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# PROCESS OPTIMIZATION FOR THE DEVELOPMENT OF NUTRITIVE SNACK FROM PUMPKIN (*Cucurbita moschata*) BY OSMOTIC DEHYDRATION TECHNIQUE

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**ABSTRACT**

Pumpkin (*Cucurbita moschata*) is a nutritionally valuable vegetable with high moisture content, appreciable carotenoids and phenolic compounds, but its high perishability limits fresh storage. The present investigation evaluated osmotic dehydration as a pretreatment for the development of a dehydrated pumpkin snack. Pumpkin pieces were treated with 50 and 60°Brix sucrose solutions for 6, 12, 18 and 24 h at a sample-to-syrup ratio of 1:2; a non-osmosed control was included. The treated samples were cabinet-dried at 55°C and stored at 10°C for 90 days. Yield, moisture, total soluble solids (TSS), total carotenoids, total phenolic content and hardness were evaluated. Initial yield ranged from 25.17 to 34.50% in osmotic treatments compared with 9.75% in the control. Initial moisture ranged from 17.42 to 21.38% in treated samples, while the control recorded 27.41%. TSS ranged from 43.90 to 56.30°Brix in treated products compared with 8.87°Brix in the control. Total carotenoids ranged from 0.158 to 0.189 mg/g in treated products and 0.200 mg/g in the control. Hardness varied substantially among treatments and declined during storage. TSS generally increased, whereas carotenoid and phenolic measurements generally decreased during storage. The findings demonstrate that osmotic dehydration substantially modifies mass transfer, soluble-solids enrichment and texture and provides a useful pretreatment for pumpkin snack development. Overall treatment selection should be based on a defined multi-response optimisation criterion rather than a single quality attribute.

***Key words*:** Pumpkin, osmotic dehydration, nutritive snack, storage stability, biochemical analysis

## Introduction

Pumpkin (*Cucurbita moschata*) is an important vegetable valued for its edible flesh, characteristic colour and contribution of carbohydrates, dietary fibre, minerals and bioactive compounds. Carotenoids and phenolic compounds contribute to its nutritional and functional value. However, the high moisture content of fresh pumpkin makes it susceptible to rapid deterioration. Dehydration and value addition can therefore extend usability and provide convenient snack products.

Osmotic dehydration is a partial dehydration process in which food pieces are immersed in a hypertonic solution. The concentration gradient promotes movement of water from the tissue into the solution while soluble substances from the osmotic medium migrate into the food. The magnitude of mass transfer depends on solution

concentration, duration, temperature, tissue structure and food-to-solution ratio. Osmotic pretreatment followed by hot-air or cabinet drying can modify drying behaviour, moisture content, soluble-solids concentration and texture.

The present study was undertaken to evaluate the effect of sucrose concentration and osmotic treatment duration on yield and selected physicochemical, bioactive and textural attributes of dehydrated pumpkin snack and to monitor quality changes during 90 days of storage at 10°C.

## Materials and Methods

Mature pumpkin fruits of Cucurbita moschata cv. Arka Suryamukhi were cleaned, peeled and cut into suitable pieces. Nine treatments were evaluated in a completely randomized design with three replications. $T_1$–$T_4$ consisted of 50°Brix sucrose syrup for 6, 12, 18 and 24 h, respectively; $T_5$–$T_8$ consisted of 60°Brix syrup for the same durations; and T9 was the control without osmotic treatment. A sample-to-syrup ratio of 1:2 and 0.3% citric acid were used. Osmotically treated samples were subsequently cabinet dried at 55°C. The control was dried without osmotic pretreatment.

The dehydrated products were packed and stored at 10°C. Observations were recorded at 0, 30, 60 and 90 days. Moisture content was determined gravimetrically, TSS was measured as °Brix, total carotenoids were estimated spectrophotometrically at 470 nm following acetone extraction, total phenolic content was determined by the Folin–Ciocalteu procedure and hardness was measured instrumentally. Yield was calculated from final dried-product mass relative to initial raw-material mass.

Data were analysed under a completely randomized design using analysis of variance. SE(m) and critical difference at 5% probability [CD (5%)] are presented in the tables. Yield was considered a process characteristic and was not treated as a storage-day response.

## Results and Discussion

The consolidated results obtained for the major quality attributes of the osmotic-dehydrated pumpkin snack are presented in Tables 1, 2 and 3. The results demonstrate that osmotic pretreatment substantially modified the physicochemical, nutritional and textural characteristics of the final dehydrated product. The response was influenced by both osmotic solution concentration and duration of osmotic treatment, followed by the effects of cabinet drying and subsequent storage. The observed changes are attributable to the simultaneous occurrence of water loss, solute gain, tissue modification, concentration of soluble constituents and thermal effects during dehydration. Similar interactions between osmotic pretreatment and subsequent drying have been reported for pumpkin and other plant tissues.

Osmotic dehydration is essentially a coupled mass-transfer process in which water migrates from the plant tissue towards the surrounding hypertonic solution, while solutes from the osmotic medium migrate into the tissue. The magnitude of these fluxes depends on the concentration gradient, duration of treatment, tissue structure and temperature. In pumpkin, Garcia *et al.*, (2007) demonstrated that sucrose-based osmotic pretreatment produces substantial water transfer and solute incorporation and can subsequently influence hot-air drying behaviour. Their study using 40, 50 and 60% sucrose solutions also demonstrated that water diffusion was greater than sucrose diffusion and that osmotic pretreatment enhanced subsequent air-drying.

### Effect of osmotic pre-treatment on product yield

Product yield exhibited considerable variation among the treatments. The initial yield of the osmotic-dehydrated products ranged from 25.17% in $T_1$ to 34.50% in $T_5$, whereas the untreated control ($T_9$) recorded a substantially lower yield of 9.75%. Thus, osmotic pre-treatment resulted in a considerable increase in the mass of finished product recovered relative to the control.

The higher yield observed in osmotic treatments can be explained by the combined effects of water removal and incorporation of osmotic solutes. During immersion in concentrated sucrose solution, water diffuses outward from the pumpkin tissue, whereas sucrose molecules simultaneously diffuse inward. Consequently, although a substantial amount of water is removed, part of the lost mass is compensated by uptake of soluble solids from the osmotic medium. This phenomenon results in a greater final dry-product mass than would be obtained when pumpkin is subjected directly to drying without osmotic pre-treatment.

The higher yield in $T_5$ compared with $T_1$ further indicates that treatment conditions influenced the extent of mass transfer. Differences between individual treatments may arise from variation in the concentration gradient, treatment duration, tissue permeability and the extent of structural modification during osmotic treatment. Çaglayan *et al.*, (2018) similarly reported that osmotic solution concentration and pre-treatment time significantly affected weight reduction, water loss and solid gain in pumpkin slices.

The present results are also in agreement with Garcia *et al.*, (2007), who observed that osmotic pre-treatment of *Cucurbita moschata* altered mass transfer during

**Table 1:** Yield and moisture content of osmotically dehydrated pumpkin snack.

| Treatment | Process Condition | Yield (%) | Moisture 0 d (%) | Moisture 30 d (%) | Moisture 60 d (%) | Moisture 90 d (%) |
|---|---|---|---|---|---|---|
| $T_1$ | 50°Brix, 6 h | 25.17 | 19.71 | 19.44 | 17.03 | 19.05 |
| $T_2$ | 50°Brix,12 h | 28.83 | 17.42 | 17.16 | 20.15 | 16.89 |
| $T_3$ | 50°Brix,18 h | 33.00 | 20.61 | 20.35 | 18.51 | 19.95 |
| $T_4$ | 50°Brix,24 h | 31.00 | 19.47 | 18.74 | 20.62 | 18.28 |
| $T_5$ | 60°Brix, 6 h | 34.50 | 21.38 | 20.85 | 16.93 | 20.38 |
| $T_6$ | 60°Brix,12 h | 31.67 | 17.52 | 17.13 | 18.59 | 16.73 |
| $T_7$ | 60°Brix,18 h | 31.00 | 19.19 | 18.79 | 17.57 | 18.39 |
| $T_8$ | 60°Brix,24 h | 30.17 | 18.13 | 17.80 | 26.68 | 17.34 |
| $T_9$ | Control (without osmosis) | 9.75 | 27.41 | 27.14 | 0.6120 | 26.21 |
| SE(m)± | | 0.28 | 0.58 | 0.65 | 1.826 | 0.67 |
| CD (5%) | | 0.85 | 1.74 | 1.95 | 17.03 | 1.98 |

subsequent hot-air drying. The authors reported enhanced mass transfer following osmotic pre-treatment, indicating that the pre-treatment modifies the tissue sufficiently to influence subsequent dehydration behaviour.

The substantially lower yield of 9.75% in $T_9$ can be attributed to the absence of osmotic solute incorporation. In the control, the product mass was reduced primarily through water removal during cabinet drying. Therefore, the control experienced a much greater net reduction in mass compared with the osmotically pre-treated samples.

However, yield should not be considered as an independent indicator of product quality. A higher yield may partly arise from greater sucrose incorporation and therefore does not necessarily indicate superior nutritional quality or sensory acceptability. Yield should consequently be interpreted together with moisture content, TSS, bioactive compounds, texture and sensory characteristics.

**Effect on moisture content**

The initial moisture content of the dehydrated products varied from 17.42 to 21.38% among the osmotic treatments, whereas the control treatment $T_9$ recorded 27.41%. The comparatively lower moisture content of the osmotically pre-treated samples indicates that osmotic dehydration promoted substantial water removal before cabinet drying.

The reduction in moisture content can principally be attributed to the high osmotic pressure generated by the concentrated sucrose solution. When pumpkin tissue is immersed in the hypertonic medium, a difference in water activity is established between the intracellular and external phases. Water consequently migrates from the tissue towards the osmotic solution. Simultaneously, sucrose enters the tissue, although its diffusion rate is generally lower than that of water. Garcia *et al.*, (2007) reported greater effective diffusivity for water than sucrose during osmotic dehydration of pumpkin, supporting the mechanism observed in the present investigation.

The lower moisture content of the treated samples also facilitated subsequent cabinet drying. Osmotic pre-treatment reduces part of the water load that otherwise has to be removed during convective drying. Lech *et al.*, (2018) observed that pumpkin moisture content decreased during osmotic pre-treatment until an equilibrium stage was approached. Their work further demonstrated that osmotic pre-treatment influenced the subsequent drying process.

The comparatively high moisture content of 27.41% in T9 indicates that direct drying without osmotic pre-treatment resulted in a product retaining more moisture under the processing conditions used. This difference is important because moisture content influences several other quality characteristics, including hardness, microbial stability, storage behaviour and perceived texture.

The observed range among the treated samples indicates that increasing osmotic severity did not produce a perfectly linear response. This is expected because osmotic dehydration is not governed exclusively by solution concentration. Tissue permeability, surface area, treatment duration, concentration gradients, structural changes and approach towards osmotic equilibrium can all influence water transfer. Therefore, the relationship between treatment conditions and final moisture content should be interpreted as a combined mass-transfer response rather than as a simple concentration-dependent phenomenon.

**Effect on total soluble solids (TSS)**

A pronounced difference was observed in total soluble solids among the treatments. The TSS values of the osmotically treated samples ranged from 43.90 to 56.30°Brix, whereas the control $T_9$ recorded only 8.87°Brix.

**Table 2:** Total soluble solids and total carotenoid content of pumpkin snack during storage.

| Treat-ment | Process Condition | TSS 0 d | TSS 30 d | TSS 60 d | TSS 90 d | Total carotenoids 0 d | Total carotenoids 30 d | Total carotenoids 60 d | Total carotenoids 90 d |
|---|---|---|---|---|---|---|---|---|---|
| $T_1$ | 50°Brix, 6 h | 46.00 | 46.60 | 47.03 | 47.60 | 0.158$^{b}$ | 0.153$^{c}$ | 0.135$^{b}$ | 0.139$^{d}$ |
| $T_2$ | 50°Brix, 12 h | 43.90 | 50.60 | 51.03 | 52.30 | 0.164$^{b}$ | 0.157$^{b}$ | 0.137$^{b}$ | 0.141$^{d}$ |
| $T_3$ | 50°Brix, 18 h | 45.57 | 54.27 | 54.60 | 55.30 | 0.170$^{b}$ | 0.167$^{b}$ | 0.146$^{b}$ | 0.145$^{c}$ |
| $T_4$ | 50°Brix, 24 h | 47.30 | 47.60 | 48.40 | 49.40 | 0.176$^{b}$ | 0.174$^{b}$ | 0.156$^{b}$ | 0.153$^{c}$ |
| $T_5$ | 60°Brix, 6 h | 52.40 | 53.70 | 54.30 | 55.70 | 0.161$^{b}$ | 0.156$^{b}$ | 0.144$^{b}$ | 0.140$^{d}$ |
| $T_6$ | 60°Brix, 12 h | 53.20 | 53.80 | 54.70 | 55.90 | 0.177$^{b}$ | 0.166$^{b}$ | 0.146$^{b}$ | 0.152$^{c}$ |
| $T_7$ | 60°Brix, 18 h | 53.90 | 54.50 | 55.30 | 56.30 | 0.180$^{a}$ | 0.176$^{a}$ | 0.157$^{b}$ | 0.158$^{b}$ |
| $T_8$ | 60°Brix, 24 h | 56.30 | 57.50 | 58.40 | 59.10 | 0.189$^{a}$ | 0.181$^{a}$ | 0.177$^{a}$ | 0.165$^{b}$ |
| $T_9$ | Control (without osmosis) | 8.87 | 9.20 | 9.30 | 9.50 | 0.200$^{a}$ | 0.195$^{a}$ | 0.192$^{a}$ | 0.188$^{a}$ |
| SE(m) ± | | 0.06 | 0.07 | 0.08 | 0.08 | 0.0071 | 0.0067 | 0.0084 | 0.0033 |
| CD (5%) | | 0.18 | 0.21 | 0.24 | 0.24 | 0.021 | 0.020 | 0.025 | 0.010 |

The marked increase in TSS of the treated products is primarily attributable to sucrose uptake from the osmotic solution. During osmotic dehydration, two simultaneous mass-transfer phenomena occur: outward movement of water and inward migration of soluble substances. Because the osmotic solution used in the present study contained a high concentration of sucrose, substantial solute incorporation occurred in the pumpkin tissue. Following subsequent drying, removal of water further concentrated the soluble solids within the tissue.

The substantially lower TSS value of the control is expected because $T_9$ did not undergo osmotic treatment and therefore did not receive the additional soluble solids supplied by the sucrose medium. The difference between $T_9$ and the osmotic treatments therefore provides direct evidence of the contribution of osmotic solute uptake to the final chemical composition.

The higher TSS values observed particularly in treatments involving the more concentrated osmotic medium are consistent with the greater concentration gradient between the tissue and osmotic solution. Çaglayan *et al.,* (2018) demonstrated that osmotic solution concentration and treatment time influence mass transfer characteristics, including solid gain, during osmotic treatment of pumpkin.

Garcia *et al*., (2007) similarly demonstrated sucrose incorporation during osmotic treatment of *Cucurbita moschata*. Their study used sucrose solutions of 40, 50 and 60% and showed that osmotic treatment influenced subsequent drying behaviour and solute transfer.

The increase in TSS should therefore be considered an important technological consequence of osmotic processing. Nevertheless, a high TSS value should not automatically be interpreted as a nutritional advantage because much of the increase is associated with incorporated sucrose. Thus, TSS represents an important indicator of osmotic solute incorporation and concentration, rather than a direct measure of nutritional quality.

**Effect on total carotenoid content**

The initial total carotenoid content ranged from approximately 0.158 to 0.189 mg/g among the osmotic treatments, whereas the control $T_9$ recorded 0.200 mg/g. The comparatively higher value observed in the control indicates that osmotic treatment and subsequent drying were associated with some reduction in measurable carotenoid content.

Carotenoids are important quality constituents of pumpkin and are particularly susceptible to changes induced by processing and storage because of their highly unsaturated molecular structures. During thermal processing and dehydration, carotenoid losses may occur through oxidation, isomerization, thermal degradation and changes in the physical state of the food matrix.

The lower carotenoid values observed in several osmotic treatments may therefore be associated with the combined effects of osmotic pre-treatment and subsequent cabinet drying. The treatment duration may also influence the extent of exposure of carotenoids to oxygen and heat.

Song *et al.,* (2018) specifically demonstrated that carotenoids in dehydrated pumpkin undergo degradation during storage and that the extent of degradation depends on storage time, temperature and oxygen availability. Their study identified β-carotene, α-carotene and lutein as important carotenoids in dehydrated pumpkin and demonstrated that storage under low-temperature, oxygen-limited conditions improved carotenoid retention.

**Table 2:** Total phenolic content and hardness of pumpkin snack during storage.

| Treat-ment | Process Condition | Total phenolics 0 d | Total phenolics 30 d | Total phenolics 60 d | Total phenolics 90 d | Hardness 0 d | Hardness 30 d | Hardness 60 d | Hardness 90 d |
|---|---|---|---|---|---|---|---|---|---|
| $T_1$ | 50°Brix, 6 h | 15.63 | 14.44 | 13.41 | 12.53 | 317.47 | 298.73 | 283.43 | 264.50 |
| $T_2$ | 50°Brix, 12 h | 13.70 | 12.43 | 11.54 | 10.86 | 336.80 | 316.53 | 299.90 | 281.00 |
| $T_3$ | 50°Brix, 18 h | 12.73 | 12.20 | 10.93 | 9.95 | 355.67 | 332.40 | 315.57 | 295.97 |
| $T_4$ | 50°Brix, 24 h | 11.31 | 10.34 | 9.40 | 8.62 | 377.53 | 352.70 | 333.90 | 313.73 |
| $T_5$ | 60°Brix, 6 h | 20.06 | 16.03 | 15.16 | 13.55 | 346.37 | 326.17 | 308.90 | 289.13 |
| $T_6$ | 60°Brix, 12 h | 17.60 | 15.73 | 13.52 | 12.24 | 370.27 | 348.53 | 329.77 | 308.90 |
| $T_7$ | 60°Brix, 18 h | 15.06 | 13.14 | 10.99 | 9.05 | 401.47 | 377.83 | 357.67 | 335.73 |
| $T_8$ | 60°Brix, 24 h | 13.38 | 12.75 | 9.51 | 8.90 | 427.73 | 401.37 | 379.83 | 358.20 |
| $T_9$ | Control (without osmosis) | 12.55 | 12.37 | 12.31 | 11.19 | 285.40 | 268.73 | 255.17 | 240.77 |
| | SE(m) ± | 0.69 | 0.52 | 0.61 | 0.50 | 1.73 | 1.26 | 1.48 | 1.33 |
| | CD (5%) | 2.07 | 1.56 | 1.82 | 1.48 | 5.15 | 3.76 | 4.40 | 3.96 |

The present values should therefore be interpreted as total carotenoid equivalents determined by the spectrophotometric procedure, rather than as concentrations of individual carotenoids. Spectrophotometric estimation provides an aggregate response and cannot distinguish individual compounds such as β-carotene, α-carotene and lutein.

Interestingly, the reduction in carotenoid content was not identical among treatments. This indicates that processing history influenced carotenoid retention. Variation may result from differences in osmotic exposure, tissue disruption, moisture level and subsequent heat transfer during cabinet drying.

Song *et al.,* (2018) further demonstrated that carotenoid stability is strongly dependent on the specific storage environment, with oxygen and temperature influencing degradation kinetics. Therefore, differences observed among treatments during the present storage study can reasonably be discussed in terms of treatment-dependent matrix and stability effects, while avoiding attribution to a single degradation mechanism without compound-specific analysis.

Supporting evidence has also been reported by Song *et al.,* (2018) in dehydrated pumpkin slices, where starch-based osmotic coating improved retention of lutein, á-carotene and â-carotene. The authors attributed the improvement partly to the formation of a coating barrier that reduced exposure of the tissue to oxygen. This demonstrates the sensitivity of pumpkin carotenoids to the processing environment and matrix structure.

**Effect on total phenolic content**

Total phenolic content showed variation among the treatments and did not exhibit a simple linear relationship with either osmotic solution concentration or treatment duration. Such behaviour is expected because phenolic compounds are affected not only by their absolute concentration but also by cellular disruption, dehydration, oxidation, polymerization and extractability.

During osmotic dehydration, removal of water can cause concentration of non-water-soluble components in the remaining tissue. At the same time, changes in cellular structure may facilitate the release of phenolic compounds during extraction. Conversely, thermal exposure and oxygen contact during subsequent drying can promote oxidation or degradation of susceptible phenolic constituents. Consequently, the final measured phenolic concentration represents the combined outcome of concentration and degradation phenomena.

Lech *et al.*, (2018) demonstrated that osmotic pre-treatment can influence polyphenolic content and antioxidant properties of dried pumpkin products. Their work showed that the choice of osmotic medium can alter the chemical characteristics of the final product, indicating that osmotic treatment affects more than simple water removal.

The variation observed in the present study should also be interpreted in relation to the analytical method. The Folin–Ciocalteu procedure is widely used for estimation of total phenolic-equivalent content; however, the reaction is not absolutely specific to individual phenolic molecules and may also respond to other reducing substances. Therefore, the measured values are appropriately interpreted as total phenolic equivalents rather than concentrations of individual phenolic compounds.

The absence of a consistent increase with increasing osmotic concentration suggests that the measured phenolic response was governed by multiple interacting

factors. Longer exposure to concentrated osmotic solution may enhance tissue modification, but prolonged exposure can also alter the chemical environment and subsequent drying behaviour. Therefore, phenolic retention should be evaluated together with other quality attributes rather than using it as a single optimization criterion.

**Effect on hardness**

Marked differences were observed in the textural property of hardness among the treatments. Hardness values ranged from 317.47 in $T_1$ to 427.73 in $T_8$, while the control $T_9$ recorded 285.40.

The higher hardness observed in several osmotic treatments can be attributed to the combined effects of moisture reduction, sucrose incorporation, cellular structural modification and concentration of tissue solids during dehydration. Removal of water reduces plasticization of the cell-wall matrix and generally increases resistance to deformation. In addition, sucrose uptake can alter the mechanical properties of the tissue by increasing the concentration of dissolved solids within the intercellular and intracellular regions.

The relatively high hardness of $T_8$ suggests that the combination of osmotic conditions used for this treatment produced a comparatively dense or rigid dried structure. In contrast, the lower hardness of $T_9$ may be related to its higher residual moisture content and the absence of sucrose incorporation.

Garcia *et al*., (2007) reported substantial structural changes and volume reduction in pumpkin during osmotic dehydration followed by hot-air drying. Such structural modification provides a mechanistic basis for differences in the mechanical properties of osmotically treated and untreated samples.

The hardness response is also important from a product-development perspective. Excessively high hardness may negatively influence consumer acceptability even when moisture and yield are desirable. Conversely, very low hardness may indicate insufficient structural development or excessive moisture retention. Therefore, an appropriate balance between hardness, moisture and sensory acceptability is required for development of a desirable pumpkin snack.

**Overall relationship among yield, moisture and TSS**

The combined results demonstrate a clear interaction between the major physicochemical characteristics. Osmotic pre-treatment increased product yield relative to the control, reduced moisture content and substantially increased TSS.

These responses are mechanistically related. The outward movement of water during osmotic dehydration reduces the water content of the tissue, whereas inward movement of sucrose increases the solid fraction. Subsequent cabinet drying further removes water and concentrates the incorporated and endogenous soluble solids.

Therefore, the increase in TSS and yield should not be considered independent responses. A treatment producing high TSS may also produce increased yield because of greater solid incorporation. Similarly, lower moisture may increase apparent concentration of soluble and bioactive components on a mass basis.

This interdependence highlights the importance of evaluating several quality attributes simultaneously. Selecting a treatment solely on the basis of yield or TSS could favour excessive solute incorporation, whereas selection only on the basis of moisture could result in an overly dry and hard product.

**Changes in quality characteristics during storage**

During storage, the physicochemical and functional characteristics of the dehydrated pumpkin product changed progressively. In general, moisture and hardness showed a declining tendency, whereas TSS generally increased. Total carotenoid and phenolic measurements also showed a general declining tendency over the storage period, although the magnitude of change varied among treatments.

The decline in moisture during storage may be related to continued moisture redistribution and equilibration within the dehydrated matrix. Even after completion of drying, moisture may not be uniformly distributed throughout the product. Differences in water activity and concentration gradients can promote redistribution of residual moisture during storage.

The observed increase in TSS during storage can partly be explained by continued moisture reduction or redistribution, which increases the concentration of soluble constituents on a mass basis. In addition, migration and equilibration of soluble solids within the tissue may contribute to changes in the measured TSS.

The reduction in hardness during storage indicates progressive structural relaxation of the dried tissue. Moisture redistribution can act as a plasticizing factor, reducing the mechanical resistance of the matrix. Structural relaxation may also occur as the product equilibrates with its storage environment.

These observations demonstrate that storage is not merely a passive period following processing; rather, several quality changes continue to occur within the dehydrated matrix.

**Storage stability of carotenoids**

The gradual reduction in total carotenoid content during storage is consistent with the known sensitivity of pumpkin carotenoids to oxygen, temperature and storage duration. Song *et al.,* (2018) demonstrated that β-carotene, α-carotene and lutein in dehydrated pumpkin undergo time-dependent degradation and that the degradation kinetics are affected by both temperature and oxygen availability. Their study found improved retention under low-temperature storage and controlled-atmosphere conditions.

The decrease observed in the present investigation may therefore be associated with oxidative reactions and/or isomerization of carotenoid molecules during storage. However, because the present analysis was based on total carotenoid spectrophotometry rather than HPLC separation of individual carotenoids, the specific contribution of oxidation versus isomerization cannot be quantitatively distinguished.

The treatment-dependent differences suggest that the initial processing history influenced subsequent storage stability. Differences in moisture content, solute concentration, matrix structure and exposure to oxygen can alter the chemical environment surrounding carotenoid molecules. Thus, osmotic pre-treatment can affect not only the initial carotenoid concentration but also the stability of the pigment during storage.

**Storage behaviour of total phenolic content**

The general reduction in total phenolic content during storage suggests progressive changes in phenolic compounds or in their extractability. Phenolic compounds may undergo oxidation, polymerization or interaction with other components of the food matrix during storage.

However, interpretation should remain cautious because Folin–Ciocalteu measurements represent total reducing/phenolic-equivalent capacity rather than individual phenolic compounds. A decline in the measured value therefore does not necessarily mean that every individual phenolic compound decreased at the same rate.

Treatment-specific differences may be associated with the different levels of osmotic solute incorporation and tissue modification. The osmotic treatment can change the physical structure of the tissue and consequently influence the accessibility of phenolic compounds to the extraction solvent. During storage, further structural changes can modify extractability.

Therefore, the observed decline should be described as a reduction in measured total phenolic-equivalent content, rather than definitive degradation of all individual phenolic compounds.

**Storage behaviour of hardness**

Hardness generally decreased during storage. The decline indicates progressive modification of the mechanical structure of the dehydrated pumpkin matrix.

Immediately after drying, the tissue structure is relatively rigid because of extensive water removal and concentration of solids. During storage, redistribution of residual moisture can reduce the glassy or rigid nature of the matrix and increase molecular mobility. Such changes can reduce resistance to deformation and consequently lower the measured hardness.

The decrease in hardness may be technologically desirable up to a certain level because extremely hard products can be less acceptable as snack foods. However, excessive softening may compromise the characteristic texture expected of a dehydrated snack.

The present observation therefore emphasizes that the desirable treatment should provide an appropriate balance between initial firmness and maintenance of acceptable texture during storage.

**Integrated interpretation of treatment effects**

The consolidated results demonstrate that osmotic dehydration generated a multi-dimensional response rather than a single desirable direction for all quality attributes.

**Osmotic treatment generally:**

- increased product yield compared with the control;
- reduced residual moisture;
- substantially increased TSS;
- modified total carotenoid retention;
- altered measured total phenolic content;
- increased hardness in several treatments; and
- influenced the subsequent rate of quality changes during storage.

These effects can be explained by the simultaneous occurrence of water loss, sucrose gain, structural modification and thermal dehydration.

The concentration of the osmotic solution is particularly important because increasing solution concentration generally increases the driving force for water transfer and promotes solute uptake. However, the response may eventually approach equilibrium and therefore need not increase indefinitely with concentration or treatment time. Garcia *et al*., (2007) demonstrated that osmotic dehydration of pumpkin is governed by diffusion and that both water and sucrose transfer occur simultaneously.

Similarly, Çaglayan *et al*., (2018) showed that both osmotic solution concentration and pre-treatment time significantly influence mass-transfer characteristics in pumpkin.

Dermesonlouoglou *et al*., (2020) further demonstrated the potential of osmotic dehydration for producing novel pumpkin products and emphasized the relationship between osmotic treatment conditions, dehydration behaviour and product quality.

The present findings therefore support the use of osmotic dehydration as an effective pretreatment for development of a shelf-stable pumpkin snack, but they also demonstrate that optimization cannot be based on a single parameter.

**Implications for process optimization**

From a process-development perspective, the results indicate that the optimum treatment should simultaneously satisfy several requirements. A desirable treatment should provide:

1. Adequate product yield, without excessive dependence on solute incorporation;
2. Appropriate residual moisture, sufficient for storage stability but not so low that excessive hardness develops;
3. Desirable TSS, reflecting appropriate osmotic impregnation without excessive sweetness;
4. Maximum feasible retention of carotenoids and phenolic constituents;
5. Acceptable hardness and structural characteristics;
6. Good stability during storage, including retention of nutritional and sensory quality.

The fact that no single treatment necessarily performs identically across all these attributes illustrates the importance of multi-response optimization. For example, a treatment that produces high yield and TSS may simultaneously have greater sucrose incorporation, whereas a treatment producing very low moisture may exhibit excessive hardness.

Consequently, the final selection of the optimized treatment should not be based solely on the highest yield, lowest moisture or highest bioactive content. Instead, the optimum should be determined through a formal multi-response optimization approach, in which the relative importance or desirability of yield, moisture, TSS, carotenoid retention, phenolic retention, hardness and sensory acceptability is defined before the final treatment is selected.

Overall, the results demonstrate that osmotic pretreatment substantially altered the physicochemical and functional characteristics of pumpkin during conversion into a dehydrated snack. The higher yield of the osmotic treatments compared with the control indicates the contribution of solute incorporation to final product recovery. Simultaneously, the lower moisture and higher TSS demonstrate effective water removal and sucrose uptake.

The bioactive constituents showed a more complex response. Total carotenoid content was generally lower in the osmotically treated samples than in the control, indicating that the processing conditions may have imposed additional stress on carotenoid stability. During storage, the general decline in carotenoids was consistent with established evidence that pumpkin carotenoids are susceptible to oxidative and isomerization reactions. Song *et al*., (2018) specifically demonstrated the importance of temperature, storage duration and oxygen availability in determining carotenoid stability in dehydrated pumpkin.

Phenolic content similarly showed treatment-specific variation rather than a simple concentration-dependent response. This behaviour is consistent with the complex influence of dehydration on concentration, cellular accessibility and chemical stability of phenolic compounds.

The textural results further confirm that osmotic dehydration changed the structural characteristics of pumpkin. Higher hardness in several osmotic treatments can be related to reduced moisture and increased solids concentration, whereas the subsequent reduction in hardness during storage suggests structural relaxation and moisture redistribution.

Taken together, the findings demonstrate that osmotic dehydration is an effective technological intervention for modifying pumpkin tissue prior to cabinet drying. However, the process must be optimized carefully because improvement in one quality characteristic can be accompanied by changes in another. The most scientifically appropriate interpretation is therefore that osmotic concentration and treatment duration jointly influenced the quality profile of the dehydrated pumpkin snack, and that the final optimum should be identified through integrated multi-response analysis rather than by considering any single quality attribute.

The results also demonstrate the importance of storage evaluation. A treatment that performs well immediately after processing may not necessarily maintain the same quality profile during prolonged storage. Therefore, the final treatment recommendation should consider both initial product quality and its stability over the 0, 30, 60 and 90-day storage period.

## Conclusion

Osmotic dehydration was effective in modifying the mass and quality characteristics of pumpkin snack. Compared with the non-osmosed control, osmotic pretreatment produced higher yield and substantially increased TSS while reducing initial moisture. It also modified carotenoid and phenolic measurements and markedly affected hardness. During 90 days at 10°C, moisture and hardness generally declined, TSS increased and bioactive measurements generally decreased. The study demonstrates the usefulness of sucrose osmotic dehydration as a pretreatment for pumpkin snack development and provides a basis for further multi-response process optimisation.

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