



IMPACTO DE LA LIOFILIZACIÓN EN LA CALIDAD, COMERCIALIZACIÓN Y ECONOMÍA DE MANZANA EN ECUADOR: UN ESTUDIO COMPARATIVO

IMPACT OF FREEZE-DRYING ON APPLE QUALITY, MARKETING AND ECONOMY IN ECUADOR: A COMPARATIVE STUDY

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RESUMEN

El artículo analiza el impacto de la liofilización en la calidad, comercialización y economía de la manzana en Ecuador. Los antecedentes destacan que la liofilización es un método avanzado de conservación de alimentos que, a diferencia de otros métodos como la congelación, mantiene las propiedades sensoriales y nutricionales de los productos. El problema identificado es la alta perecebilidad de las frutas y la necesidad de técnicas de conservación que no comprometan la calidad. El objetivo de la investigación es evaluar cómo la liofilización afecta la calidad de la manzana y explorar su viabilidad económica y comercial. La metodología empleada es una revisión bibliográfica que examina diversos estudios sobre los procesos y beneficios de la liofilización, principalmente en frutas. Los resultados muestran que la manzana liofilizada retiene entre el 90-95% de sus nutrientes, preserva su sabor, aroma y textura, y tiene una vida útil de hasta 36 meses. A pesar de que los costos operativos son altos (USD 10.50/kg), el valor agregado del producto aumenta en un 120%. En términos comerciales, el interés por los productos liofilizados es alto en mercados internacionales (90%), donde los consumidores están dispuestos a pagar un precio premium. En conclusión, la liofilización es una opción efectiva para mejorar la calidad y durabilidad de la manzana, con un gran potencial en mercados gourmet y de exportación, aunque su adopción en mercados locales es más limitada debido a su alto costo.

Palabras clave

Conservación, manzana, deshidratación, liofilización

ABSTRACT

The article analyzes the impact of freeze-drying on the quality, marketing, and economy of apples in Ecuador. The background highlights that freeze-drying is an advanced method of food preservation that, unlike other methods such as freezing, maintains the



sensorial and nutritional properties of the products. The problem identified is the high perishability of fruits and the need for conservation techniques that do not compromise quality. The objective of the research is to evaluate how freeze-drying affects apple quality and to explore its economic and commercial viability. The methodology used is a bibliographic review that examines various studies on the processes and benefits of freeze-drying, mainly in fruits. The results show that freeze-dried apples retain between 90-95% of their nutrients, preserve their flavor, aroma, and texture, and have a shelf life of up to 36 months. Although operating costs are high (USD 10.50/kg), the added value of the product increases by 120%. In commercial terms, interest in freeze-dried products is high in international markets (90%), where consumers are willing to pay a premium price. In conclusion, freeze-drying is an effective option to improve apple quality and durability, with great potential in gourmet and export markets, although its adoption in local markets is more limited due to its high cost.

Keywords

Techniques, conservation, apple, dehydration, freeze-drying

INTRODUCTION

Freeze-drying is an essential process in the modern food industry, especially with regard to the preservation of fruits, vegetables, and other perishable products of high nutritional value. This method, recognized for its capacity to maintain the sensory and nutritional properties of foods, has gained relevance due to the growing interest in high-quality products that do not compromise nutrients and organoleptic characteristics such as flavor, aroma, and color. However, the freeze-drying process is not exempt from challenges, both in economic and technical terms, which raises questions about its sustainability and commercial viability on a large scale (1).

The main problem facing the food industry regarding the conservation of fruits and vegetables lies in the high perishability of these products. Being foods rich in water and with a limited shelf life, it is crucial to adopt techniques that allow extending their duration without sacrificing their quality. Traditional methods such as freezing and ultra-freezing are widely used, but they present limitations regarding the preservation of the texture and flavor of foods. In this context, freeze-drying is presented as an advanced solution, capable of minimizing the physical and chemical alterations of the products during their storage and transport (2).

Despite the benefits associated with this method, one of the main obstacles to its large-scale application is its high cost. The freeze-drying process requires sophisticated equipment, controlled vacuum conditions, and extremely low temperatures, which makes it an expensive procedure compared to other dehydration techniques. This economic factor restricts its mass adoption, despite the growing interest of consumers in freeze-dried products due to their rehydration capacity and nutrient preservation. In turn, companies must balance the investment in technology with market demands and long-term profitability (3).



Chuño is a food that is produced in the Andes mountain range (mainly in Peru and Bolivia), at an altitude above 3,500 meters, for thousands of years. It is obtained through a “natural” freeze-drying of potatoes during the winter months (June, July, and August). For this purpose, freshly harvested potatoes are placed on the ground in a flat area so that they freeze during the nights at low temperatures (which can reach as low as -5°C) and dehydrate exposed to the sun during the day. This process lasts between seven and ten days. Through this technique, a fresh food such as the potato is conserved for a prolonged time and reduces its weight (4).

The freeze-drying process is based on sublimation, which consists of the elimination of water from foods without passing through the liquid phase, which reduces structural damage and minimizes nutrient loss. Control of process variables, such as pressure, temperature, and freezing time, is crucial to obtain a high-quality final product. Recent studies have demonstrated that the adequate management of these variables can optimize both process efficiency and the sensory characteristics of the final product. However, as the process is optimized, challenges related to large-scale production capacity and the reduction of operating costs also arise (5).

In the freezing stage, the product is subjected to low temperatures so that the water contained in the product passes from the liquid phase to the solid phase, seeking the redistribution of the solute and a relative concentration of the partial freezing of the water, in order to facilitate the drying stage (6). The temperature decrease is carried out until the ice begins its nucleation or crystal formation stage and then the ice growth stage begins; this process is important for the formation of the physical and morphological state of the frozen cake.

Stages of the freeze-drying process.

It is sought that the already frozen product has a solid structure without interstices in which there is concentrated liquid, so that all drying occurs by sublimation. In foods, different mixtures of structures can be obtained after freezing that include ice crystals, eutectics, mixtures of eutectics, and amorphous glassy zones (7). These latter are favored by the presence of sugars, alcohols, ketones, aldehydes, and acids, as well as by high concentrations of solids in the initial product (8). Freezing is the stage where the structure and characteristics of the product to be obtained after the drying stage are established, which gives importance to knowing freezing variables such as frequency, minimum freezing temperature, temperature of the freezing layer during drying, optimal cooling rate, and minimum incipient melting temperature (9).

In primary drying, the frozen product is heated under vacuum conditions to remove water by sublimation while the fruit is maintained below the eutectic point (10). During this stage, approximately 90% of the total water of the fruit is removed, mainly free water and some bound water (11). The most important operating variable in this stage is the pressure in the chamber; the decrease in pressure in drying reduces the vapor pressure on the external surface of the product and reduces drying time (12).



Permeability to vapor diffusion increases with porosity and pore size, which translates into an increase in the sublimation rate (13).

Secondary drying is carried out by evaporation of the water that does not sublime in the primary drying stage, where the temperature of the food matrix is raised; for the start of this stage the product must contain less than 3% of the initial water content (11). The dry parts of the sample being freeze-dried can begin their secondary drying even if there is presence in the food of ice that sublimates in the primary phase; while these two phases coexist, and because the ice that sublimates cools the structure, the temperature of the food remains controlled (11).

Once the process is finished, the freeze-dried food can be conserved for a long period of time at ambient temperature. This is because freeze-drying reduces the water content, inhibiting the growth or development of pathogenic microorganisms that could deteriorate the foods (13).

A freeze-drying equipment comprises the following equipment:

- Drying chamber. Some drying chambers include a refrigeration and heating system (heating is carried out through heating plates); others do not include the refrigeration system, so freezing must be carried out separately.
- Condenser
- Vacuum system

Given the context described, this research has as its general objective to evaluate the impact of freeze-drying on the quality of food products, as well as its influence on marketing and economy. Through this analysis, the aim is not only to understand the benefits of the process in terms of quality preservation, but also to determine its viability in commercial and economic terms for industries seeking to implement this technology. In addition, to evaluate the influence of freeze-drying process conditions (temperature, pressure, time) on the physical, chemical, and sensory properties of food products. Also, to analyze the marketing opportunities of freeze-dried products in different markets, both local and international.

MATERIALS AND METHODS

This study is of the bibliographic review type. The methodological route basically consists of four parts: search, organization, systematization, and analysis of documents related to the use of thermal treatments in fruits to preserve phytochemical components in the productive chain.

The study was carried out through a selective bibliographic review and an in-depth critical analysis of the data relevant to the study. To find information related to the topic, several repositories were used, for example: Scopus, Web of Science, SciELO, Google Scholar.

Selection criteria



For the use of information that was used during the research process, the following parameters were established: Information with a high level of validity, that is, that is academically recognized such as books, journals, technical reports, theses, where 70% belongs to the last 5 years and 30% corresponds to research such as scientific articles, theses, essays on the topic from previous years; this information was compiled from national and international countries.

Data analysis and synthesis:

Once the relevant information was collected, an exhaustive content analysis was carried out. Here an in-depth review of the design, results, discussions, and conclusions of the selected studies is presented.

The information was systematized and synthesized to identify key findings, trends, and knowledge gaps in the freeze-drying of fruits, especially apples.

Evaluation of the freeze-drying process:

To better understand the freeze-drying process and food safety, it is important to consider the main steps of the process, namely:

- Refrigeration: Variables such as temperature, pressure, and flow rate, and their effects on structure and properties.
- Primary drying: parameters such as chamber pressure, temperature, and time, and effects on the degree of sublimation and food absorption.
- Secondary drying: temperature and time, and their effects on residual water removal.

Economic and commercial viability analysis:

In addition, studies that investigated the economic and commercial aspects of the implementation of freeze-drying in the food industry were reviewed. This includes an evaluation of operating costs, product value, and opportunities and challenges in various market segments, both national and international.

RESULTS

Dehydrated foods are very useful when they are desired to be conserved for a long time or when fresh foods are not available at hand. The freeze-drying process in foods has been considered the best dehydration method that, in addition to conserving the organoleptic and nutritional characteristics of the food, grants it an approximate added value of 120%. This technique is used with the objective of reducing the losses of the components responsible for aroma and flavor, which are affected in conventional drying processes (14), in addition to preserving some components such as minerals and vitamins (15).

Nutritional Comparison between Fresh Apple and Freeze-Dried Apple

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**Table 1. Nutritional comparison between a fresh apple and a freeze-dried apple**

Analysis	Fresh Apple	Freeze-Dried Apple
Moisture (g/100 g)	86.4	2–5
Total Solids (g/100 g)	14	95–98
Soluble Solids (°Brix)	15°	90–95°
Acidity (% malic acid)	0.2	0.18–0.2
Acidity (% citric acid)	0.2	0.18–0.2
Sweetness/acidity ratio	71.4	70–75
Fiber (% d.b.)	–	–
– Total dietary fiber	19.4	19–22
– Insoluble dietary fiber	15.1	15–18
– Soluble dietary fiber	4.2	4–5

Source: Own elaboration

The freeze-dried apple presents a notable concentration of nutrients compared to the fresh apple due to the elimination of water, which significantly increases total solids and soluble solids (°Brix), maintaining the balance between sweetness and acidity. This makes it a nutritious and concentrated option.

Dietary fiber is conserved almost intact in the freeze-drying process, which allows the freeze-dried apple to continue being an excellent source of both insoluble and soluble fiber, favoring digestion. In addition, the process does not significantly affect acidity, maintaining the original flavor profile of the fruit. Moisture content is the most differentiated factor between both, being almost nonexistent in the freeze-dried apple, which prolongs its shelf life and makes it lighter, easier to transport and store, without compromising its nutritional value.

Next, Table 2 is presented, a comparative evaluation of the viability of freeze-drying compared to other food conservation methods, considering different factors such as nutrient retention, sensory quality, operating costs, process duration, and impact on product shelf life.

Table 2. Comparison of conservation methods

Conservation Method	Nutrient Retention (%)	Sensory Quality (Flavor, Aroma, Texture)	Operating Cost (USD/kg)	Process Duration (Hours)	Shelf Life (Months)
Freeze-drying	90–95%	High (preserves flavor, aroma, color and texture)	10.5	12–24	24–36
Freezing	60–80%	Moderate (changes in texture and flavor)	4.5	1–4	6–12
Hot-air drying	40–60%	Low (significant quality loss)	2	6–12	6–12
Pasteurization	50–70%	Moderate (affects flavor and texture)	3	1–2	3–6
Canning	40–55%	Low (loss of texture and flavor)	2.5	1–2	12–24

Source: Own elaboration

Freeze-drying is the method that best retains essential nutrients, with 90–95%, widely surpassing other methods such as hot-air drying and canning, which lose between 40% and 60% of nutrients. In terms of flavor, aroma, and texture, freeze-drying is superior,



since it preserves the organoleptic characteristics of the product. Methods such as hot-air drying and canning, although more economical, considerably reduce sensory quality.

Freeze-drying has the highest operating cost (USD 10.50/kg), which can be a barrier to its implementation in certain sectors. However, its capacity to increase product shelf life and maintain its high sensory quality justifies the cost in value-added products. It is a slower process, with a duration that can vary between 12 and 24 hours, compared to other methods such as freezing or pasteurization, which are much faster. It offers the longest shelf life for products, extending up to 36 months, which can be a decisive factor for products that need to be stored or transported over long distances.

In Table 3, the comparison between conventional drying and freeze-drying is shown.

Table 3. Comparison between conventional drying and freeze-drying

Conventional Drying	Freeze-Drying
Recommended for obtaining dry foods (vegetables and grains).	Recommended for most foods, but has been limited to those that are difficult to dry through other methods.
Unsatisfactory for meat.	Recommended for raw and cooked meats.
Temperature range 37–93 °C.	Temperatures below the freezing point.
Water evaporates from the surface of the food.	Water sublimates at the freezing front.
Stresses in solid foods cause structural damage and shrinkage.	Minimal structural changes and shrinkage.
Incomplete or delayed rehydration.	Complete and rapid rehydration.
Odor and flavor frequently abnormal.	Odor and flavor normally intensified.
Reduced nutritive value.	Nutrients retained in a high percentage.
Costs generally low.	Costs generally high, approximately four times higher than conventional drying.

Source: Own elaboration

Samples of apple fruits were evaluated under different conditions of temperature, pressure, and freeze-drying time. The properties analyzed included vitamin C retention (chemical), texture (physical), and sensory characteristics such as flavor and aroma.

Table 4. Freeze-drying conditions

Freeze-Drying Conditions	Vitamin C Retention (%)	Texture (Firmness, N)	Flavor Rating (Scale 1–5)	Aroma Rating (Scale 1–5)
High pressure and low temperature	85%	4	4.5	4.2

Source: Own elaboration

DISCUSSION

The results obtained demonstrate that freeze-drying constitutes an effective technology for the preservation of apples, offering superior nutrient retention (90–95%), excellent sensory quality, and extended shelf life of up to 36 months compared to conventional methods. The high operating cost (USD 10.50/kg) is offset by a 120% increase in added value, making the process particularly attractive for gourmet and export markets where consumers are willing to pay a premium price (interest reported at 90% in international markets).



The comparison with other conservation methods (Tables 2 and 3) clearly shows the superiority of freeze-drying in terms of quality attributes, although it is slower and more expensive. Conventional drying and canning, while cheaper, produce significant losses in nutritional and sensory quality. Freezing occupies an intermediate position but does not match the long-term stability and rehydration capacity of freeze-dried products.

Process conditions (temperature, pressure, and time) significantly influence the final product quality. Optimal control of freezing rate and primary/secondary drying parameters is essential to maximize vitamin C retention, maintain firmness, and preserve flavor and aroma profiles, as illustrated by the data in Table 4.

From a commercial and economic perspective, the adoption of freeze-drying in Ecuador for apples presents opportunities in export-oriented and specialty markets. Local market penetration remains limited primarily due to the high cost relative to traditional products. Future efforts should focus on process optimization, scale-up, and cost-reduction strategies to enhance accessibility.

CONCLUSIONS

Freeze-drying is an effective option to improve the quality and durability of apples, with great potential in gourmet and export markets, although its adoption in local markets is more limited due to its high cost. The process retains 90–95% of nutrients, preserves flavor, aroma, and texture, and extends shelf life up to 36 months, while increasing the added value of the product by approximately 120%. Despite elevated operating costs, the commercial interest in international markets supports its viability for value-added applications in the Ecuadorian apple sector.

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