

## Development of Osmotic and Osmo-dried *Asparagus racemosus* Substitute using Maltitol and Applications of Linear Programming for Product Planning

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### Abstract

This study aimed to develop osmotic and osmo-dried *Asparagus racemosus* (Shatavari) using maltitol as a sucrose substitute and to optimize production planning through linear programming (LP). Shatavari samples were subjected to osmotic dehydration using sucrose or maltitol solutions at varying concentrations, followed by drying to produce osmo-dried products. Physicochemical properties, water activity, and sensory characteristics were evaluated to determine product quality and consumer acceptance. Results showed that substitution with maltitol yielded products with desirable sensory attributes comparable to those obtained with sucrose, particularly in osmo-dried samples, which demonstrated higher scores for color, texture, and overall acceptability, with overall liking scores ranging from 5.4 to 6.3 on a 7-point hedonic scale, indicating moderate to high consumer acceptance. The osmo-dried product exhibited lower water activity ( $0.65 \pm 0.021$ ), which may contribute to improved microbial stability by inhibiting the growth of most bacteria and yeasts, although some molds may still grow under favorable conditions. Production optimization using the LP graphical method indicated that the maximum profit 385.35 THB could be achieved by producing 1.08 kg of osmo-dried Shatavari. A mixed production of 1.01 kg osmotic and 0.20 kg osmo-dried Shatavari yielded a profit of 293.23 THB. The integration of osmotic dehydration technology with sugar alcohol substitution and mathematical optimization demonstrates a promising approach for developing value-added, health-oriented products. These findings highlight the potential of *Asparagus racemosus* as a functional ingredient and underscore the relevance of LP modeling for small-scale food production and resource-efficient process design.

**Keywords:** *Asparagus racemosus*, Shatavari, Osmotic dehydration, Linear programming

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### Introduction

Linear programming (LP) is a mathematical optimization technique widely used to support decision-making in production planning and resource allocation (Dantzig, 1963). In food processing industries, LP models help determine the optimal product mix and production quantities while considering constraints such as raw material availability, processing capacity, and operational costs (Baki & Cheng, 2021; Adriantantri & Indiani, 2021). Solution methods for LP problems include the graphical method, which is suitable for models with two decision variables, and the simplex method, commonly applied to large-scale optimization problems (Palayukan, 2021). Previous studies have demonstrated the usefulness of LP in agro-food industries, such as optimizing fruit juice production and improving profitability in feed mill operations (Danfulani et al., 2022; Solaja et al., 2019). However, the application of mathematical optimization in the development and production planning of functional food products remains limited.

*Asparagus racemosus* (Shatavari) is a medicinal plant widely distributed in South and Southeast Asia, including Thailand, India, Sri Lanka, China, and Malaysia. Its roots contain various bioactive compounds such as steroidal saponins, alkaloids, and flavonoids, which are associated with several health-promoting properties (Devadasu & Martin, 2025; Kohli et al., 2023; Singh et al., 2014). Because of these functional compounds, Shatavari has been incorporated into various food systems, including fermented products and bakery applications, to enhance nutritional and functional properties (Hor et al., 2022; Singh et al., 2014). Nevertheless, the development of value-added processed Shatavari products, particularly through innovative drying technologies, remains limited.

Osmotic dehydration is a commonly used pre-drying technique that partially removes water from plant tissues by immersing food materials in hypertonic solutions. This process involves mass transfer phenomena such as water diffusion from the food matrix, solute uptake, and the leaching of soluble components (Akbarian et al., 2013). While sucrose is widely used as an osmotic agent, alternative sweeteners such as polyols have attracted increasing interest due to their lower caloric value and reduced glycemic response (Naknean et al., 2013). Among these, maltitol possesses physicochemical properties similar to sucrose, good solubility, and stability during processing, making it a promising sugar substitute for reduced-sugar food products (Cichowska et al., 2018). The quality of osmotically treated and dried Shatavari products is influenced by several processing factors, including the concentration of the osmotic solution, immersion time, and drying conditions. These parameters affect mass transfer phenomena such as water loss and solute gain, which in turn influence the texture, flavor, and overall acceptability of the final product. In addition, drying temperature and duration play important roles in determining moisture content and water activity, both of which are critical for product stability and shelf life. Structural changes in plant tissues during osmotic dehydration and drying, such as cell shrinkage and modification of the cellular matrix, further contribute to variations in texture and quality attributes. Therefore, careful control of these processing factors is essential to obtain high-quality dried products.

Despite the growing interest in functional plant-based foods, research on osmotic or osmo-dried Shatavari products remains limited, particularly when using alternative osmotic agents such as maltitol. Moreover, studies that integrate food product development with mathematical optimization for production planning are rarely reported. Therefore, the main research question of this study is whether maltitol can be effectively used as a sucrose substitute in osmotic and osmo-dried Shatavari while maintaining product quality and improving economic feasibility. Accordingly, this study aims to develop osmotic and osmo-dried Shatavari using maltitol as a sugar substitute and to apply linear programming to determine the optimal production strategy for maximizing profitability in small-scale food processing. The strength of this work lies in the integration of food processing and economic modeling, providing both scientific and practical insights for value-added product development.

## Materials and methods

### 1. Raw material

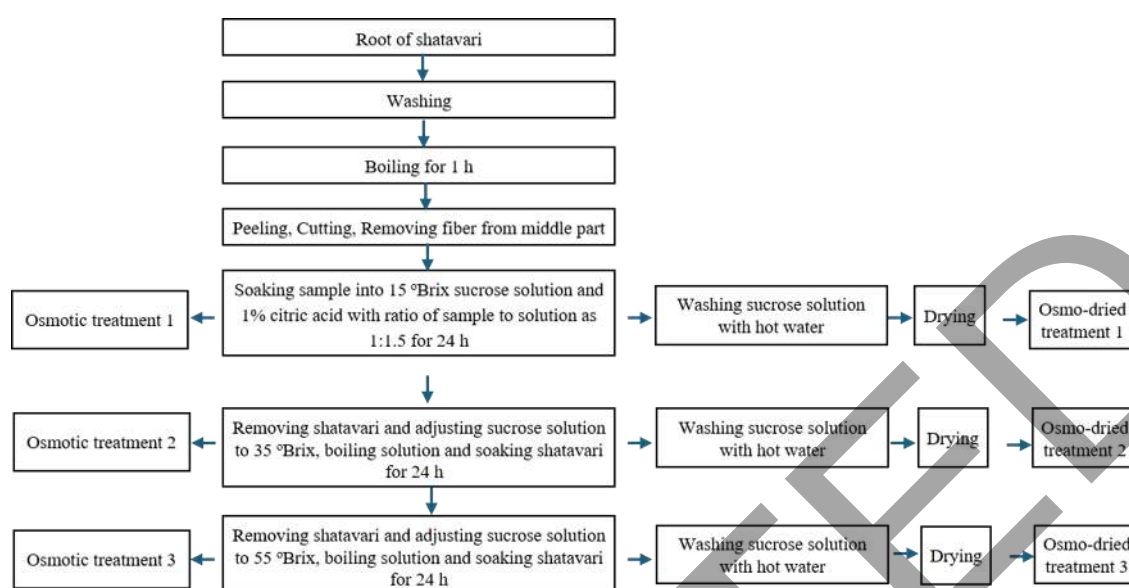
Roots of fresh Shatavari were obtained from a local vendor in Nakhon Ratchasima, Thailand, via an online marketplace. The roots were selected based on their freshness, appropriate maturity, and absence of defects. Selected Shatavari roots had a diameter of 0.8–1.2 cm and a length of 6–8 cm. The fresh roots were processed within 24 h after receipt to ensure quality and minimize deterioration. They were washed, boiled for 1 h, allowed to cool, peeled, cut into 1.5 cm pieces, and the hard fiber in the center was removed.

### 2. Osmotic and osmo-dried Shatavari with sucrose solution

A completely randomized design (CRD) was used for the experimental design, consisting of 3 treatments with different sucrose solution concentrations of 15, 35, and 55°Brix that also contained 1% citric acid. These concentrations were selected to represent low, medium, and high osmotic pressures commonly used in osmotic dehydration processes. The differences in sucrose concentration provide sufficiently distinct osmotic gradients to evaluate their effects on mass transfer, moisture reduction, and sensory properties of the final product (Shi & Le Marguer, 2002). The osmotic dehydration and osmo-drying processes are illustrated in Fig. 1. For osmo-dried Shatavari production, after osmotic soaking for 24 h, the samples were dried in a hot-air dryer at 60°C for 2–3 h until the water activity was below 0.75.

The optimal treatment was selected based on the highest sensory acceptance scores (greater than 5 on a 7-point hedonic scale) and acceptable physical characteristics. The final product was characterized as an osmotic and osmo-dried Shatavari product with water activity below 0.75, which is suitable for shelf-stable intermediate-moisture food products.

When sensory attributes were not significantly different among treatments ( $p > 0.05$ ), researchers selected the treatment with the lower sucrose concentration as the optimal formulation, after considering cost-effectiveness.



**Fig. 1** The process of osmotic and osmo-dried Shatavari

### 3. Product development of osmotic and osmo-dried with maltitol substitution

The acceptable treatment from the previous experiment, which received a sensory score greater than 5 on a 7-point hedonic scale, was selected for further development by replacing sucrose with maltitol. The amount of maltitol used was calculated based on its sweetness, equivalent to 0.9 times the sweetness of sucrose. The production processes were the same as those used in the sucrose treatment.

The osmotic and osmo-dried products with maltitol substitution were further analyzed for physical quality, including water activity (AW2101, Rotronic, Switzerland) and color (CR-10, Minolta, Japan). Color measurements were performed using a standard illuminant D65 and a 10° observer, and the results were expressed as lightness ( $L^*$ ), redness ( $a^*$ ), and yellowness ( $b^*$ ).

Water activity and color were selected as important physical quality indicators because they are closely related to product stability and consumer perception. Water activity is a critical parameter for determining the microbial stability and shelf life of intermediate-moisture foods, as lower  $a_w$  values inhibit microbial growth and improve product stability (Fellows, 2017; Barbosa-Cánovas et al., 2007). In addition, color is one of the most important visual attributes influencing consumer acceptance, since it directly affects the initial perception of food quality. Osmotic dehydration and drying may cause color changes due to pigment degradation, concentration effects, or non-enzymatic browning reactions. Therefore, measuring  $a_w$  and color helps explain the relationship between processing conditions and sensory perception of the final product (Barbosa-Cánovas et al., 2007; Pathare et al., 2013).

### 4. Sensory evaluation

Sensory evaluation was conducted using untrained panelists recruited from lecturers, students, and staff of Payap University, Mae Khao Campus, Chiang Mai, Thailand, aged 20–59 years. For product development experiments, 50 panelists participated in the sensory evaluation using a randomized complete block design (RCBD), in which panelists served as blocks.

Three pieces of each treatment were served in small plastic cups with lids to prevent aroma loss and contamination. Each sample was labeled with a random three-digit code, and the presentation order was randomized for each panelist to minimize bias. The evaluation was conducted individually at room temperature in a quiet environment with adequate lighting. Drinking water was provided for palate cleansing between samples.

Panelists evaluated the samples using a 7-point hedonic scale (1=strongly disliked, 2=moderately disliked, 3=slightly disliked, 4=neither like nor dislike, 5=slightly liked, 6=moderately liked, and 7=strongly liked) for appearance, aroma, taste, texture, and overall acceptability.

For the final product acceptance test, 100 consumers aged 20–59 years from Chiang Mai Province, Thailand, participated in the sensory evaluation. Participants were required to be general consumers within the specified age range, able to read and communicate in Thai, and to lack a history of allergy to Shatavari. The study protocol was approved by the Human Research Ethics Committee of Payap University (Approval No. PYU\_REC 064/43).

## 5. Statistical analysis

A completely randomized design (CRD) was used for the osmotic and osmo-dried Shatavari treated with sucrose solution. All experiments were conducted in triplicate, and results were expressed as mean±standard deviation. Sensory evaluation was conducted using a randomized complete block design (RCBD), in which 50 untrained panelists served as blocks. The sensory scores were expressed as mean±standard deviation; the data were analyzed using analysis of variance (ANOVA). Mean comparisons were performed using the Least Significant Difference (LSD) test at a significance level of 0.05. The best osmotic and osmo-dried Shatavari treatments were chosen to be confirmed by physical properties and sensory evaluation with 50 untrained panelists.

Statistical analysis for both physical properties and sensory evaluation parameters was performed using an independent two-sample *t*-test to evaluate the significant differences between the osmotic Shatavari (formulated at 35% sucrose sweetness equivalent) and the osmo-dried Shatavari (formulated at 55% sucrose sweetness equivalent). Statistical significance was determined at a level of  $p \leq 0.05$ .

## 6. Analysis of maximum profit using linear programming

Maximum profit was analyzed using linear programming, a procedure consisting of 3 main steps. First, information required for calculating the maximum return was collected, such as the costs of raw materials (Shatavari, maltitol, citric acid, and water); energy costs (cooking gas and electricity); labor costs (wages); production overhead expenses; and the selling price and required profit margin. Second, the production cost per unit of osmotic and osmo-dried Shatavari products was calculated. Finally, a linear programming model was developed to determine the optimal production plan that maximizes profit.

A linear programming model for a maximization objective function is expressed mathematically as follows:

$$\text{Maximize } Z = C_1X_1 + C_2X_2 + C_3X_3 + \dots + C_nX_n \quad (1)$$

Subject to

$$a_{11}X_1 + a_{12}X_2 + \dots + a_{1n}X_n \leq b_1 \quad (2)$$

$$a_{21}X_1 + a_{22}X_2 + \dots + a_{2n}X_n \leq b_2 \quad (3)$$

$$a_{m1}X_1 + a_{m2}X_2 + \dots + a_{mn}X_n \leq b_m \quad (4)$$

$$X_1 \geq 0, X_2 \geq 0; \dots, X_n \geq 0 \quad (5)$$

Let  $X_1$  represent the production quantity of osmotic Shatavari (kg) and  $X_2$  represent the production quantity of osmo-dried Shatavari (kg).

Where  $a_{ij}$  represents the input–output coefficients,  $b_1, b_2, \dots, b_m$  represent the available limited resources; and  $Z$  represents the objective function indicating the total profit to be maximized.  $C_i$  represents the unit profit coefficient associated with each product.

## 7. Solving the mathematical model of the linear programming problem

The linear programming model was solved using PHPSimplex (version 0.81, S.M. Mármol and J.M. Romero, Spain), a free web-based linear programming solver developed by Daniel Izquierdo Granja and Juan José Ruiz Ruiz, available at <http://www.phpsimplex.com>. The model was constructed based on the following assumptions and constraints.

### 7.1 The objective function

This function aims to maximize the profit obtained from the sales volume of osmotic Shatavari and osmo-dried Shatavari products. Profit was determined by considering raw material costs, energy costs, labor costs, and production overhead expenses. The selling prices of the products were set to ensure a required profit margin of at least 30% of the production cost/kg.

### 7.2 Raw material cost constraint

The total cost of raw materials used in the production process was limited to no more than 250 THB/kg. This constraint was established based on a market survey indicating that the selling prices of osmotic and osmo-dried fruits and vegetables were approximately 200 THB/kg and 250 THB/kg, respectively. Therefore, the raw material cost for producing osmotic and osmo-dried Shatavari products should not exceed the typical market price levels.

### 7.3 Energy cost constraint

The total energy cost associated with the production process was limited to no more than 125 THB. This constraint was established based on the electricity tariff structure announced by the Provincial Electricity Authority, which applies to small-scale enterprises consuming electricity

at a voltage level lower than 22 kV. The energy cost included expenses related to liquefied petroleum gas (LPG), electricity consumption of the hot-air dryer, and electricity used for refrigeration during product storage. Based on the production cost analysis, energy costs represented the second-largest cost component after raw materials. Therefore, to maintain economic feasibility and cost efficiency, the energy cost was limited to half of the raw material cost.

#### 7.4 Labor cost constraint

The total labor cost was limited to no more than 127 THB. This constraint was based on the minimum daily wage in Chiang Mai Province, Thailand, which is 340 THB/day. The production processes of osmotic and osmo-dried Shatavari from 1 kg of raw material were assumed to require no more than 3 h of labor.

#### 7.5 Production overhead constraint

The production overhead cost, including indirect materials, indirect labor, depreciation of tools and equipment, water consumption for washing raw materials and utensils, and electricity for lighting, was limited to 30% of the raw material cost. Since the raw material cost was limited to 250 THB, the maximum allowable production overhead cost was set at 75 THB.

#### 7.6 Non-negativity constraint

The production quantities of osmotic Shatavari and osmo-dried Shatavari must be non-negative, ensuring that no negative production levels occur in the model.

Before constructing the constraint equations, the input–output coefficients ( $a_{ij}$ ) were determined based on the estimated resource consumption per unit of product. These coefficients represent the amount of resources required for producing one unit of osmotic Shatavari ( $x_1$ ) and osmo-dried Shatavari ( $x_2$ ) including raw materials, energy, labor, and production overhead. These values were calculated from the production process analysis and cost estimation conducted in this study. The coefficients were then used to formulate the constraint equations representing the limitations of available resources in the production system.

$$a_{11}x_1 + a_{12}x_2 \leq 250 \quad (2)$$

$$a_{21}x_1 + a_{22}x_2 \leq 125 \quad (3)$$

$$a_{31}x_1 + a_{32}x_2 \leq 127 \quad (4)$$

$$a_{41}x_1 + a_{42}x_2 \leq 75 \quad (5)$$

$$x_1 \geq 0, x_2 \geq 0 \quad (6)$$

## Results and Discussion

### 1. Production of osmotic and osmo-dried Shatavari using sucrose solution as an osmotic agent

Sensory evaluation using a 7-point hedonic scale of osmotic and osmo-dried Shatavari at different sucrose concentrations (15, 35, and 55%) is presented in Table 1 and Table 2 respectively. The data were analyzed using one-way analysis of variance (ANOVA), and mean comparisons were performed using LSD at a significance level of  $p \leq 0.05$ . The results indicated that increasing sucrose concentration influenced the sensory characteristics of Shatavari. Samples treated with higher sucrose concentrations generally showed improved sweetness, texture, and overall acceptability. This effect may be attributed to the osmotic dehydration mechanism, in which water diffuses from plant tissues into the hypertonic solution while solutes simultaneously diffuse into the tissue, resulting in structural modification and flavor enhancement. Increased osmotic solution concentration has been reported to promote water loss and enhance dehydration efficiency due to the greater osmotic pressure gradient between the plant tissue and the surrounding solution (Garcia-Noguera et al., 2010a).

For osmotic Shatavari (Table 1), no significant difference in appearance was observed among the samples. Panelists also showed no significant difference in preference between the samples treated with 35 and 55% sucrose solutions. Therefore, the treatment using a 35% sucrose solution was selected for further production of osmotic Shatavari using maltitol as the osmotic agent, primarily due to its lower cost and comparable sensory acceptance.

**Table 1** Sensory evaluation of osmotic Shatavari at different sucrose concentrations

| Attribute                | Osmotic Shatavari (% sucrose) |                       |                      |
|--------------------------|-------------------------------|-----------------------|----------------------|
|                          | 15                            | 35                    | 55                   |
| Appearance <sup>ns</sup> | 5.5±1.3                       | 5.7±1.1               | 5.9±1.1              |
| Color                    | 5.5±1.2 <sup>b</sup>          | 5.8±1.0 <sup>ab</sup> | 6.0±1.0 <sup>a</sup> |
| Texture (firmness)       | 5.1±1.5 <sup>b</sup>          | 5.8±1.1 <sup>a</sup>  | 6.1±1.0 <sup>a</sup> |
| Odor                     | 4.5±1.6 <sup>b</sup>          | 5.5±1.0 <sup>a</sup>  | 5.9±1.1 <sup>a</sup> |
| Flavor                   | 4.1±1.7 <sup>b</sup>          | 5.6±1.1 <sup>a</sup>  | 5.9±1.2 <sup>a</sup> |
| Taste                    | 3.8±1.7 <sup>b</sup>          | 5.6±1.1 <sup>a</sup>  | 5.8±1.1 <sup>a</sup> |
| Overall liking           | 4.3±1.7 <sup>b</sup>          | 5.8±1.0 <sup>a</sup>  | 6.0±1.0 <sup>a</sup> |

**Remark:** Values represent mean preference scores±standard deviation. Means with different superscript letters within the same row are significantly different ( $p \leq 0.05$ ) based on One-way ANOVA and LSD test. ns=non-significant.

For osmo-dried Shatavari (Table 2), the sample treated with 55% sucrose solution received the highest scores for color, texture (firmness), aroma, flavor, taste, and overall liking. Notably, most of these attributes were significantly higher than those treated with 15 and 35% sucrose solutions. The improved sensory quality of the osmo-dried samples may be associated with structural changes occurring during osmotic treatment and subsequent drying. During osmotic dehydration, solute uptake and moisture removal alter the physical and chemical structure of plant tissues, where water is bound within the solid matrix through capillary forces and physicochemical interactions. These changes influence mass transfer behavior and affect the quality characteristics of the dried product (Azoubel et al., 2009). Such structural modifications may contribute to improved texture and flavor concentration in the final osmo-dried product. Based on these results, the 55% sucrose treatment was selected for the subsequent production of osmo-dried Shatavari using maltitol as the osmotic agent.

**Table 2** Sensory evaluation of Osmo-dried Shatavari at different sucrose concentrations

| Attribute                | Osmotic Shatavari (% sucrose) |                      |                      |
|--------------------------|-------------------------------|----------------------|----------------------|
|                          | 15                            | 35                   | 55                   |
| Appearance <sup>ns</sup> | 3.7±1.6                       | 5.0±1.2              | 5.3±1.4              |
| Color                    | 4.1±1.5 <sup>b</sup>          | 5.2±1.2 <sup>a</sup> | 5.3±1.3 <sup>a</sup> |
| Texture (firmness)       | 4.0±1.7 <sup>c</sup>          | 5.5±1.1 <sup>b</sup> | 5.9±1.0 <sup>a</sup> |
| Odor                     | 4.1±1.6 <sup>c</sup>          | 5.2±1.1 <sup>b</sup> | 5.6±1.2 <sup>a</sup> |
| Flavor                   | 4.0±1.5 <sup>c</sup>          | 5.3±1.0 <sup>a</sup> | 5.6±1.0 <sup>a</sup> |
| Taste                    | 4.0±1.6 <sup>c</sup>          | 5.1±1.2 <sup>b</sup> | 5.8±0.9 <sup>a</sup> |
| Overall liking           | 4.0±1.5 <sup>c</sup>          | 5.4±1.0 <sup>b</sup> | 5.9±1.0 <sup>a</sup> |

**Remark:** Values represent mean preference scores±standard deviation. Means with different superscript letters within the same row are significantly different ( $p \leq 0.05$ ) based on One-way ANOVA and LSD test. ns=non-significant.

## 2. Production of osmotic and osmo-dried Shatavari using maltitol as a sugar substitute

The sensory evaluation of both osmotic and osmo-dried Shatavari, prepared using maltitol (equivalent to approximately 90% of sucrose sweetness), is presented in Table 3. Overall, the osmo-dried products received higher scores for texture and overall acceptability, likely due to the further moisture reduction during the drying stage, resulting in a firmer and more desirable texture.

For osmotic Shatavari, 7-point hedonic scores for appearance, color, texture, and odor ranged from 5.1 to 6.0, corresponding to levels between “slightly like” to “moderately like”. In contrast, scores for flavor, taste, and overall liking were lower, ranging from 4.6 to 4.8, falling between “neither like nor dislike” and “slightly like”. This lower preference may be attributed to the mild aroma of the osmotic samples, which some panelists found difficult to detect, subsequently affecting evaluation of these attributes.

Osmo-dried Shatavari showed improved scores across all attributes. Appearance, color, odor, flavor, and taste received scores between 5.3 and 5.9, while texture and overall liking ranged from 5.4 to 6.3, indicating moderate to high consumer acceptance (ranging from “like” to “like very much”). The enhanced texture preference is likely due to the drying process, which created a firmer and more appealing mouthfeel.

The relatively large standard deviations observed in flavor and taste ( $SD=1.5-1.7$ ) suggest high variability in panelist preferences. Some participants noted a slight bitterness, which was acceptable to some but disliked by others. According to Singla and Jaitak (2014), Shatavari roots contain volatile compounds such as 4,6-dihydroxy-2-O-(2-hydroxyisobutyl), benzaldehyde, and undecanyl cetanoate, which contribute to an initial starchy flavor, followed by slight bitterness and a sweet aftertaste. These inherent sensory characteristics likely explain the mixed responses. Furthermore, the use of maltitol as an osmotic solute has been reported to minimize browning and enhance texture, consistent with findings in osmo-dried cantaloupe (Naknean et al., 2013).

**Table 3** Sensory evaluation of osmotic and osmo-dried Shatavari using maltitol as a sugar substitute

| Attribute                | Osmotic Shatavari<br>(Equivalent to 35% sucrose<br>sweetness) | Osmo-dried Shatavari<br>(Equivalent to 55% sucrose<br>sweetness) |
|--------------------------|---------------------------------------------------------------|------------------------------------------------------------------|
| Appearance <sup>ns</sup> | 5.8±0.8                                                       | 5.7±1.1                                                          |
| Color <sup>ns</sup>      | 6.0±0.9                                                       | 5.9±0.9                                                          |
| Texture (firmness)       | 5.6±1.2 <sup>b</sup>                                          | 6.3±0.7 <sup>a</sup>                                             |
| Odor                     | 5.1±1.2 <sup>b</sup>                                          | 5.7±1.1 <sup>a</sup>                                             |
| Flavor                   | 4.7±1.5 <sup>b</sup>                                          | 5.7±1.1 <sup>a</sup>                                             |
| Taste                    | 4.6±1.7 <sup>b</sup>                                          | 5.3±1.5 <sup>a</sup>                                             |
| Overall liking           | 4.8±1.6 <sup>b</sup>                                          | 5.4±1.3 <sup>a</sup>                                             |

**Remark:** Values represent mean preference scores±standard deviation. Means with different superscript letters within the same row are significantly different ( $p\leq 0.05$ ) based on an independent two-sample t-test. ns=non-significant.

Osmo-dried Shatavari formulated with maltitol received higher sensory scores compared to the osmotic product, particularly in terms of texture, flavor, and overall acceptability. This preference is directly governed by the mass transfer phenomena occurring during osmotic dehydration followed by convective hot-air drying. During the osmotic stage, water diffuses out of the plant tissue while maltitol solutes concurrently penetrate the cellular matrix, which alters the original composition and modifies the internal tissue structure (Ahmed et al., 2016; González-Pérez et al., 2021; Yadav & Singh, 2014). This simultaneous water loss and solute gain contribute to enhanced flavor and nutritional retention (Chiralt & Fito, 2003). Subsequent hot-air drying further eliminates moisture and concentrates the soluble compounds within the Shatavari matrix, resulting in a firmer, more desirable texture and enhanced organoleptic perception. Therefore, the combination of osmotic treatment and hot-air drying provides a final product with superior consumer acceptance compared to osmotic treatment alone.

Based on the physical properties presented in Table 4, the osmo-dried Shatavari product (formulated with a maltitol concentration equivalent to 55% sucrose sweetness) exhibited a significantly lower water activity ( $a_w$ ) of  $0.65\pm 0.021$  compared to the osmotic Shatavari product (formulated with a maltitol concentration equivalent to 35% sucrose sweetness), which had an  $a_w$  of  $0.890\pm 0.005$  ( $p\leq 0.05$ ). This substantial difference is attributed to two combined factors: first the higher initial solute concentration (55% sweetness equivalent) which drives greater osmotic dehydration, and second the subsequent hot-air drying stage that actively eliminates the remaining free water from the plant tissue while concentrating the dissolved solids.

Despite these favorable sensory attributes, the water activity ( $a_w$ ) of both osmotic and osmo-dried Shatavari samples presented a critical concern for product safety, as they exceeded the allowable limits specified by the Thai Community Product Standard for candied products (TCPS No. 161/2558). The osmotic product exhibited an  $a_w$  of  $0.890\pm 0.005$ , which is higher than the TCPS maximum limit of 0.85. Such an elevated moisture state generally increases the risk of microbial growth and reduces shelf stability during ambient storage (Beuchat, 1981). Furthermore, modern microbiological insights emphasize that even when high solute concentrations inhibit active bacterial multiplication, various foodborne pathogens can still successfully persist and survive for extended periods within such intermediate-moisture matrices if the water activity is not strictly minimized (Beuchat et al., 2013).

On the other hand, the osmo-dried Shatavari showed a lower  $a_w$  value of  $0.65\pm 0.021$ , indicating vastly improved microbiological stability compared to the osmotic product, since water activity strongly dictates microbial proliferation (Labuza, 1984). However, this value still slightly exceeds the strict TCPS threshold of 0.60 designated for dried candied fruits and vegetables. Therefore, further optimization remains

mandatory to ensure absolute compliance with the national standard. Potential interventions include extending the hot-air drying duration, employing alternative techniques such as vacuum drying, or modifying the formulation parameters. For the osmotic product that maintains a relatively high  $a_w$ , strict refrigerated storage must be implemented to retard microbial growth and preserve quality over time.

**Table 4** Physical properties of osmotic and osmo-dried Shatavari using maltitol as a sugar substitute

| Physical properties               | Osmotic Shatavari<br>(Equivalent to 35% sucrose<br>sweetness) | Osmo-dried Shatavari<br>(Equivalent to 55% sucrose<br>sweetness) |
|-----------------------------------|---------------------------------------------------------------|------------------------------------------------------------------|
| Water activity ( $a_w$ )          | 0.890±0.005 <sup>a</sup>                                      | 0.65±0.021 <sup>b</sup>                                          |
| <b>Color</b>                      |                                                               |                                                                  |
| Lightness ( $L^*$ ) <sup>ns</sup> | 38.33±1.12                                                    | 39.33±0.42                                                       |
| Redness ( $a^*$ )                 | 2.83±0.15 <sup>b</sup>                                        | 3.10±0.17 <sup>a</sup>                                           |
| Yellowness ( $b^*$ )              | 3.73±0.46 <sup>b</sup>                                        | 5.27±0.45 <sup>a</sup>                                           |

**Remark:** Values represent mean±standard deviation. Means with different superscript letters within the same row are significantly different ( $p \leq 0.05$ ) based on an independent two-sample *t*-test. ns=non-significant.

Regarding the color profile presented in Table 4, the lightness ( $L^*$ ) of Shatavari samples did not change significantly between the osmotic stage (38.33±1.12) and the osmo-dried stage (39.33±0.42). This stability in lightness indicates that the combinations of maltitol and acid solution effectively preserved the product's original brightness. Since maltitol is a sugar alcohol without a reducing group (non-reducing sugar), it does not participate in the non-enzymatic Maillard browning reaction during thermal processing (Grembecka, 2015). Concurrently, the added acid lowers the pH of the plant tissue, which successfully deactivates polyphenol oxidase (PPO), thereby completely blocking enzymatic browning during hot air exposure (Rastogi et al., 2002).

The redness ( $a^*$ ) increased significantly ( $p \leq 0.05$ ) from 2.83±0.15 in osmotic Shatavari to 3.10±0.17 in the osmo-dried product. This slight shift toward the red-brown spectrum is typically governed by the thermal degradation of heat-sensitive flavonoids and phenolic compounds during prolonged exposure to drying temperatures (Thiangma et al., 2022).

The yellowness ( $b^*$ ) value exhibited a substantial and significant increase ( $p \leq 0.05$ ) from 3.73±0.46 to 5.27±0.45 after convective drying. Although maltitol and acid treatment successfully prevented browning, as evidenced by the stable lightness value, the intensification of yellowness is primarily attributed to the concentration effect. The substantial evaporation of water during drying concentrates the naturally occurring yellow flavonoids within the Shatavari root matrix. Furthermore, thermal processing can induce minor structural modifications or isomerization of these heat-sensitive pigments, further shifting the final color profile toward a distinct yellow-amber hue (Garcia-Noguera et al., 2010b).

The osmo-dried processing approach shows considerable potential for the development of value-added fruit and vegetable products. Similar techniques have been successfully applied to various fruits, including banana, jackfruit, guava, mango, and pineapple, where osmotic pretreatment combined with drying improves product quality and stability (Rahman, 2007). In addition, studies on specific fruits such as kiwi have also demonstrated the effectiveness of osmotic dehydration in modifying product characteristics (Brochier et al., 2019).

### 3. Application of linear programming for production planning of osmotic and osmo-dried Shatavari

The data used for the production planning model were collected on January 3, 2023. The cost components associated with the production of osmotic and osmo-dried Shatavari were calculated based on the quantities of raw materials, energy consumption, labor requirements, and manufacturing overheads. Due to the relatively high-water activity of the osmotic Shatavari product, refrigerated storage was applied to maintain product quality and reduce the risk of microbial spoilage during the storage period. This condition reflects practical handling in real production systems. The associated energy consumption from refrigerated storage was therefore, included in the cost calculation and incorporated into the linear programming model. The detailed cost structure and unit prices used for the linear programming model are summarized in Table 5. In this table, the production cost of osmotic Shatavari using maltitol (sweetness equivalent to 35% sugar) was compared with that of osmo-dried Shatavari using maltitol (sweetness equivalent to 55% sugar). These cost data were subsequently used to formulate the objective function and constraints in order to determine the optimal production quantities that maximize profit under the given resource limitations.

**Table 5** Relevant data for cost calculation

| Cost items                                          | Unit price     | Osmotic Shatavari using maltitol (Sweetness equivalent to using 35% sugar) |        | Osmo-dried Shatavari using maltitol (Sweetness equivalent to using 55% sugar) |          | Constrains |
|-----------------------------------------------------|----------------|----------------------------------------------------------------------------|--------|-------------------------------------------------------------------------------|----------|------------|
|                                                     |                | Quantity                                                                   | Cost   | Quantity                                                                      | Cost     |            |
| Raw materials                                       |                |                                                                            |        |                                                                               |          |            |
| Shatavari                                           | 150 THB/kg     | 1.00 kg                                                                    | 150.00 | 1.00 kg                                                                       | 150.00   |            |
| Maltitol                                            | 130 THB/kg     | 0.39 kg                                                                    | 0.70   | 0.61 kg                                                                       | 79.30    |            |
| Citric acid                                         | 125 THB/kg     | 0.01 kg                                                                    | 1.25   | 0.01 kg                                                                       | 1.25     |            |
| Water                                               | 0.5 THB/kg     | 0.65 kg                                                                    | 0.33   | 0.45 kg                                                                       | 0.23     |            |
| Total raw materials cost                            |                |                                                                            | 202.28 |                                                                               | 230.78   | 250        |
| Energy                                              |                |                                                                            |        |                                                                               |          |            |
| LPG (Cooking gas)                                   | 4.10 THB/h     | 1.5 h                                                                      | 6.15   | 2 h                                                                           | 8.20     |            |
| Hot air oven (6 kW)                                 | 26.53 THB/h    | 0 h                                                                        | 0.00   | 2 h                                                                           | 53.06    |            |
| Refrigerator storage                                | 7.56 THB/day   | 14 days                                                                    | 105.84 | 0 h                                                                           | 0.00     |            |
| Total energy cost                                   |                |                                                                            | 111.99 |                                                                               | 61.26    | 125        |
| Labor cost                                          | 340.00 THB/day | 1.5 h                                                                      | 63.75  | 2 h                                                                           | 85.00    | 127        |
| Manufacturing overheads (30% of raw materials cost) |                |                                                                            | 60.68  |                                                                               | 69.23    | 70         |
| Total production cost/amount of product             |                | 0.72 kg                                                                    | 417.45 | 0.39 kg                                                                       | 446.27   |            |
| Product cost/kg                                     |                | 1 kg                                                                       | 579.79 | 1 kg                                                                          | 1,144.28 |            |
| Selling price/kg                                    |                | 1 kg                                                                       | 800.00 | 1 kg                                                                          | 1,500.00 |            |
| Profit/kg                                           |                | 1 kg                                                                       | 220.21 | 1 kg                                                                          | 355.72   |            |

Based on the cost data presented in Table 5, the unit profit obtained from osmotic Shatavari and osmo-dried Shatavari was calculated as 220.21 THB/kg and 355.72 THB/kg, respectively. Consequently, a linear programming model was formulated to identify the optimal product mix of osmotic Shatavari ( $x_1$ ) and osmo-dried Shatavari ( $x_2$ ) that maximizes the overall net profit.

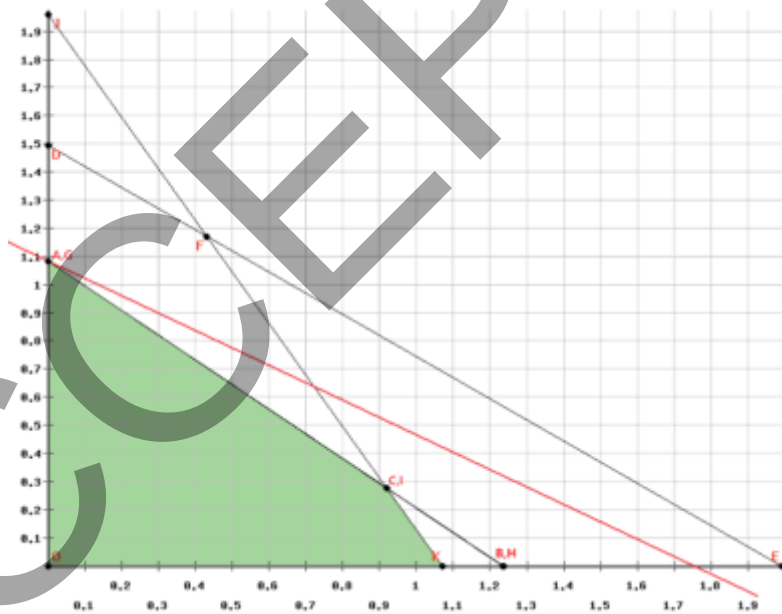
The objective function of the model is expressed as:

$$\text{Maximize } Z = 220.21x_1 + 355.72x_2$$

Subject to the following constraints:

|                                |                                  |
|--------------------------------|----------------------------------|
| Raw material cost constraint:  | $202.28x_1 + 230.78x_2 \leq 250$ |
| Energy cost constraint:        | $111.99x_1 + 61.26x_2 \leq 125$  |
| Labor cost constraint:         | $63.75x_1 + 85.00x_2 \leq 127$   |
| Production expense constraint: | $60.68x_1 + 69.23x_2 \leq 75$    |
| Non-negativity constraints:    | $x_1 \geq 0, x_2 \geq 0$         |

The formulated linear programming problem was solved using the graphical method facilitated by the PHPSimplex online optimization tool, which allows for the precise visualization of the feasible region and identification of the optimal corner points. The graphical representation of the feasible region and the constraint lines is illustrated in Fig. 2. According to linear programming theory, the optimal solution always occurs at one of the vertices or corner points of the feasible region formed by the intersection of these constraint boundaries.



**Fig. 2** Feasible region and optimal solution of the linear programming model for production planning of osmotic and osmo-dried Shatavari

Graphical analysis of Fig. 2 revealed that only three intersection points—A (or G), C (or I), and K—reside within the boundaries of the feasible region. Evaluating the objective function at these specific vertices indicated that Point A (or G) yielded the maximum profit of 385.35 THB, followed by Point C (or I) with 293.23 THB, while Point K provided the lowest feasible return of 245.79 THB. Therefore, the optimal production strategy to achieve peak profitability dictates manufacturing 0 kg of osmotic Shatavari and 1.08 kg of osmo-dried Shatavari, generating a maximum profit of 385.35 THB. However, if the broader business strategy mandates a multi-product portfolio to satisfy diverse market demands, an alternative product combination at Point C (or I) consisting of 1.01 kg of osmotic Shatavari and 0.20 kg of osmo-dried Shatavari could be adopted, delivering a compromised yet sustainable profit of 293.23 THB.

**Table 6** Feasible points and profit values in the linear programming model

| Point | Quantity of osmotic Shatavari<br>(X coordinate, X1) | Quantity of osmo-dried Shatavari<br>(Y coordinate, X2) | Objective function result<br>(Profit in THB) |
|-------|-----------------------------------------------------|--------------------------------------------------------|----------------------------------------------|
| O     | 0                                                   | 0                                                      | 0                                            |
| A     | 0.00                                                | 1.08                                                   | 385.35                                       |
| B     | 1.24                                                | 0.00                                                   | 272.16                                       |
| C     | 1.01                                                | 0.20                                                   | 293.23                                       |
| D     | 0.00                                                | 1.49                                                   | 531.49                                       |
| E     | 1.99                                                | 0.00                                                   | 438.69                                       |
| F     | 0.51                                                | 1.11                                                   | 507.88                                       |
| G     | 0.00                                                | 1.08                                                   | 385.37                                       |
| H     | 1.24                                                | 0.00                                                   | 272.18                                       |
| I     | 1.01                                                | 0.20                                                   | 293.26                                       |
| J     | 0.00                                                | 2.04                                                   | 725.84                                       |
| K     | 1.12                                                | 0.00                                                   | 245.79                                       |

Table 6 summarizes the feasible solutions obtained from the linear programming model and their corresponding profit values. These results highlight the trade-off between product combinations and resource constraints in determining the optimal production strategy. Among these solutions, Points A (or G), C (or I), and K satisfy all constraints and therefore represent feasible production options. The results confirm that Point A (or G) provides the optimal solution under the defined resource limitations, indicating that the production of osmo-dried Shatavari yields the highest economic return under the given conditions.

The application of linear programming (LP) as a practical decision-making tool to optimize product mix and resource allocation aligns with previous food and beverage manufacturing studies. For instance, an LP model was successfully utilized at the Oda Natural Spring Water Factory to identify the most profitable daily production quantities across four bottled water sizes under strict constraints of production time, budget, and market demand (Ashine & Jiru, 2026). Similarly, Oluwaseyi et al. (2020) applied this mathematical approach to optimize the daily production of various bread sizes under raw material and processing limits. Consistent with their findings, which recommended a production pivot toward the most profitable extra-large variant to maximize returns, the optimization matrix in this study highlights a strategic reallocation of resources toward the higher-margin osmo-dried Shatavari.

These findings underscore the practical significance of integrating food processing techniques with economic optimization. By coupling osmotic dehydration using maltitol as a sugar substitute with linear programming for production planning, this study provides a novel contribution to food science and engineering. While conventional research predominantly focuses on product quality attributes, this work successfully demonstrates how product development and cost-based decision-making can be simultaneously optimized to enhance commercial viability.

## Conclusion

This study successfully developed osmotic and osmo-dried *Asparagus racemosus* (Shatavari) products using maltitol as a sugar substitute, evaluating their physicochemical and sensory characteristics alongside production optimization via linear programming. The results demonstrated that osmo-dried Shatavari exhibited improved sensory quality and lower water activity, while the LP model effectively identified optimal product-mix strategies for maximizing profitability under rigid resource constraints.

Nevertheless, several limitations must be acknowledged. The experiments were conducted strictly at a laboratory scale, and the financial data were based on estimated operational values, which may vary from actual industrial conditions. Furthermore, product stability under diverse storage environments was not extensively investigated. Therefore, future research should focus on pilot-scale or large-scale validation, optimization of drying kinetics to further minimize water activity, and comprehensive shelf-life studies.

Additionally, further studies are required to investigate the retention of bioactive compounds and the medicinal properties of Shatavari after osmotic dehydration and thermal drying. Given that Shatavari is traditionally recognized for its therapeutic and functional benefits, evaluating the impact of processing parameters on its phytochemical composition would be highly valuable for the development of functional foods or nutraceutical products. Overall, the integration of food processing and economic modeling demonstrated in this work provides a useful, practical framework for the sustainable and profitable production of value-added intermediate-moisture plant products, bridging the gap between food product development and operational optimization.

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### Conflicts of interest

The authors declare no conflicts of interest.

### Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used Grammarly AI, Jenni AI, and ChatGPT for enhancing language clarity or improving grammar. The final content was reviewed and edited by the authors, who take full responsibility for the accuracy and integrity of the publication.

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