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Dehydration of Potato Slices Following Brief Dipping In Osmotic Solutions: Effect of Conditions and Understanding the Mechanism of Water Loss

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ABSTRACT

A novel variant of osmotic dehydration, named here as post-dipping dehydration – where a material is dipped in a salt or sugar solution for a very short time followed by simple exposure to ambient conditions was explored with the aim of lowering water content of potato slices but at the same time not gain a high level of sugar/salt. The rate of water loss, which was rapid initially, was found to approach equilibrium. This paper also explored whether the water loss process could subsequently be kick started once again, by employing a multi-stage process, where each stage consisted of osmotic solution dipping followed by ambient holding of the potato slices that had reached equilibrium in the earlier stage. Water loss values comparable to conventional osmotic dehydration could be achieved thus, but with significantly lower overall solid gain (less than 50%) – which can potentially yield a significantly healthy product option.

KEYWORDS: Osmotic dehydration, post dipping dehydration, multi-stage dehydration, solid gain, process efficiency index.

Introduction

Hot air drying is an ancient and extensively employed process to reduce moisture content and increase the shelf life and stability of food products. The process involves simultaneous heat and mass transfer [1]. A major drawback of hot air drying is quality deterioration of the products due to exposures to a high temperature for extended periods of time. Another drawback is that this technique requires the expenditure of high energy [2]. Therefore, a number of alternative energy efficient dehydration techniques have been developed resulting in better quality food products.

Osmotic dehydration eliminates water from materials without expending latent heat. It essentially involves immersion of materials such as fresh fruits or vegetables in a concentrated solution. Due to osmotic driving force generated between the hypertonic solution and tissue, three mass transfer phenomena occur i.e. i) water removal from tissue, ii) leaching out of other components from the tissue, and iii) influx of solute from the concentrated solution into the tissue [3,4]. This method of dehydration has yielded promising results for a variety of foods including potato[5,6], banana[7,8], yacon[9], mango[10,11], berries[12] and pineapple[13,14]. In addition to low energy consumption, this method also preserves some key sensory characteristics of the fruit and vegetable. Due to its simple and inexpensive operation, it has also been applied as a pre-processing step prior to operations such as conventional drying[15,16,17], freezing[18] and frying[19].

Despite the advantages of osmotic dehydration, it also suffers several limitations such as floating of fruit in solution, osmotic solution managements and the main ones being high solute uptake due to diffusion of solute towards tissue cell[20], which can potentially pose major health issues and the leaching out of water and other nutritious components from the

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tissue, which not only affects the product but also dilutes the osmotic solution thereby adversely influencing the osmotic driving force[21]. [22,23,24,25] were demonstrated a thin layer of osmotic solution by on the fruit surface by using spray mode in order to overcome this problem. However, a spray mode has potential in non-uniform distribution of solution on the entire fruit surface. Thus, there is an acute need to find ways of enabling the water from the tissue to diffuse into the osmotic solution, but at the same time, not allow high levels of the osmotic solute to diffuse into the tissue.

This study aims to achieve this objective by employing brief dipping of fresh material slices, in order to allow the osmotic medium to occlude to the surface of the slices, then hold the slice under ambient conditions, which allows the osmotic driving force generated between the surface of the slice and interior to expel water, which subsequently drips out or evaporates from the surface. Water loss can therefore, be achieved for as long as the osmotic driving force prevails between the surface and the interior of the slice, without expending any energy or even gaining significant levels of solid. This novel method of water loss has not been studied so far, and the specific objectives of the study are to: (1) investigate the effects of the concentration of the dip solution, dipping time and post-dipping holding time on the water loss and solid gain patterns; (2) compare the extents of water loss and solid gain with conventional osmotic dehydration; (3) understand the mechanism of water loss; and (4) explore whether a multi-stage process consisting of repeated dipping in osmotic solution followed by holding under ambient conditions, can be used as an alternative to conventional osmotic dehydration.

<div align="center">**Materials and methods**</div>

Materials

Fresh potatoes (*Solanum tuberosum* L.) of Maris Piper variety were purchased from local store and kept in a refrigerator at 4°C. Commercial sucrose and sodium chloride (NaCl) were purchased from local markets.

Preparation of Potato Slices and Osmotic Solutions

Potatoes were removed from the refrigerator and left out for at least 12 hours to reach the ambient temperature before processing. Potatoes weighing around 170 – 230 g were selected for experiments. The potatoes were washed, peeled and horizontally sliced (perpendicular to the longer side) into 1.5 mm thick slices using an adjustable hand slicer (Mandoline slicer, Lakeland, UK). Subsequently, the potato slices were cut into disk shape (50 mm diameter) using a circular mould to ensure uniformly sized experimental slices. Potato slices were rinsed in running water (for 30 s) immediately after slicing in order to remove the excess starch adhering on the surface, and finally the surface water was eliminated using tissue paper and weighted. The osmotic solutions were obtained by dissolving commercial sucrose or NaCl in distilled water.

Single Stage Dip Dehydration and Osmotic Dehydration Treatments

For each experiment, 10 g of identical potato slices were dipped in osmotic solution (sucrose solution: 30, 40 and 50% w/v or NaCl: 5, 10 and 15% w/v) for short time at 0.5 or 1.5 min. These times were sufficient to ensure that the entire potato slices surfaces were occluded with osmotic solution and at the same time, to study the effect of dipping time on the mass transfer. The dip solution concentrations used were selected so as to result in water loss rates which were significant enough to validate our hypothesis. To be very specific, the water

activity a_w of the dip solutions were: 0.983 ± 0.005, 0.956 ± 0.009 and 0.932 ± 0.004 for 30%, 40% and 50% sucrose solutions, and 0.976 ± 0.002, 0.924 ± 0.003 and 0.891 ± 0.010 for 5%, 10% and 15% NaCl solutions, respectively. Preliminary studies showed that the post-dipping water loss was very low when the dip solution concentration was less than 30% in the case of sucrose and 5% in the case of NaCl. Preliminary experiments also showed that there was no added benefit of raising the solution concentration above 50% in case of sucrose and 15% in case of NaCl, because the subsequent water loss kinetics were not significantly different from the highest concentrations used in this work. The mass ratio of the potato slices to the osmotic solution was kept at 1:30 and the dipping temperature was maintained between $20 - 22^oC$.

After dipped for the stipulated time, the potato slices were taken out and then placed on a stainless steel mesh under ambient conditions (temperature: $20 - 22^oC$ and relative humidity: $29 - 33\%$) for dehydration to occur. At given total times, which is a combination of dipping and holding time at 5, 10, 20, 30, 40 and 60 min, samples were very gently blotted with a tissue paper to eliminate the adhering osmotic solution on the potato surface and analysed.

Osmotic dehydration of similar potato slices was also carried out in sucrose 50% and NaCl 10% solutions in order to compare the water loss and solid gain values with dip dehydration process. In this case, the potato slices were immersed in the osmotic solution, and samples were taken out after 5, 10, 20, 40, 60, 80, 120, 160, 200 and 240 minutes (in sucrose) and 5, 10, 20, 30, 40, 50, 60, 70 and 80 minutes (in NaCl) immersion, gently blotted with a tissue paper to remove the excess osmotic solution and analysed.

Multi-stage Dip Dehydration

Multi-stage dipping and holding was carried out in two ways. In treatment A, two osmotic solutions which are sucrose 50% and NaCl 10% were chosen. Potato slices were dipped for 0.5 min in the osmotic solution and held for dehydration to occur under ambient conditions for approximately 40 mins (in sucrose case) and 10 mins (in NaCl case) of total time, when the osmotic driving force between the surface of the slice and the interior was too low for dehydration to occur as observed on the single stage dip dehydration case. The slices were then again dipped in the same osmotic solution at the same dipping time and held under ambient conditions for another 40 mins (in sucrose case) and 10 mins (in NaCl case) of total time, and the process of dipping and holding were repeated 6 times (in sucrose case) and 8 times (in NaCl case) in order to achieve equilibrium of water loss rate. In another multi-stage treatment B, subsequent dipping involved brief immersion in progressive concentrated solutions. Table 1 summarises the osmotic solution concentrations and total times (combination of dipping and holding times) employed in this study. At every 40 min (in sucrose case) and 10 min (in NaCl case) of total time, replicate samples were blotted with tissue and analysed.

Water Activity and Moisture Content Determination

Water activity of osmotic solution and potato slices were analysed using HygroLab 3 (Rotronic, Sussex, U.K.). Meanwhile , for moisture content analyses, samples were weighed and dried at 105°C in a convection oven (Weiss-Gallenkamp, Loughborough, U.K.) for approximately 24 hours until a constant weight was achieve[26]. The moisture content wet basis and dry basis were determined from:

$$MC_{wet\ basis}\ (\%) = \frac{M_{wet} - M_{dry}}{M_{wet}} \times 100 \tag{1}$$

$$MC_{dry\ basis}\ (\%) = \frac{M_{wet} - M_{dry}}{M_{dry}} \times 100 \qquad (2)$$

where M_{wet} is a mass of the wet sample (g) and M_{dry} is a mass of the solid content of the

sample after drying to constant weight in an oven at 105°C (g).

Water Loss (WL) and Solute Gain (SG) Determination

The WL and SG were calculated from the following equations[27]:

$$WL\left(\frac{g}{100g} of\ fresh\ sample\right) = \frac{(M_0 x_0 - M_t x_t)}{M_0} \times 100 \qquad (3)$$

$$SG\left(\frac{g}{100g} of\ fresh\ sample\right) = \frac{(M_t s_t - M_0 s_0)}{M_0} \times 100 \qquad (4)$$

where M_0 and M_t are the sample masses initially and at time, t respectively; x_0 and x_t are the

moisture fractions (g/g wet basis) initially and at time, t; and s_0 and s_t are the dry solid

fractions (g/g) initially and at time, t . The above equations assume that there is no solute

transferred from the sample to the solution.

Determination of Remaining Total Solute Content of Osmotic Solution on Potato Slices

The remaining total sucrose or NaCl that occluded and diffused into the potatoes slices after

dipped in osmotic solution over total time was determined by other experimental works. After

potato slices were taken out from dipping solution and hold at the given total time of dip

dehydration treatment, samples were dried in an oven until constant weight in order to

determine the total sucrose or NaCl content on the potato slices. The total sucrose or NaCl

content was calculated from the weight of difference between dipped and fresh samples and

expressed as g/100g of the fresh sample.

Process Modelling

Three well-known empirical models (Table 2) were used to fit the water loss kinetics [2][28][29] of dip dehydration and the fitting was performed using cftool in MATLAB (R2016b) software (The MathWorks, Inc., UK) in order to determine the model constants.

The statistical parameters such as coefficient of determination (R^2), root mean square error (RMSE), average relative error (E) were used to compare the goodness of fit [30]. The best model must possess the highest R^2, the least of RMSE and *E*, defined as follows [31]:

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{N}(WL_i - WL_{pre,i}).(\sum_{i=1}^{N}(WL_i - WL_{exp,i})}{\sqrt{\left[\sum_{i=1}^{N}(WL_i - WL_{pre,i})^2\right].\left[\sum_{i=1}^{N}(WL_i - WL_{exp,i})^2\right]}} \right] \quad (8)$$

$$RMSE = \sqrt{\left[\frac{\sum_{i=1}^{N}(WL_{pre,i} - WL_{exp,i})^2}{N}\right]} \quad (9)$$

$$E = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{Experimental\ value - Predicted\ value}{Experimental\ value}\right| \quad (10)$$

Statistical Analysis

Two batches of each experiment were performed and potato samples were collected from each batch in triplicate for analysed. All experimental data reported in figures and tables are the mean and standard deviation values that calculated by using Microsoft Office Excel 2013 and were evaluated using Minitab 17 Statistical Software. A t-test was used to determine the significant difference involving two samples (each sample with replication data), while a one-way analysis of variance (ANOVA) with Tukey's test was used to determine the significant difference involving more than two samples (each sample with replication data) at 95% confidence level.

Results and discussion

Effect of Process Parameters and Nature of Osmotic Solutions on Single Stage of Dipping Dehydration Water Loss

Fig. 1 depicts WL as a function of total time (i.e. expressed as a combination of dipping and holding times). The potato samples were dipped in sucrose (30 to 50%) and NaCl (5 to 15%) solutions for 0.5 and 1.5 min, withdrawn, and left to dehydrate. Fig. 1 clearly demonstrates high initial water loss (WL) which becomes progressively slower in all cases. This patterns of water loss is similar to conventional osmotic dehydration [8][32][33]. Based on statistical analysis, the value of WL significantly increased with total time for 10 min ($p<0.05$) in the case of NaCl and for 40 min in the case of sucrose solutions, after which the values of WL increased at a much slower rate. It can be postulated that the initial increase in WL is more pronounced due to the existence of a greater osmotic driving force between the fresh sample and concentrated solution which adheres to the surface of the sample.

Subsequently, water diffusion rate from interior to the surface becomes slower as the osmotic agent adhering to the potato surface, becomes diluted by the water that has already diffused from the interior. Fig. 1 shows that there is no significant ($p>0.05$) effect of dipping time on WL in all cases. This is because the dipping times are relatively short and insufficient either for the sugar/salt to penetrate, or for the water to leave the tissue. Hence, the dipping time of 0.5 min was chosen for performing further experiments. Fig. 1 also shows that the WL curve for sucrose and NaCl solutions follow similar trend, and as expected, the WL values are higher when the samples are dipped in solutions having greater concentrations.

Fig. 1 also shows that WL increased with the concentration of the dip solution ($p<0.05$) for both sucrose and NaCl solution. For example, the maximum WL value for samples dipped in

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50% sucrose at 0.5 min is 31.09 ± 0.74 g/100 g whereas it is only 22.86 ± 0.51 g/100 g for samples dipped in 30% sucrose solution. Likewise, in the case of NaCl solution, the maximum WL value for 10% solution is 18.76 ± 0.76 g/100 g whereas for the 5% solution, it is 16.56 ± 0.42 g/100 g. It is also interesting to note that the increase in WL with dip solution concentration tapers off in the case of NaCl because there is no significant difference between the WL values between 10 and 15% solutions. These observations on the effects of dip solution concentrations are similar to those in conventional osmotic dehydration. For example, [9,10,34,35] observed that WL increases with osmotic solution concentrations. [36,37] have also reported in the case of apricot and potato that WL does not change dramatically at high osmotic solution concentration, which these authors attribute to "case hardening" caused by high concentrations of infuse salt. It is necessary to note that even though the trends in variation of WL with solution concentrations are similar to osmotic dehydration, the solute concentration in the tissue are significantly lower (Table 5).

It is also interesting to compare the above WL values obtained after dipping the potato sample in various solutions, with the values for identical samples which are not subjected to any dipping process (control), and samples subjected to conventional osmotic dehydration treatment. For untreated samples, the dewatering is due to natural evaporation. It is obvious that the dipped slices gave significant higher water loss ($p<0.05$) according to Fig. 1. The results show that the non-dipped control sample attained a WL value of only 10.75 ± 0.45 g/100 g after 60 min whereas the samples dipped in sucrose attained three times this value. In the case of osmo-dehydrated samples, the WL value is four times higher than control sample at 42.86 ± 1.61 g/100 g of fresh sample.

In order to demonstrate the practical benefits of post-dip dehydration, it is illustrative to compare the actual moisture content of the various samples (Table 3). The average initial moisture content of samples was 475 ± 47 %, which, after 60 minutes reduced to $225.65 \pm 15.10\%$ in the case of post-sugar-dip water loss, $175.73 \pm 13.47\%$ in the case of conventional osmotic dehydration in the same solution, and $392.20 \pm 6.54\%$ in the case of ambient air drying. It is obvious that post-dip moisture loss is significantly closer to conventional osmotic dehydration than to air drying. Of course, the moisture loss in the case of conventional osmotic dehydration is higher, which can simply be attributed to the higher sugar/salt concentrations. It is also for this very reason that osmotically dehydrated samples lose water continuously while the dipped samples attain constant moisture content values. Table 3 also lists the water activity for all cases. According to [38], water activity is good indicator to determine the shelf life of food products. Table 3 shows that the water activity decreased over time for dip-dehydrated samples due to decrease water loss as discussed before. Generally, further process such as drying and frying is operate to minimize water activity of osmo-dehydrated samples at desired value to prevent any microbial activity.

Mechanism of Dip Dehydration Water Loss

When the sample is withdrawn from the dip solution, a layer of the dip solution gets occluded to the surface, and a concentration driving force results between the bulk and the surface of the potato sample, which moves the water from the interior towards the surface. At the surface, the water can evaporate or the solution can drain out of the sample. The concentration of the solute at the surface does not reach a steady state and therefore the commonly assumed quasi-steady state surface concentration does not apply. The osmotic gradient between the tissue cells and the surface is also unsteady and therefore the rate of water loss from the tissue remains unsteady. Fig. 2 illustrates the rate of water loss in the case

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of samples dipped in 50% sucrose and 10% NaCl solutions, and compares these rates with the values observed in non-dipped samples. It may be noted that the rates in Fig. 2 essentially represents the local gradients of WL versus time data shown in Fig. 1. It is evident from Fig. 2 that the dehydration rate generally decreases with time in all cases. For the untreated sample, the initial dehydration rate is 0.37 g H_2O (100g of fresh sample)$^{-1}$ min^{-1} and decreases steadily to less than 0.13 g H_2O (100g of fresh sample)$^{-1}$ min^{-1} in later stages. Water loss from the surface sample is essentially by evaporation, and since all samples are dehydrating under the same ambient conditions the rates of evaporation would be expected to be the same. It is clear from Fig. 2 that after 10 min, the control sample is dehydrating at the rate of 0.21 g H_2O (100g of fresh sample)$^{-1}$ min^{-1}, which may be assumed to represent the rate of evaporation. At the same time, the salt and sucrose dipped samples are losing water at a much higher rate. The difference between the two rates can be assumed to indicate the rate at which the water drains from the sample in the liquid state taking with it some solute.

Kinetics in Water Loss

The water loss data shown in Fig. 1 can be fitted to three selected empirical models, which are commonly used in dehydration literature: Azuara[28], Page[2] and Peleg[29]. The values of the model parameters and relevant statistical data are given in Table 4, which shows that R^2 for all models are greater than 0.91 with low RMSE values (<0.024). However, it was found that Peleg model satisfactorily described the dehydration behaviours with the highest R^2 (>0.98) and lowest RMSE (<0.018).

Solute Gain (SG) Behaviour

The solute gain estimated from Eq. 4 is given in Table 5. It may be noted that the solute gain is expressed in g solid per 100g fresh sample. Table 5 shows that there are significant

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increases in solute gain values with total time for both dip dehydration and conventional osmotic dehydration in sucrose and NaCl solutions, but conventional osmotic dehydration always exhibits higher solute gain value than dip dehydration samples. For example, solute gain in the case of conventional osmotic dehydration were 7.06 ± 0.44 g/100g for sucrose 50% and 5.00 ± 0.48 g/100g for NaCl 10% after 60 min of osmotic dehydration. These values are nearly twice the value of the solid gain in the case of dip dehydration. Thus, by employing dip dehydration, we can achieve osmotic water loss with considerably reduced solid gain, which is potentially health beneficial.

Table 6 shows the values of process efficiency index (WL/SG) for both dip and osmotic dehydration of potato slices. This ratio of water loss/solid gain is an important indicator to evaluate the efficiency of osmotic dehydration technique [39]. It was observed, in general, the dipped samples presented higher value of efficiency index as compared with osmo-dehydrated samples. The advantage of dip dehydration treatment which lowers solid gain substantially, is the main factor contributing to the higher WL/SG values. Thus, these results indicate the superiority of dip dehydration over the osmotic dehydration treatment with respect to the lower solid gain.

Fig. 3 shows the variation in remaining total sucrose and NaCl, which amount of solute gain and occluded on slices, expressed as the g of solute per 100g of fresh sample, as a function of time. It is clear that the mass of solute in the potato decreases for sucrose (for the first 20 minutes) as well as NaCl (for the first 10 minutes) and then remains constant. The loss of solute in the initial stage is due to the solution draining from the surface. We can postulate that the water diffusing towards the surface under the osmotic gradient, dissolves the solute present near the surface, and leaches it out with the draining solution. It clearly seen from

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Fig. 3 that solute content decreased from 13.31 g/100g to 7.39 g/100g of fresh sample after 20 minutes in the case of sucrose, and from 4.38 g/100g to 2.58 g/100g in the case of NaCl after 10 minutes. This reduction in solute content also lowers the osmotic gradient, which in turn lowers the rate of water loss; this is clearly seen in Fig. 2. Thus the dewatering process due to osmotic dehydration becomes less effective over the period of time and ceases to occur; any water loss from surface occurring thereafter is mainly due to natural evaporation.

Multi-stage Dip Dehydration

As discussed in the previous section, the WL after the first dip in osmotic solution becomes constant after 40 min in the case of sucrose and 10 min in the case of NaCl, due to decreases in the osmotic driving force. It was therefore thought desirable to find out whether the dehydration process could, once again, be re-started by dipping the partially dehydrated product, once again, in the osmotic solution. It is true that we are re-exposing the product to more water, but, given the short dipping time, the amount of water and salt taken up thus, will be very low. If dehydration could be successfully re-started, it was also thought desirable to explore whether water loss comparable to conventional osmotic dehydration could be achieved by a series of repeated dipping and holding processes, in other words, multi-stage dipping and dehydration. As mentioned earlier, two approaches were considered: repeated dipping in the same concentrated solution (treatment A) and dipping in progressively concentrated solution (treatment B).

Fig. 4 shows the transient WL values for multi-stage dipping and compares the data with the water loss observed in the case of conventional osmotic dehydration in the same solution. It is clear that the water loss patterns for the multi-stage process is similar to conventional osmotic dehydration, i.e. the rate WL values increase rapidly soon after dipping, but slow down in the

later stages. It is clear from Fig. 4 that initially, the water loss values for dip dehydration is lower than conventional osmotic dehydration in the same dip solution, which is naturally expected; this is indeed a key disadvantage of the process in relation to conventional osmotic dehydration. The water loss for treatment B appears to be lower than treatment A, but this is simply because the first dip solution had a lower concentration. In the case of sucrose solution, it is clearly seen that the value of WL does not significantly change ($p>0.05$) for all treatments after 240 min. Although the potato slices underwent dipping in progressively higher concentrated sucrose solution up to 60% (treatment B), the WL values did not continually rise. This is due to the decrease in chemical potential of water between the tissue and solution over the process time, and the high viscosity of concentrated sucrose solution that adheres to the potato surfaces. [40] also mentioned that the increasing sucrose concentration leads to a high viscosity of solution which creates external resistance to the water transfer rate.

It is interesting to note that even though the water loss values achieved in dip dehydration is comparable to osmotic dehydration, the solute gain (SG) is significantly lower and the process efficiency index (WL/SG) values for dip dehydration is significantly higher (Table 7).

 In the case of NaCl, the most effective method was found to be treatment B which achieved a maximum value of WL of 37 g/100g of fresh sample after 80 min, whereas the WL value for treatment A and conventional OD was around 30 g/100g of fresh sample. However, it may be noted that there is no significant different in SG values between treatment B and conventional OD after 50 min, thus resulting in treatment B giving lower WL/SG value than treatment A, but still higher than conventional OD as shown in Table 7. Furthermore, the

lower molecular weight of NaCl (58.4 g/mol) than sucrose (342 g/mol) enables the solute to diffuse more easily into the tissue [4].

Conclusion

In this study, dehydration of potato slices was explored after dipping the slices briefly in concentrated sugar (30-50%) and salt solutions (5-15%), and leaving the slices to lose water under ambient conditions. The absorption of sugar and salt resulted in the movement of water towards the surface of the slices under osmotic gradients, which was subsequently lost from the slices by a combination of evaporation and draining. Initially, the loss of water by draining was more significant, but later on evaporation tended to dominate. The moisture content of the slices could be reduced thus from 475 ± 47 % to 225.65 ± 15.10 % in an hour, without any significant expenditure of energy and the water loss was three times higher when compared to natural air drying. It was also found that dipped potato slices gained much lower amount of sugar/salt, which could be half or even lower than the value gained during osmotic dehydration in the same solution, thus yielding higher effectiveness index (WL/SG). This technique was further extended by investigating repeated dipping in the same concentration solution (treatment A) or by dipping in progressively concentrated solutions (treatment B). It was found that the water loss in multi-stage dip dehydration was comparable to osmotic dehydration but with significantly lower solid gain. The process efficiency index (WL/SG) was also higher for multi-stage dip dehydration. Thus, dip dehydration can be used instead of osmotic dehydration to achieve the same levels of water loss but with substantially lower solid gain.

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Figure 1. The variation of water loss as a function of time (a) sucrose; (b) NaCl solutions for post-dipping and conventional osmotic dehydration treatments, and control samples. The concentration of the solution and dipping time is minutes are shown in figure. (OD = osmotic dehydration).
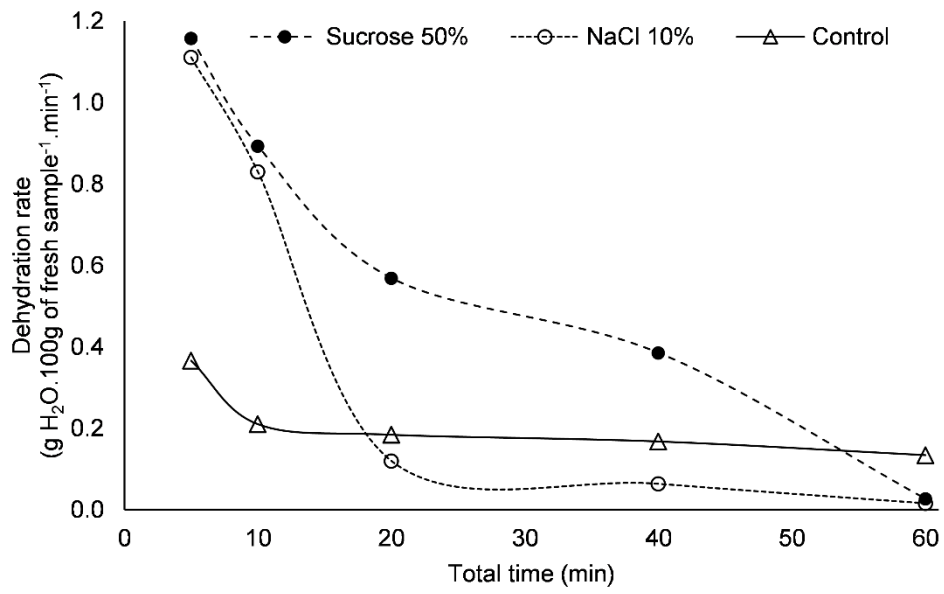
Figure 2. Dehydration rate curve of single stage of post-dipping treatment for sucrose 50% and NaCl 10%, and control samples.
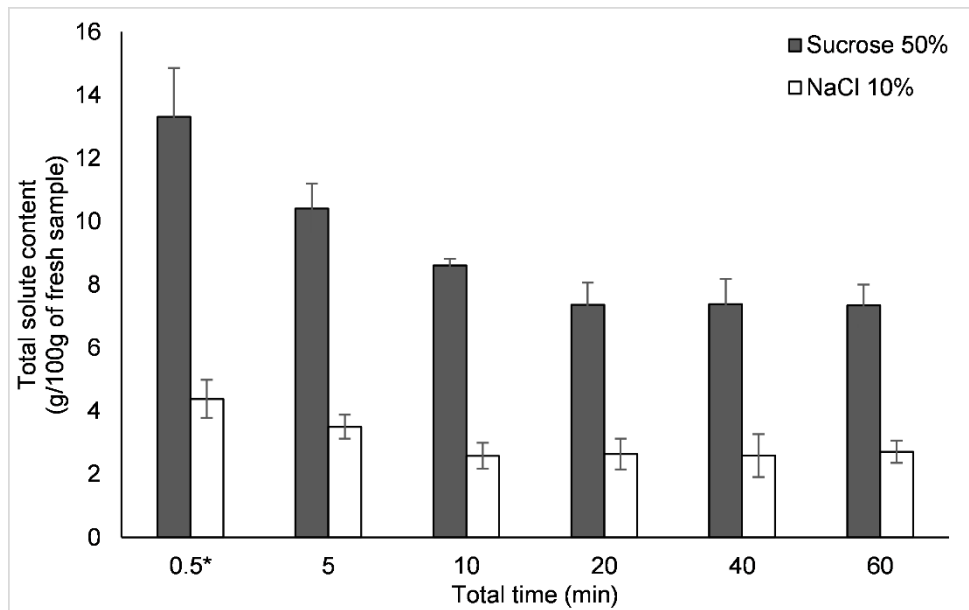
Figure 3. Variation in sucrose and NaCl content (g/100g fresh sample weight) on the sample with total time. (0.5* is the time after sample withdrawn from the osmotic solution and immediately measured the solute content, which is at 0 min of holding time).
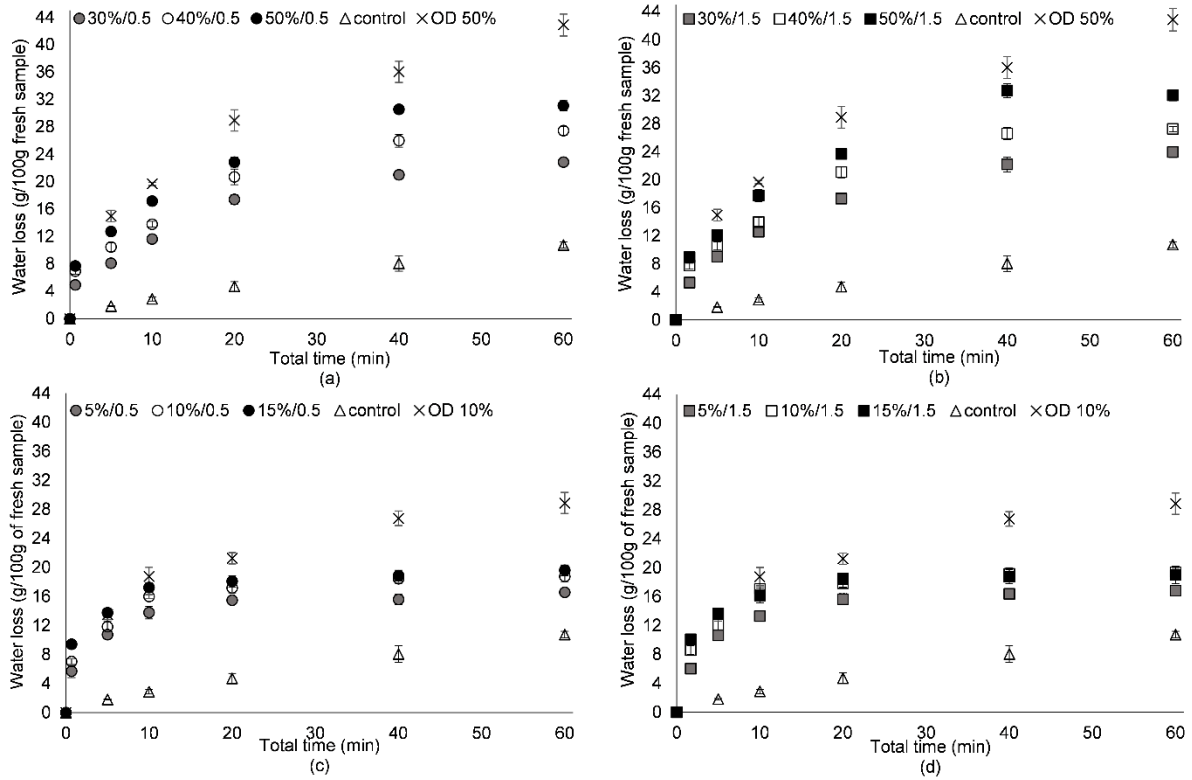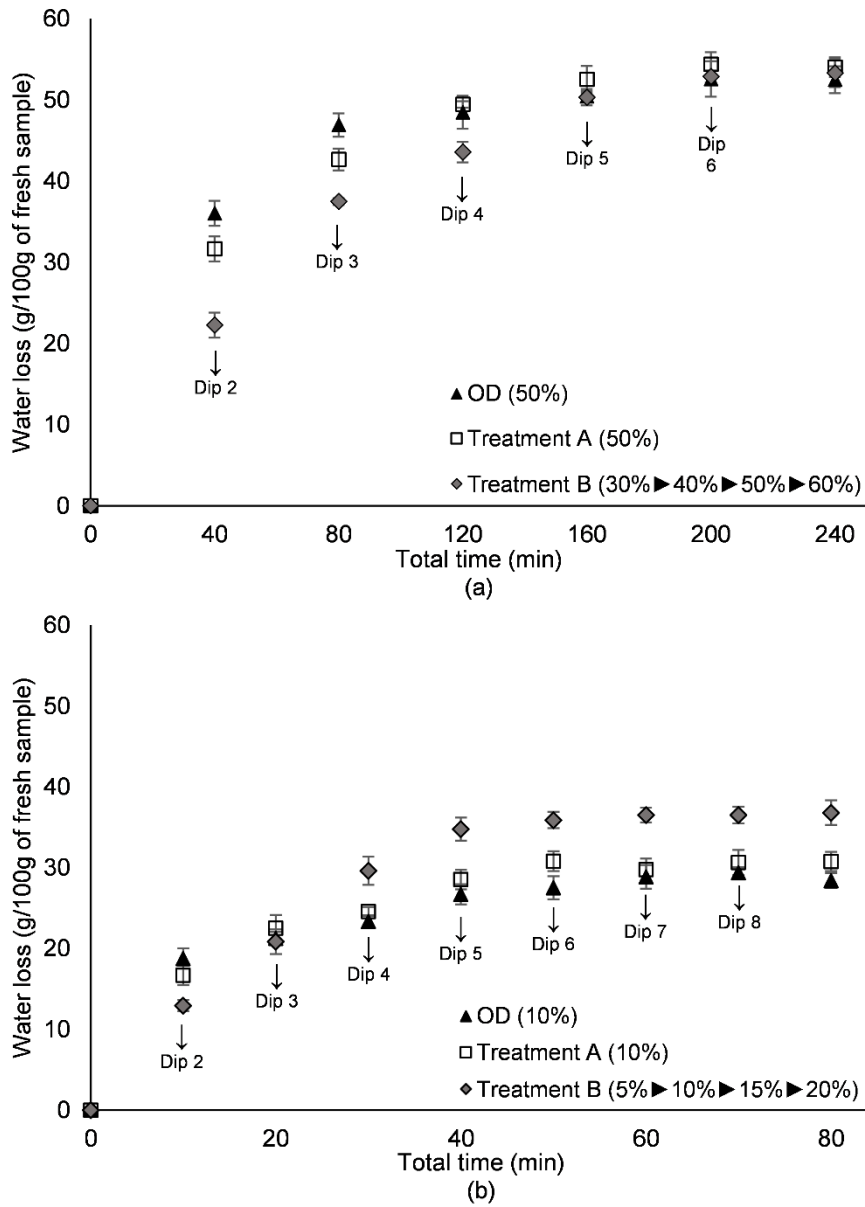
Figure 4. The variation of water loss as a function of time (a) sucrose; (b) NaCl solutions for conventional osmotic dehydration, (OD), multi-stage dipping and dehydration in same solution (Treatment A) and multistage dipping and dehydration in progressively solution (Treatment B). The concentrations of the dip solution employed are stated in the figure. (↓ shows the time which the re-dipping occurred. In treatment A, samples were re-dipped in same solution as shown in figure, while in treatment B, samples were re-dipped in progressive concentrated solutions based on Table 1).

Table 1. List of the osmotic solution concentrations and total time employed in treatment B. All dipping time was employed at 0.5 min.

Sucrose case		NaCl case	
Total time (min)	Osmotic solution (w/v)	Total time (min)	Osmotic solution (w/v)
0 (Dip 1)	Sucrose 30%	0 (Dip 1)	NaCl 5%
40 (Dip 2)	Sucrose 40%	10 (Dip 2)	NaCl 10%
80 (Dip 3)	Sucrose 50%	20 (Dip 3)	NaCl 15%
120 (Dip 4)	Sucrose 60%	30 (Dip 4)	NaCl 20%
160 (Dip 5)	Sucrose 60%	40 (Dip 5)	NaCl 20%
200 (Dip 6)	Sucrose 60%	50 (Dip 6)	NaCl 20%
		60 (Dip 7)	NaCl 20%
		70 (Dip 8)	NaCl 20%

Table 2. Kinetic models used in modelling

Model	Equation	Equation no.	Reference
Azuara	$WL_t = \dfrac{s_1 t (WL_\infty)}{1 + s_1 t}$	(5)	[20]
Page	$WL_t = \exp(-At^B)$	(6)	[2]
Peleg	$WL_t = \dfrac{t}{k_1 + k_2 t}$	(7)	[19]

WL_t = water loss at any time, t, WL_∞ = equilibrium water loss, s_1 = Azuara's constant, A and B = Page's constants, k_1 and k_2 = Peleg's constants.

Table 3. Moisture content (in % dry basis) and water activity, a_w of potatoes after withdrawn from dip solution at 0.5 min of dipping time, potatoes for conventional osmotic dehydration and control samples

Moisture content (% dry basis)				
Total time (min)	Post-dipping dehydration		Osmotic dehydration		Control
	Sucrose 50%	NaCl 10%	Sucrose 50%	NaCl 10%	
5	$355.37 \pm 45.96^{a,B}$	$352.40 \pm 30.36^{a,B}$	$347.38 \pm 11.84^{a,B}$	$349.37 \pm 10.93^{a,B}$	$465.11 \pm 20.80^{a,A}$
10	$301.37 \pm 21.12^{b,B}$	$310.67 \pm 15.08^{ab,B}$	$279.41 \pm 5.15^{b,B}$	$288.31 \pm 14.63^{b,B}$	$453.35 \pm 24.07^{ab,A}$
20	$265.58 \pm 12.54^{bc,C}$	$296.81 \pm 19.85^{b,B}$	$233.42 \pm 8.62^{c,D}$	$273.16 \pm 13.80^{b,BC}$	$443.19 \pm 8.05^{ab,A}$
40	$224.70 \pm 6.88^{c,C}$	$294.64 \pm 33.68^{b,B}$	$197.73 \pm 6.55^{d,D}$	$229.67 \pm 10.93^{c,C}$	$426.84 \pm 36.62^{bc,A}$
60	$225.65 \pm 15.10^{c,C}$	$291.46 \pm 23.03^{b,B}$	$175.73 \pm 13.47^{e,D}$	$224.57 \pm 14.03^{c,C}$	$392.20 \pm 6.54^{c,A}$
a_w					
Total time (min)	Post-dipping dehydration		Osmotic dehydration		Control
	Sucrose 50%	NaCl 10%	Sucrose 50%	NaCl 10%	
5	$0.988 \pm 0.003^{a,A}$	$0.987 \pm 0.007^{a,A}$	$0.988 \pm 0.002^{a,A}$	$0.986 \pm 0.001^{a,A}$	$0.991 \pm 0.005^{a,A}$
10	$0.986 \pm 0.001^{a,A}$	$0.984 \pm 0.001^{a,A}$	$0.981 \pm 0.005^{a,A}$	$0.982 \pm 0.002^{ab,A}$	$0.988 \pm 0.004^{a,A}$
20	$0.977 \pm 0.007^{ab,A}$	$0.977 \pm 0.007^{ab,A}$	$0.967 \pm 0.005^{b,B}$	$0.977 \pm 0.008^{ab,A}$	$0.987 \pm 0.005^{a,A}$
40	$0.969 \pm 0.008^{b,B}$	$0.977 \pm 0.003^{ab,B}$	$0.962 \pm 0.005^{b,BC}$	$0.976 \pm 0.012^{ab,A}$	$0.987 \pm 0.006^{a,A}$

| 60 | 0.968 ± 0.005[b,BC] | 0.977 ± 0.001[b,B] | 0.961 ± 0.001[b,C] | 0.969 ± 0.004[b,B] | 0.985 ± 0.002[a,A] |

Means within a column for each parameter and treatment between total times marked with the same lowercase letters do not differ significantly at $P < 0.05$.

Means within a row for each parameter and times between treatments marked with the same uppercase letters do not differ significantly at $P < 0.05$.

Table 4. Fitting of water loss data shown in Fig. 1 to Azuara model: $WL_t = \dfrac{s_1 t (WL_\infty)}{1 + s_1 t}$,

Page model: $WL_t = \exp(-At^B)$ and Peleg model: $WL_t = \dfrac{t}{k_1 + k_2 t}$.

Model	Parameter	Osmotic solution		

		Sucrose 30%	Sucrose 40%	Sucrose 50%	NaCI 5%	NaCI 10%	NaCI 15%
Page	A	3.372	3.489	3.005	2.61	2.441	2.226
	B	-0.2089	-0.2531	-0.2332	-0.0964	-0.0981	-0.0809
	R^2	0.9835	0.9868	0.9654	0.9706	0.9788	0.9869
	RMSE	0.0125	0.0131	0.0241	0.01157	0.0110	0.0089
	E	0.1166	0.1339	0.1201	0.0851	0.0647	0.046
Peleg	k_1	49.4	42.73	35.65	10.54	16.39	11.84
	k_2	3.406	2.806	2.541	6.132	5.056	4.921
	R^2	0.9872	0.9836	0.9811	0.9767	0.9819	0.9821
	RMSE	0.0110	0.0146	0.0178	0.0103	0.0102	0.0103
	E	0.1379	0.1536	0.1568	0.0684	0.1148	0.1147
Azuara	WL_∞ (g/g)	0.27	0.32	0.35	0.17	0.19	0.20
	s_1 (min^{-1})	0.10	0.103	0.1196	0.4783	0.4995	0.5165
	R^2	0.9706	0.9381	0.9594	0.9802	0.9538	0.9187
	RMSE	0.0141	0.0240	0.0236	0.0080	0.0137	0.0186
	E	0.1673	0.1784	0.1722	0.0764	0.1177	0.1120

Table 5. Solute gain (in g/100g of fresh sample) of potatoes after withdrawn from dip solution at 0.5 min of dipping time and potatoes for conventional osmotic dehydration.

Total time	Sucrose solution		
(min)	Single stage dip dehydration		Osmotic dehydration

	30%	40%	50%	50%
5	$1.52 \pm 0.17^{a,a}$	$2.41 \pm 0.24^{a,b}$	$2.53 \pm 0.42^{a,b}$	$3.62 \pm 0.45^{a,c}$
10	$1.60 \pm 0.30^{ab,a}$	$2.65 \pm 0.20^{a,b}$	$2.73 \pm 0.41^{ab,b}$	$5.59 \pm 0.49^{b,c}$
20	$1.89 \pm 0.22^{ab,a}$	$2.77 \pm 0.24^{a,b}$	$3.32 \pm 0.30^{bc,c}$	$6.48 \pm 0.43^{bc,d}$
40	$1.90 \pm 0.20^{ab,a}$	$2.87 \pm 0.66^{a,b}$	$3.48 \pm 0.35^{c,b}$	$6.67 \pm 0.17^{c,c}$
60	$1.95 \pm 0.25^{b,a}$	$2.91 \pm 0.55^{a,b}$	$3.52 \pm 0.33^{c,b}$	$7.06 \pm 0.44^{c,c}$

Total time	NaCl solution			
	Single stage dip dehydration			Osmotic dehydration
(min)	5%	10%	15%	10%
5	$0.74 \pm 0.15^{A,A}$	$1.07 \pm 0.09^{A,A}$	$1.82 \pm 0.34^{A,B}$	$3.06 \pm 0.55^{A,C}$
10	$0.86 \pm 0.25^{A,A}$	$1.53 \pm 0.38^{AB,AB}$	$1.98 \pm 0.40^{A,B}$	$3.40 \pm 0.85^{A,C}$
20	$1.01 \pm 0.20^{AB,A}$	$1.92 \pm 0.38^{BC,B}$	$2.27 \pm 0.30^{A,B}$	$4.26 \pm 0.98^{AB,C}$
40	$1.35 \pm 0.32^{BC,A}$	$2.04 \pm 0.18^{BC,B}$	$3.18 \pm 0.58^{B,C}$	$4.99 \pm 0.55^{B,D}$
60	$1.54 \pm 0.32^{C,A}$	$2.15 \pm 0.49^{C,A}$	$3.16 \pm 0.69^{B,B}$	$5.00 \pm 0.48^{B,C}$

Means within a column for each parameter and treatment between total times marked with the same first letters do not differ significantly at $P < 0.05$.

Means within a row for each parameter and times marked between treatments with the same second letters do not differ significantly at $P < 0.05$.

Table 6. Process efficiency index (WL/SG) of potatoes under dip dehydration and conventional osmotic dehydration treatments.

Total Time (min)	Single stage dip dehydration	Osmotic dehydration

	Sucrose 50%	NaCl 10%	Sucrose 50%	NaCl 10%
5	$5.13 \pm 0.91^{a,a}$	$11.13 \pm 1.35^{A,B}$	$4.17 \pm 0.35^{ab,a}$	$4.52 \pm 0.86^{A,A}$
10	$6.42 \pm 1.04^{ab,b}$	$11.05 \pm 2.82^{A,B}$	$3.54 \pm 0.35^{a,a}$	$5.76 \pm 1.33^{A,A}$
20	$6.92 \pm 0.53^{b,b}$	$9.23 \pm 1.65^{A,B}$	$4.48 \pm 0.28^{b,a}$	$5.15 \pm 0.92^{A,A}$
40	$8.84 \pm 0.86^{c,b}$	$9.08 \pm 0.55^{A,B}$	$5.40 \pm 0.29^{c,a}$	$5.39 \pm 0.54^{A,A}$
60	$8.88 \pm 0.72^{c,b}$	$9.11 \pm 1.98^{A,B}$	$6.10 \pm 0.52^{c,a}$	$5.79 \pm 0.34^{A,A}$

Means within a column for each parameter and treatment between total times marked with the same first letters do not differ significantly at $P < 0.05$.

Means within a row for each parameter and total times between treatments marked with the same second letters do not differ significantly at $P < 0.05$.

Table 7. Comparison of solute gain (in g/100g of fresh sample) and process efficiency index (WL/SG) of potato samples under different treatment conditions: conventional osmotic dehydration (OD), multi-stage dip dehydration in same solution (treatment A) and multi-stage

dip dehydration in progressively concentrated solution (treatment B). The concentrations of the solutions employed are stated in the table.

Time (min)	Sucrose solution					
	SG (g/100g of fresh sample)			WL/SG		
	OD (50%)	Treatment A (50%)	Treatment B (30%►40%►50%►60%)	OD (50%)	Treatment A (50%)	Treatment B (30%►40%►50%►60%)
40	$6.67 \pm 0.17^{a,c}$	$3.07 \pm 0.55^{a,b}$	$2.18 \pm 0.07^{a,a}$	$5.40 \pm 0.29^{a,a}$	$10.58 \pm 2.07^{ab,b}$	$10.22 \pm 0.82^{b,b}$
80	$7.72 \pm 0.67^{a,b}$	$3.29 \pm 0.80^{a,a}$	$2.79 \pm 0.20^{ab,a}$	$6.11 \pm 0615^{a,a}$	$13.48 \pm 2.89^{a,b}$	$13.65 \pm 0.97^{c,b}$
120	$8.45 \pm 0.68^{ab,b}$	$4.34 \pm 0.47^{ab,a}$	$3.84 \pm 0.32^{bc,a}$	$5.77 \pm 0.57^{a,a}$	$11.49 \pm 1.15^{ab,b}$	$11.39 \pm 1.01^{bc,b}$
160	$9.87 \pm 1.36^{abc,b}$	$5.03 \pm 0.59^{bc,a}$	$4.84 \pm 0.65^{c,a}$	$5.17 \pm 0.60^{a,a}$	$10.51 \pm 0.91^{ab,b}$	$10.58 \pm 1.86^{b,b}$
200	$11.16 \pm 1.97^{bc,b}$	$6.10 \pm 0.48^{cd,a}$	$7.28 \pm 0.86^{d,a}$	$4.84 \pm 0.98^{a,a}$	$8.96 \pm 0.78^{a,b}$	$7.35 \pm 0.98^{a,b}$
240	$11.97 \pm 2.34^{c,b}$	$6.73 \pm 0.89^{d,a}$	$7.14 \pm 0.43^{d,a}$	$4.53 \pm 0.99^{a,a}$	$8.12 \pm 1.00^{a,b}$	$7.49 \pm 0.54^{a,b}$
Time (min)	NaCl solution					
	SG (g/100g of fresh sample)			WL/SG		
	OD (10%)	Treatment A (10%)	Treatment B (5%►10%►15%►20%)	OD (10%)	Treatment A (10%)	Treatment B (5%►10%►15%►20%)

10	$3.40 \pm 0.85^{A,B}$	$1.41 \pm 0.18^{A,A}$	$1.10 \pm 0.35^{A,A}$	$5.76 \pm 1.33^{A,A}$	$11.96 \pm 1.13^{AB,B}$	$12.72 \pm 3.94^{AB,B}$
20	$4.26 \pm 0.98^{AB,B}$	$2.14 \pm 0.75^{A,A}$	$1.61 \pm 0.44^{AB,A}$	$5.15 \pm 0.92^{A,A}$	$11.33 \pm 3.31^{AB,B}$	$13.90 \pm 4.94^{B,B}$
30	$4.56 \pm 0.74^{ABC,B}$	$1.75 \pm 0.35^{A,A}$	$2.36 \pm 0.33^{BC,A}$	$5.20 \pm 0.72^{A,A}$	$14.50 \pm 3.23^{AB,B}$	$12.83 \pm 2.55^{AB,B}$
40	$4.99 \pm 0.55^{BC,C}$	$1.93 \pm 0.20^{A,A}$	$3.21 \pm 0.55^{CD,B}$	$5.39 \pm 0.54^{A,A}$	$14.93 \pm 1.60^{B,C}$	$11.11 \pm 2.25^{AB,B}$
50	$5.17 \pm 0.68^{BC,B}$	$2.34 \pm 0.28^{AB,A}$	$4.20 \pm 0.57^{DE,B}$	$5.37 \pm 0.51^{A,A}$	$13.28 \pm 1.01^{AB,C}$	$8.66 \pm 1.10^{AB,B}$
60	$5.00 \pm 0.48^{BC,B}$	$2.45 \pm 0.57^{AB,A}$	$5.33 \pm 0.20^{E,B}$	$5.79 \pm 0.34^{A,A}$	$12.73 \pm 3.30^{AB,B}$	$6.86 \pm 0.23^{A,A}$
70	$5.89 \pm 0.40^{C,B}$	$3.20 \pm 0.33^{B,A}$	$5.11 \pm 0.81^{E,B}$	$4.99 \pm 0.24^{A,A}$	$9.64 \pm 1.00^{A,C}$	$7.26 \pm 1.01^{A,B}$
80	$6.05 \pm 0.54^{C,B}$	$3.32 \pm 0.56^{B,A}$	$5.24 \pm 0.34^{E,B}$	$4.73 \pm 0.49^{A,A}$	$9.43 \pm 1.29^{A,C}$	$7.04 \pm 0.55^{A,B}$

Means within a column for each parameter and treatment between times marked with the same first letters do not differ significantly at $P < 0.05$.

Means within a row for each parameter and times between treatments marked with the same second letters do not differ significantly at $P < 0.05$.