters estimated from the experimental data (Table 3).

vitamin C (81.7 ± 7.2%) compared to leaching (5.1 ± 2.8%) at the end of the process. The decreasing difference of vitamin C concentration between mango and OD-solution results in a lower r_L compared to r_D. This main role of degradation on vitamin C loss during OD was consistent with those of previous studies on papaya and kiwi fruits (Cao et al., 2006; Heng et al., 1990; Vial et al., 1991). Nevertheless, the OD solution still has significant amounts of vitamin C (around 1.5 mg/100 g). Also previous studies report significant amounts of vitamin C in the OD-solutions especially after repeated cycles among others, for OD guava, reaching 95 mg/100 g in 15 cycles (Germer et al., 2016); for grapefruit, up to 4 mg/100 mL in 5 cycles (Moraga et al., 2011) and up to 2 mg/100 g in 8 cycles (Peiró et al., 2006). Based on this study, use of longer OD times might have a practical interest if the OD-solutions were used repeatedly.

The ascribed first-order kinetic model for vitamin C degradation of this study supports evidence from previous OD observations (Dhakal et al., 2018; Marfil et al., 2008). Marfil et al. (2008) found that ascorbic acids degradation fitted by a first order reaction during drying of OD peeled whole tomatoes at 50, 60 and 70 °C with similar k_D values between 15.10^{-3} h^{-1} - 48.10^{-3} h^{-1}. Thermal processing of pineapple juice at 75 °C resulted in higher k_D values of 252.10^{-3} h^{-1} (Dhakal et al., 2018). This value is approximately ten times higher than the degradation rate constant found in this study, which can be explained by the 25 °C higher temperature.

3.3. Scenario simulations

To demonstrate the value of the models, the quality attributes (WR, WL, SSG and vitamin C contents) and processing time were predicted for two target settings based on practical applications (Table 5). Scenario 1: target value is 35% WR of initial mango weight; Scenario 2: the target value is 50% WL of initial mango weight. Based on these scenarios, the treatment time was calculated by the Weibull equation of the target variable WR for scenario 1 and WL for scenario 2, using the estimated mass transfer parameters (Table 3). Based on this treatment time the other mass transfer variables were calculated by Eqs. (5) and (8). The vitamin C contents was calculated by Eqs. (12) and (13) with the estimated k_L and k_D (Table 4).

Both scenarios resulted in the lowest vitamin C concentration in mango treated with OD-VI/No PME, which is mainly a consequence of the longest process time needed to achieve the WL/WR targets. The other three treatments result in quite similar vitamin C values, with OD/PME giving the highest retention for both scenarios (Table 5). For both scenarios the lowest SSG was obtained for OD/PME, while OD-VI/No PME gave the highest SSG ($P > 0.05$). Hence, depending on the desired quality attributes of OD mango (e.g., high vitamin C and high/low sugar content) different optimal process conditions can be recommended in a quantitative way based on the predictive models.

4. Conclusions

The soluble solid gain kinetics of osmo-dehydrated mango was described well by the Peleg model, while the Weibull model described the water loss and weight reduction better. Vacuum impregnation prior to osmotic dehydration of mango increased the soluble solid gain, reflected in the lower value of k_2Peleg-parameter. For pectin methylesterase addition no effect on mass transfer parameters was found.

Vitamin C loss during osmotic dehydration of mango was well described by a multiresponse model including two mechanisms: leaching and degradation (in both mango and in the OD-solution). For all treatments, the major cause of vitamin C loss was degradation. The treatments have no significant effect on the degradation and leaching rate constants of vitamin C in mango.

This study indicates that applying VI and adding PME with calcium affected especially the SSG kinetics but did not affect the kinetics of vitamin C loss of osmo-dehydrated mango. The observed effects of VI applied to mango are valuable to modify OD mass transfer and therefore the required processing time. The predictive modelling of two scenarios suggested that OD with PME is favorable to produce OD mango with lowest sugar uptake, highest vitamin C retention and shortest treatment time. OD-VI with PME is favorable to produce sweeter OD mango with moderate vitamin C retention. Adding vitamin C to the OD-solution could further increase the vitamin C content of the OD mango. The combination of modelling the mass transfer and vitamin C loss is a valuable tool to design OD processes for a specific product quality.

CRediT authorship contribution statement

Ita Sulistyawati: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration, Funding acquisition. **Ruud Verkerk:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision. **Vincenzo Fogliano:** Conceptualization, Writing - review & editing, Supervision. **Matthijs Dekker:** Conceptualization, Methodology, Validation, Formal analysis, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision.

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Appendix A. Supplementary data

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