

Enhancing the physicochemical and sensory qualities of mangoes (*Mangifera indica* L.) through freeze-drying

¹Pham, B.A., ¹Tran, T.Y.N., ²Nguyen, T.X.T., ³Huynh X.P., ¹Ton, N.T.A., ⁴Vo, T.L. and ^{1,*}Vu, D.N.

¹*Institute of Applied Technology and Sustainable Development, Nguyen Tat Thanh University, Ho Chi Minh City 700000, Vietnam*

²*Center of Water Management and Climate Change, Institute for Environment and Resources, Vietnam National University - Ho Chi Minh City (VNU-HCM), Ho Chi Minh City 700000, Vietnam*

³*Institute of Food and Biotechnology, Can Tho University, Can Tho City 94000, Vietnam*

⁴*Faculty of Chemical and Food Technology, University of Technology and Education, Ho Chi Minh City 700000, Vietnam*

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Abstract

This study investigated the enhancement of the physicochemical and sensory qualities of mangoes (*Mangifera indica* L.) using controlled freeze-drying techniques. The research aimed to optimize the use of mango remnants, which are typically discarded during production, by converting them into high-quality freeze-dried products. The study assessed the impact of various processing stages-freezing, freeze-drying, and vacuum drying on product quality, focusing on key attributes such as color, texture, moisture content, and sensory properties. Results indicated that freezing mangoes at -20°C for 4 h, followed by 25 h of freeze-drying and 15 h of vacuum drying, produced the highest quality products in terms of sensory appeal and texture. The study highlighted the potential of freeze-drying as a sustainable approach to reduce waste and maximize the economic value of mango production by creating diverse, high-value products. These findings provide valuable insights for the mango processing industry to improve product quality and sustainability.

1. Introduction

Mango (*Mangifera indica* L.) is rich in essential nutrients and minerals, such as 36.4 mg of vitamin C and 1082 IU of vitamin A per 100 grams (Siddiq *et al.*, 2017). The high concentration of β -carotene and other phytochemicals in mangoes may prevent leukemia and the progression of prostate, breast, and colon cancer (Rajendran *et al.*, 2015; Baliga *et al.*, 2018; Zeng *et al.*, 2020; Lebaka *et al.*, 2021; Shang *et al.*, 2021). However, the fruit is prone to rapid spoilage, with its freshness only lasting up to 30 days at temperatures of 4-5°C. This spoilage compromises the quality of vital nutrients like vitamins and polyphenols due to degradation and oxidation (Iturralde-García *et al.*, 2022), leading to significant economic losses for producers.

To mitigate these losses and enhance the economic value of mangoes, various mango-based products, including jams, dried mango, and canned juices, have been developed (Ciurzyńska *et al.*, 2021). Freeze-drying, in particular, has shown promise in extending the shelf

life of fruits while preserving their nutritional value (Li *et al.*, 2018). However, traditional drying techniques often degrade valuable nutrients and alter the fruit's color and structure. Freeze-drying, by contrast, preserves the fruit's structural integrity and nutritional content by directly converting water from solid to gas (Ansari *et al.*, 2016).

Despite the potential of freeze-drying, its application in the mango industry remains underutilized, particularly in Vietnam, where the focus is on fresh fruit exports. Additionally, while freeze-drying has been explored in other high-value fruits like durian, limited studies have examined its application to mangoes, especially second- and third-grade mangoes that do not meet export standards. Therefore, the objective of this study is to utilize all leftover mangoes after processing and develop the freeze-drying process for mango by systematically evaluating the effects of freezing time, freeze-drying time, and subsequent vacuum-drying time on the physicochemical attributes and sensory quality of the

*Corresponding author.

Email: vdngoc@ntt.edu.vn

final product, thereby identifying the processing conditions that yield the best overall quality. The findings are expected to broaden the range of mango products and reduce the degradation of mango quality and quantity post-harvest by maximizing the use of mango flesh.

2. Materials and methods

2.1 Samples

The Tu Quy mangoes, harvested in Ben Tre, were conveyed to the Institute of Applied Technology and Sustainable Development's laboratory at Nguyen Tat Thanh University for research purposes. Classified as type II and III according to Codex Stan 184: 1993, these mangoes were chosen for study due to their inability to meet export standards or fetch competitive prices in the domestic market. The laboratory where these mangoes were analyzed is situated within the High-Tech Zone of Thu Duc City, Ho Chi Minh City.

2.2 Processing

Leftover mango flesh resulting from the slicing and processing stages was pureed and, if needed, seasoned. This mango puree was then carefully placed into crescent-shaped molds, measuring 1.2 cm in thickness, 5.5 cm in length, and 1.7 cm in width. The drying process proceeds by setting the equipment to initiate freezing, achieving a chamber temperature of -20°C . The mango puree was then frozen for a period that varies between 4, 7, and 10 h, followed by a freezing cycle that maintains temperatures below 0°C for 15 to 30 h. After freezing, the mango undergoes a vacuum drying cycle lasting between 10 to 25 h. The product was packaged for further use or analysis.

2.3 Determination of moisture content

The method involves measuring the weight of the sample before and after the drying process. The drying was conducted at a temperature of 105°C and continued until there was no further change in weight, indicating that all moisture had been removed (UN30, Memmert, Germany) (Olalusi and Erinle, 2019).

2.4 Determining the color value

The method utilizes a Colormeter measuring device to accurately assess and record color (L^* , a^* , b^*) changes (Konica Minolta Chromameter in Japan - CR400 0001).

2.5 Determining the texture

The hardness of the freeze-dried sample was determined using Texture Profile Analysis (TPA), a

method that involves a tool to measure the structural properties of food by applying mechanical compression force. TPA is particularly useful for assessing various characteristics such as hardness, elasticity, and viscosity in a single test. Principle of TPA: the process includes two main cycles - compression and decompression. During the test, the sample can be compressed up to 90% of its original size. The force applied over time, and the force relative to deformation are both recorded throughout these cycles. From the recorded force/time curve, numerous structural parameters can be derived, including breakability, hardness, chewiness, and elasticity. The hardness of the food was specifically measured during the initial compressions, or the 'first bites', and was indicated by the peak force observed in the first compression cycle.

2.6 Determining the structure by scanning electron microscopy

The scanning electron microscopy (SEM) (FE-SEM S4800 Hitachi, Japan) method uses electron beams to analyze the sample surface. Initially, the sample undergoes preparation through cutting, grinding, or other methods to ensure it has a flat and smooth surface. Once prepared, the sample was placed inside the scanning machine. In this device, electron beams are systematically moved up and down across the sample's surface. As these beams interact with the sample's atoms and molecules, they generate electronic signals. These signals are then collected and used to construct detailed images of the sample's surface, revealing its topographical and compositional characteristics.

2.7 Statistical analysis

All experiments were carried out in triplicate. The mean and standard deviation of the results were calculated using Statgraphics Centurion XV version 15.1.02 was used in this study with statistical significance ($p < 0.05$) (Vu *et al.*, 2022).

3. Results and discussion

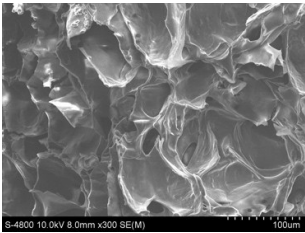
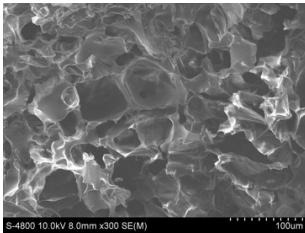
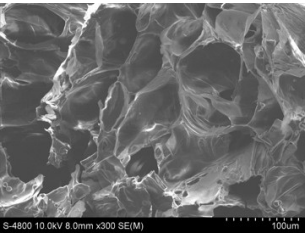
3.1 Impact of freezing time on the quality of freeze-dried mango products

Freezing has long been recognized as an effective preservation method widely used in the food technology industry. The freezing process helps inhibit the activity of microorganisms and enzymes in food, minimizing the degradation of nutritional components and extending the product's shelf life (James *et al.*, 2015; You *et al.*, 2021; Köprüalan Aydın *et al.*, 2023). Additionally, the freezing stage serves both as a means of preserving fruits and as the initial phase of freeze-drying processing. However, differences in the freezing times of mango puree

significantly affect the physicochemical and sensory quality of the product ($p<0.05$). The moisture content after freeze-drying is a crucial factor determining product quality, as it impacts the structure, sensory appeal, and storage duration of the product. ANOVA results indicate that after drying under specified conditions (*), the three products at different freezing temperatures did not show statistically significant effects on moisture content post-drying, with moisture levels ranging from 6.01 to 6.23% corresponding to freezing times of 4 - 10 h. Previous reports suggest that dehydration occurs during the freezing of fruits, leading to weight loss (Mulot *et al.*, 2019). However, drying under the conditions (*) may lead to complete dehydration in the dried material to a state of equilibrium. Therefore, no significant statistical differences were observed between the different freezing storage durations. Similarly, water activity showed no significant differences between freezing durations, ranging from 0.47 to 0.48. A positive correlation between moisture content and water activity was also noted in a report on the dehydration process in fish cakes (Vu *et al.*, 2023). Texture is considered one of the most critical criteria related to consumer acceptance and reflects the quality of freeze-dried products. Post-drying shrinkage often results in a hard structure due to the distribution of bonds and the concentration of cells, leading to significant deformation and a decline in sensory quality (Huang *et al.*, 2011). For freeze-dried mango puree, texture is an essential factor. Results show that product hardness tends to decrease from 610 to 422 g, but no significant statistical differences were found

between the freezing time levels ($p>0.05$). The highest hardness was recorded at a freezing time of 4 h, which could be explained by longer freezing times enlarging ice crystals, further hollowing the internal structure of the product (Jia *et al.*, 2022). After drying, a significant amount of water is removed from the ingredients, resulting in a structure that becomes more hollow and less hard (Duan *et al.*, 2016; Köprüalan Aydın *et al.*, 2023). Sensory perception is a crucial aspect of food, encompassing appearance and overall evaluation, including color, smell, taste, and texture. Simultaneously, color is determined based on the L^* , a^* , and b^* color system. Color is an important aspect affecting high sensory acceptance (Starowicz and Zieliński, 2019). ANOVA results show no significant differences in color L^* and a^* , meaning that the freezing times studied do not affect the brightness L^* and redness a^* . The color retention after drying is thought to be due to the inhibitory effect of freezing conditions on the browning process caused by enzyme activity (Ceballos *et al.*, 2012; Köprüalan Aydın *et al.*, 2023). However, a difference in the b^* value was observed, with the product tending to be more yellow at a freezing time of 7 h. The sensory quality among the three levels of freezing time was detailed in Table 1. Additionally, regardless of the freezing mode, the material must be completely frozen before entering the freeze-drying phase, as any surface melting during freeze-drying or any melting of the ice layer may cause product faults such as puffing up, shrinking, and a structure filled with liquid (Sadikoglu *et al.*, 2006; Fonseca *et al.*, 2008).

Table 1. Influence of pretreatment conditions on physicochemical characteristics of products.

Criteria	Time (H)		
	4	7	10
Moisture content (%)	6.11±0.11 ^a	6.23±1.01 ^a	6.01±1.11 ^a
Water activity	0.47±0.00 ^a	0.48±0.00 ^a	0.47±0.00 ^a
Hardness (g)	610±110 ^a	437±87 ^a	422±64 ^a
L*	L* = 81.26±1.12 ^a	L* = 79.86±1.02 ^a	L* = 80.86±1.12 ^a
a*	a* = 1.10±0.14 ^a	a* = 1.21±0.23 ^a	a* = 0.90±0.14 ^a
b*	b* = 30.25±0.11 ^b	b* = 32.35±0.20 ^a	b* = 30.15±0.1 ^b
SEM			
Sensory	The structure is brittle, porous, and bright yellow; the surface is heavily concave, retains the natural mango flavor	The sweetness does not change, the texture is more crispy, durable, with a slightly concave face, retaining the natural mango flavor.	The sweetness does not change, the texture is much crisper, and the surface is less concave, retaining the natural mango flavor.

Processing conditions: Vacuum drying for 25 h, freeze-drying for 25 h.

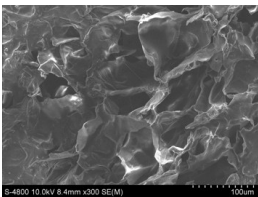
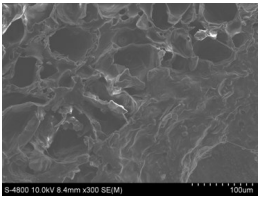
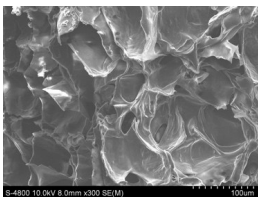
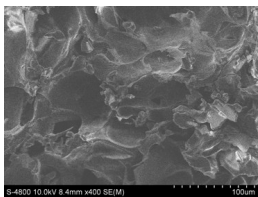
3.2 Impact of freeze-drying time on the quality of freeze-dried mango products

Freeze-drying is one of the best drying methods for retaining nutrients and protecting the appearance of products compared to fresh materials. This may be due to the dehydration process being performed at low temperatures (Ciużyńska and Lenart, 2011; Xu *et al.*, 2015). However, freeze-drying has not become widespread due to the high costs of energy, operation, equipment investment, and maintenance (Ratti, 2001; Hande *et al.*, 2014). Energy analysis studies of freeze-drying and conventional drying methods indicate that the energy required to remove 1 kg of moisture from the freeze-dried product is twice as high as that needed for conventional methods (Dincer, 2002; Liu *et al.*, 2008). The application of freeze-drying in food products requires the optimization of parameters to reduce operational costs and product prices. According to ANOVA results, moisture content changes significantly over time during freeze-drying ($p < 0.05$) (Table 2); the longer the drying time, the lower the moisture content. The lowest moisture at 30 h was 5.31% and the highest at 15 h was 10.31%. As the freeze-drying process lengthens, more moisture is lost (Peiren *et al.*, 2016; Nowak and Jakubczyk, 2020). Similarly, water activity also decreases gradually as the freeze-drying time increases, with the lowest water activity at 30 h being 0.45. A previous study also shows a correlation between moisture content and water activity (Vu *et al.*, 2023).

The analysis of product hardness using ANOVA revealed a statistically significant difference in the

impact of freeze-drying time on product hardness ($p < 0.05$). The hardness of the product decreases slightly but not significantly when the freeze-drying time is increased from 15 to 20 h, but a mild reduction was observed when it reaches 30 h, with a remaining hardness of 478 g. This indicates that prolonging the freeze-drying time reduces the hardness of the product. As the freeze-drying process prolongs, more water transitions from a solid to a liquid state, yet the structure does not shrink due to the raw material being in a frozen environment. According to the ANOVA results, the L^* , a^* , b^* colors tend to increase over the freeze-drying time. This was because increasing the freeze-drying time results in a higher amount of water being removed during this phase, inversely proportional to the amount of water removed during the vacuum drying process. Ending the freeze-drying process early leads to a higher water content in the raw material when transferred to the vacuum drying stage, and under the influence of temperature, oxidation processes and enzyme activities occur. This results in a color increase with longer freeze-drying times (Xu *et al.*, 2015). Additionally, SEM images reveal that the porosity tends to increase progressively. Previous reports have indicated that the longer the freeze-drying time, the more and clearer the porous structure becomes (Oikonomopoulou *et al.*, 2011). The longer the freeze-drying time, the better the physicochemical and sensory properties. However, the economic value increases with prolonged freeze-drying due to the high energy requirements for this stage. Conversely, reducing the freeze-drying time would shift to the vacuum drying stage at temperatures above 0°C,

Table 2. The effect of freeze-drying time on the quality of freeze-dried mango products.

Criteria	Freeze-drying time			
	15	20	25	30
Moisture content (%)	10.31±1.11 ^a	8.31±1.11 ^{ab}	6.11±0.11 ^{bc}	5.31±1.11 ^c
Water activity	0.51±0.00 ^a	0.49±0.00 ^b	0.47±0.00 ^c	0.45±0.00 ^d
Hardness (g)	712±63 ^a	792±83 ^a	610±110 ^{ab}	478±97 ^b
L*	L* = 74.12±0.22 ^b	L* = 79.22±0.24 ^c	L* = 81.26±1.12 ^a	L* = 82.26±1.12 ^a
a*	a* = 1.17±0.12 ^a	a* = 1.19±0.11 ^a	a* = 1.21±0.13 ^a	a* = 1.30±0.14 ^a
b*	b* = 29.15±0.11 ^c	b* = 28.25±0.21 ^d	b* = 30.25±0.11 ^b	b* = 31.15±0.12 ^a
SEM				
Sensory	The sweetness does not change, the texture is not crispy, the surface is concave, soft, limiting the natural mango flavor.	The sweetness does not change, the texture is less crunchy, durable with a slightly concave face, does not retain the natural mango flavor.	The sweetness does not change, the texture is crispy, durable with little concave face, retains the natural mango flavor.	The sweetness does not change the crunchy texture, durable face does not concave, retains the natural mango flavor.

Processing conditions: Freezing time 4 h, vacuum drying time 15 h.

causing unfrozen ice crystals to melt into liquid, damaging the structure. If the freeze-drying temperature is not suitable, rapid ice melting may occur, potentially leading to structural collapse, capillary blockage, resulting in decreased and uneven dehydration, and porous structure (Duan *et al.*, 2016). Any melting of the material's surface during freeze-drying or any melting of the ice layer may cause product defects such as swelling, shrinkage, and a structure filled with liquid (Sadikoglu *et al.*, 2006; Fonseca *et al.*, 2008).

3.3 Impact of vacuum drying time on freeze-dried mango product quality

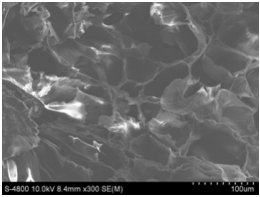
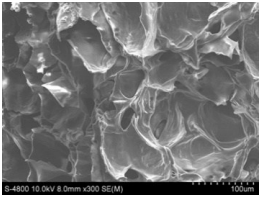
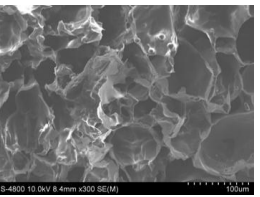
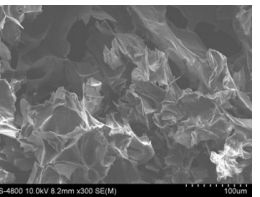
The moment when the temperature exceeds 0°C is considered the endpoint of the freeze-drying process (Sadikoglu *et al.*, 2003). Vacuum drying starts at the end of the freeze-drying stage, with moisture evaporating through channels formed by pores in the dried material (Sadikoglu *et al.*, 1998; Duan *et al.*, 2016). Previous freeze-drying does not create large pores because dehydration leads to obstruction of water movement and its bonding with cells, affecting the product's structure. The vacuum drying process aims to dry the remaining moist portions to a low moisture content. ANOVA results show a statistically significant difference in the impact of vacuum drying time on moisture content and water activity among different vacuum drying intervals ($p < 0.05$) (Table 3). Longer vacuum drying times lead to lower moisture content and water activity (Wu *et al.*, 2007; Richter Reis *et al.*, 2017). At 25 h of vacuum drying, the moisture content was at its lowest at 4.81%, and the water activity was at its lowest at 0.44.

Additionally, there was a positive correlation between moisture content, water activity, and product hardness. The highest hardness value was recorded at 25 h of vacuum drying (892 g). Vacuum drying increases hardness while reducing stickiness, elasticity, and residual adhesiveness. A previous report also noted that increasing the vacuum drying time enhances the hardness of freeze-dried products (Ashmawy and Ahmed, 2016). Concerning color, ANOVA analysis indicates differences between different vacuum drying intervals. The best color value was recorded at 15 h of vacuum drying with an L^* value of 81.26 ± 1.12 , and the lowest at 25 h with an L^* value of 76.26 ± 1.12 . Previous reports have shown that longer vacuum drying times negatively affect the color quality of products after freeze-drying (Duan *et al.*, 2016; Nowak and Jakubczyk, 2020). SEM structures show no clear differences across the times due to the structure formed from the prior freeze-drying process. However, a slight difference indicates that increasing vacuum drying time causes cell structures to break down and no longer form distinct cell pores. Sensory evaluation results show high sensory quality at 15 h of drying.

4. Conclusion

This study has effectively developed a freeze-drying process for converting mango puree into dried mango. Our exploration of different drying conditions yielded the following protocol: the process begins with a freezing stage at -20°C lasting 4 h, followed by a freeze-drying phase at temperatures below 0°C for 25 h, and concludes with a vacuum drying stage at temperatures

Table 3. Influence of vacuum drying time on freeze-dried mango product quality.

Criteria	Vacuum drying time			
	10	15	20	25
Moisture content (%)	7.31±0.14 ^a	6.11±0.11 ^b	5.11±0.11 ^c	4.81±0.12 ^d
Water activity	0.48±0.00 ^a	0.47±0.00 ^b	0.45±0.00 ^c	0.44±0.00 ^d
Hardness (g)	550±88 ^c	610±110 ^{bc}	812±89 ^{ab}	892±89 ^a
L*	L* = 77.16±1.02 ^b	L* = 81.26±1.12 ^a	L* = 77.26±1.12 ^b	L* = 76.26±1.12 ^b
a*	a* = 1.10±0.14 ^b	a* = 1.10±0.14 ^b	a* = 1.10±0.14 ^a	a* = 1.10±0.14 ^a
b*	b* = 30.25±0.11 ^a	b* = 30.25±0.11 ^a	b* = 30.25±0.11 ^a	b* = 30.25±0.11 ^a
SEM				
Sensory	The sweetness does not change, the bright yellow color is less bright, and less hard.	The sweetness does not change, the texture is crispy, durable, with a little concave face, and retains the natural mango flavor.	The sweetness does not change, the texture is crispy, the surface is much concave, retaining the natural mango flavor	The sweetness does not change, the product is dry, the hardness is high, and the color is less bright.

Processing conditions: Freezing time 4 h, freeze-drying 25 h.

above 0°C for 15 h. These procedures are recommended based on optimizing both the product quality and economic feasibility.

Conflict of interest

The authors declare no conflict of interest.

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