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Characterization of Powdered Ungurahui *(oenocarpus bataua)* through Freeze-Dying Processes

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Abstract

This research focuses on developing and characterizing a nutritional supplement in powder form derived from Ungurahui (Oenocarpus bataua) using freeze-drying processes. Native to the Peruvian Amazon, Ungurahui is rich in antioxidants, polyphenols, tocopherols, and healthy fatty acids, offering significant nutritional and functional benefits. A study by the Instituto de Investigaciones de la Amazonía Peruana highlights Ungurahui's cardiovascular health benefits and its role in preventing cellular damage due to its high content of unsaturated fatty acids (81.50% of total fatty acids) and antioxidants (DPPH: 82.13 µmol TE/g fresh sample) (Vargas-Arana 2022). This study addresses food preservation challenges, such as perishability and nutrient retention, by utilizing lyophilization, which effectively preserves the fruit's bioactive compounds and sensory properties. Objectives include evaluating the state of the art in Ungurahui and lyophilization, designing a freeze-drying methodology, and formulating a powder with enhanced antioxidants and sensory profiles. Experiments at the University of Lima included proximate analysis, antioxidant tests, and sensory evaluations. Results demonstrated lyophilization's potential to produce a high-quality, shelf-stable powder with antioxidant levels exceeding 200 mg GAE/100 g. Market trends indicate increasing demand for health-focused, convenient powder foods, with a 35% growth over the past five years. This research emphasizes innovation in Amazonian fruit utilization, promoting sustainable agriculture and reducing food waste. The final product is a freeze-dried Ungurahui powder nutritional supplement, preserving its nutritional, physicochemical, and organoleptic properties, ideal for applications in beverages, juices, and desserts.

Keywords
Ungurahui, Freeze-drying, Preservation, Powder and Antioxidants.

1. Introduction
Nowadays, the demand for healthy food has grown significantly. Consumers are increasingly aware of their dietary choices and prioritize products that offer health benefits. According to The Food Tech (2023), 61% of global consumers acknowledge that product labels significantly influence their purchasing decisions, and nearly 25% are willing to pay a premium for functional ingredients.

This research aims to make a powder rich in antioxidants by preserving the nutritional value of the fruit ungurahui. This fruit is highly perishable in nature and its limited market reach hinders its broader utilization and commercial potential. The freeze-drying process, selected for its proven ability to preserve nutritional and sensory qualities, offers a sustainable and effective method for extending the shelf life of ungurahui while maintaining its bioactive compounds.

The significance of this study lies in addressing pressing issues in the Peruvian agricultural sector. Limited arable land restricts agricultural productivity, while the perishability of products leads to significant food waste and logistical challenges in storage and transportation. Additionally, dependence on climatic conditions exposes crop yields to environmental vulnerabilities, exacerbating instability in production. These factors highlight the urgent need for sustainable and efficient solutions to improve agricultural resilience.

Motivated by these challenges, this research proposes an innovative pathway for utilizing ungurahui fruit through freeze-drying technology. By transforming the fruit into a powdered form, the study reduces post-harvest losses, enhances market accessibility, and contributes to the diversification and added value of Peruvian agricultural exports. Furthermore, it responds to the growing global demand for functional, convenient food products with high nutritional value.

To calculate the potential demand for this project, we have considered the following demographic criteria. The demand study is focused on Peru, specifically in the Lima department, which represents 33.20% of the total Peruvian population (INEI, 2024). Additionally, regarding socioeconomic criteria, our target audience consists of the following: NSE A (1.2%), NSE B (10.6%), and NSE C (30.3%), representing a total of 42.1% (APEIM, 2023). Furthermore, according to the Universidad de San Martin de Porres (2022), 42% of the population in Peru consumes nutritional supplements. Regarding psychographic criteria, we considered individuals with a healthy lifestyle, those interested in health, athletes, and those engaged in fitness. Thus, we factored in that 62% of Peruvians participate in sports or physical activities (Gestión 2024). For calculation purposes, a survey was conducted with a sample of 100 people, resulting in a purchase intent of 87% and an intensity of 86%, which yields a corrected intent of 74.82%. Therefore, the projected potential demand for the project in 2028 is 1,056.87 tons. Considering a market share of 0.12%, the projected specific demand for the project in 2028 is 1.27 tons.

1.1 Objectives

- Evaluate the state of the art of ungurahui and the freeze-drying process in Peru, identifying current technological advances, limitations, and opportunities in the field.
- Design the freeze-drying process for ungurahui fruit in the Operations and Unit Processes Laboratory at the University of Lima, optimizing parameters to ensure the preservation of nutritional and sensory properties.
- Develop the formulation of powder supplement from freeze-dried ungurahui.
- Assess the physical, chemical, and organoleptic properties of powder derived from freeze-dried ungurahui, including sensory acceptability and its nutritional profile, with a focus on antioxidant content.
- Contribute to scientific knowledge on tropical fruit processing by developing a high-value product that aligns with current market demands for functional and sustainable food innovations.

2. Literature Review

In Peru, the market for vitamins and supplements has reached unprecedented growth, transforming pharmacies into the primary points of sale. According to data from the National Association of Pharmaceutical Laboratories (Alafarpe), imports of nutritional supplements totaled $40.8 million in the first half of 2024, with a cumulative growth of 35% over the past five years. A study by Insight Hunting SEO conducted by Vitagel (2024) revealed that interest in nutritional supplements in Peru increased by 405% between 2019 and 2023. Another recent study highlighted that searches for collagen-based supplements and antioxidant formulas have grown by 250% in the past year.

Freeze-drying, also known as lyophilization, is a process in which water in the form of ice under low pressure is removed from a material by sublimation. This process has found many applications to produce high-quality food and pharmaceuticals (Nowak 2020). Freeze-drying is an optimal process for food preservation and meets all the best indicators in terms of preservation performance and maximization of fruit nutrients (Chumacero et al. 2020). The variables that most affect freeze-drying are the quality of the machines and the characterization of the specific fruit. According to Navarro-Valdez et al. (2020) it is important to evaluate the macronutrients of the peel and pulp of ungurahui, which compared to other fruits can affect freeze-drying in the time it may take to reach a result and the yield it will have. Or, according to Sanchez et al. (2020), to evaluate different preservation conditions needed several machines, some responding better than others with respect to freeze-drying. And nutritional and bioactive properties can be related to neurodegenerative diseases, therefore, freeze-drying increases more its nutritional value (Vargas-Arana et al. 2022).

Ungurahui is a fruit of Amazonian Peruvian origin, and it is consumed as a ripe fruit, drink, or refreshing beverage in various flavors (Quispe Herrera et al. 2022). This fruit grows on a palm tree throughout almost the entire Amazon basin, regardless of soil types. In Peru, this nutritious fruit is cultivated in the regions of Loreto, San Martin, Madre de Dios, Huánuco, Pasco, and Junin (Gonzales et al. 2011). Due to its high content of essential amino acids and proteins, ungurahui is considered one of the most nutritionally valuable fruits, comparable to meat, legumes, and cow's milk. Its composition of unsaturated fatty acids is quite similar to olive oil (Nua Peru 2019), as it is rich in oleic acid, which is beneficial for cardiovascular health. However, ungurahui stands out for its higher concentration of antioxidants, including polyphenols (procyanidins, stilbenes, and caffeoylquinic acids), tannins, and anthocyanins, which contribute to cellular regeneration, immune system support, and overall well-being (Quispe Herrera et al. 2022). Additionally, its oil has traditional uses in skin and hair care, joint health, and muscle recovery, making it valuable in both the nutraceutical and cosmetic industries.

Finally, freeze-drying foods contribute positively to society, if it is used for fruits that elevate their high nutrient content and help to improve the health of citizens. De Paiva et al. (2023), highlights the importance of using freeze-drying fruits to provide a concentrated source of natural antioxidants and preserve heat-sensitive nutrients. It is a practical and healthy solution to consume fruit daily. In addition, freeze-drying stands out as a high-quality drying method to preserve bioactive compounds. Furthermore, this technique offers several potential benefits, including the preservation of heat-sensitive compounds, prevention of structural changes, inhibition of bacterial growth, and reduced reliance on preservatives and harsh chemicals (Trimleaf 2024).

3. Methods

This research project focuses on the ungurahui fruit (*Oenocarpus bataua*) as the central subject of study. This Peruvian fruit will undergo a lyophilization process in the Unit Operations Laboratory at the University of Lima to develop a powdered supplement with high nutritional value, highlighting its antioxidant properties. Below, some characteristics of the fruit and the lyophilization process are presented.

Table 1. Proximal Analysis and Morphological Characteristics of Ungurahui

Characteristics	**Ungurahui**
Length	33.57 mm
Average Diameter	22.25 mm
Weight	11.06 g
Seed Weight (Core)	7.78 g (70.35%)
Peel and Pulp Content	3.279 g (29.64%)

Note. Adapted from *Characterization of oils, cakes, and flours from ungurahui (Jessenia polycarpa) and aguaje (Mauritia flexuosa L.) fruits from the Peruvian Amazon*, by Quispe Jacobo, Fredy et al., 2009. (http://www.scielo.org.pe/scielo.php?script=sci_arttext&pid=S1810-634X2009000200012&lng=es&tlng=es.)

For the morphological analysis and proximal composition of ungurahui fruits, the research Characterization of oils, cakes, and flours from ungurahui (Jessenia polycarpa) and aguaje (Mauritia flexuosa) fruits from the Peruvian Amazon evaluated 20 ungurahui fruits. Tests were conducted in the laboratories of Physical Chemistry, Instrumentation, and the Food Pilot Plant of the Faculty of Food Industries at the National Agrarian University of La Molina.

Table 2. Morphological Analysis of Ungurahui Fruits

Characteristics	Average Value	Standard Deviation (SD)
Length (cm)	33.57	2.2
Diameter (cm)	22.25	1.1
Fruit Weight (g)	11.06	1.35
Peel + Pulp Weight (g)	3.28	1.15
Seed Weight (g)	7.78	0.95
Peel + Pulp Percentage (%)	29.64	2.55

Note. Adapted from Characterization of oils, cakes, and flours from ungurahui (Jessenia polycarpa) and aguaje (Mauritia flexuosa L.) fruits from the Peruvian Amazon, by Quispe Jacobo, Fredy et al., 2009. (http://www.scielo.org.pe/scielo.php?script=sci_arttext&pid=S1810-634X2009000200012&lng=es&tlng=es.)

Table 3. Proximal Composition of Ungurahui Fruit before and after lyophilization

Ungurahui	Moisture (%)	Fat (%)	Ash (%)	Priotein (%)	Carbohydrates (%)
Before lyophilization	39.83 ± 0.73	21.77 ± 0.176	1.00 ± 0.024	3.12 ± 0.060	23.74 ± 1.21
After lyophilization	0.97 ± 0.01	29.23 ± 0.501	2.56 ± 0.021	4.69 ± 0.018	62.55 ± 0.542

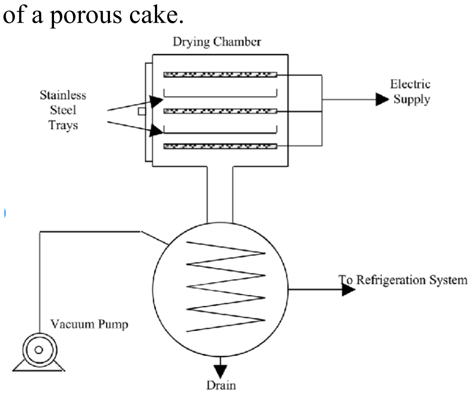
Note. Adapted from Characterization of oils, cakes, and flours from ungurahui (Jessenia polycarpa) and aguaje (Mauritia flexuosa L.) fruits from the Peruvian Amazon, by Quispe Jacobo, Fredy et al., 2009. (http://www.scielo.org.pe/scielo.php?script=sci_arttext&pid=S1810-634X2009000200012&lng=es&tlng=es.)

Lyophilization (freeze-drying) is a dehydration technique that removes a solvent, typically water, from a pharmaceutical or biological formulation through sublimation (Bhosale et al., 2021). This process occurs under vacuum conditions at pressures below the triple point (4.58 mmHg) and temperatures lower than 0.0098°C, ensuring a direct transition from the solid to the vapor phase without passing through the liquid state. The freeze-drying method is particularly suitable for high-value, heat-sensitive products, as it minimizes thermal degradation while preserving structural and functional integrity. The lyophilization cycle consists of three key phases: freezing, primary drying, and secondary drying.

1. **Freezing Phase:** The sample is frozen at temperatures below -40°C to promote ice formation. The freezing rate influences the ice crystal size, which directly affects the efficiency of sublimation. Proper freezing ensures a stable ice matrix and prevents structural collapse during subsequent drying stages.

2. **Primary Drying (Sublimation):** Under vacuum conditions (<100 mTorr), ice is directly converted into vapor without entering the liquid phase. The driving force for water removal is the concentration gradient of water vapor between the drying front and the condenser. A condenser maintained at -55°C captures the sublimated water vapor, preventing reabsorption. This phase removes approximately 95% of the total water content, preserving the structural integrity of heat-sensitive materials.

3. **Secondary Drying (Desorption):** Once sublimation is complete, residual moisture bound to the product matrix is eliminated through desorption. This step is conducted at, approximately, 25°C, further reducing water activity and enhancing the long-term stability of the product. The final dry product retains its original solid-state structure in the form of a porous cake.



4.
5. Figure 1. Freeze dryer functional diagram
6.
7. *Note. From https://www.researchgate.net/figure/Schematic-diagram-of-freeze-dryer-FD_fig4_244603684*

The freeze dryer used for this process is the Christ Alpha 1-2 LD plus model, designed for precise sublimation control under low temperatures and pressures. By carefully managing these parameters throughout the lyophilization cycle, this technique ensures the preservation of pharmaceuticals, biomolecules, and other thermosensitive compounds, extending their shelf life and maintaining their functional properties.

Table 4. Freeze dryer Specifications

Brand and Model	Condenser Capacity	Condenser Temperature	Condenser Performance	Communication Interface	Refrigerant System	Voltage / Amperage	Weight
Christ Alpha 1-2 LD plus	2.5 kg	-55 °C	2 kg/24 hours	RS 232	R404A	220V / 3A	28 kg

Note. Adapted from Technical Visit Guide to the Unit Operations Laboratory, by the University of Lima, 2023.

The Process Operations Diagram (DOP) is presented below, detailing the key stages in the production of ungurahui powder. The process begins in the Laboratory of Operations and Unit Processes (OPU), where the fruit undergoes an initial washing step (1), followed by de-seeding to separate the pulp from the seed (2). Next, the initial moisture content of the pulp is measured (3), blended (4), and subjected to the lyophilization process to remove water content (5). Once lyophilized, the moisture is measured again (6) before sealing the product for transfer (7). In the Food Laboratory, the powder undergoes a proximal analysis to evaluate its nutritional composition (8), followed by antioxidant capacity tests (9) and phenolic analysis (10). Then, physical properties such as solubility (11) and density (12) are evaluated. Finally, the product is packaged (13), resulting in a high-quality powder ready for distribution.

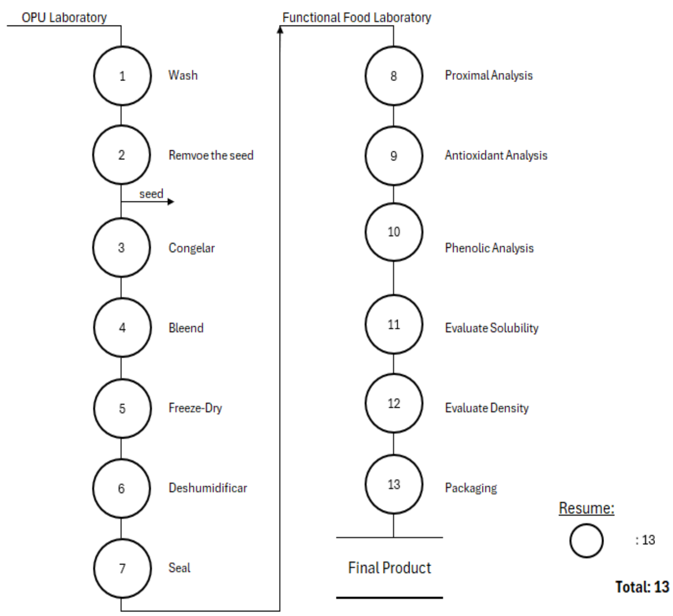


Figure 2. DOP Freeze dryer process

The final product is an instant ungurahui powder obtained through lyophilization. The product has been packaged in boxes containing 30 sachets (5g per sachet), designed for easy use and optimal storage. The experimentation phase successfully determined the ideal quantities and proportions to ensure high-quality nutritional benefits and a stable final product.

The following table outlines the project's key indicators. Three critical factors have been identified to ensure the project's success: antioxidant capacity, flavour, and texture.

Table 5. Indicators

Indicator	Measurement Method	Parameter	Expected Result	Evaluation Frequency
Antioxidant Capacity	Antioxidant capacity test with Folin-Ciocalteu and spectrophotometry (absorbance at 517 nm).	Absorbance in mg equivalents of gallic acid per gram of sample.	Minimum 200 mg equivalents of gallic acid / 100 g of dry sample.	For each production batch.
Flavor	Sensory evaluation using the 9-point Hedonic Scale with at least 30 participants.	Average score on the hedonic scale.	Minimum of 6.5 on the hedonic scale.	Sensory tests with each new batch.
Texture	Sensory evaluation and dissolution tests in dense liquids.	Mouthfeel and analysis of powder fineness.	Texture score of at least 7 on the hedonic scale and no clumping.	Evaluation with each batch and test in culinary applications.

4. Data Collection

The ungurahui fruit was obtained from the city of Yurimaguas, located in the Amazon rainforest of Peru, by air. The process of acquiring this fruit was challenging due to its limited cultivation; it is not commonly grown in many areas and is available only during specific fruiting seasons. The availability of ungurahui is highly dependent on both climate conditions and the quality of the land, which directly influences its nutritional value. Once harvested, the fruit was transported by plane to the city of Lima, where the freeze-drying and validation processes were carried out at the University of Lima. This journey and the careful handling of the fruit ensured the preservation of its unique properties for our study. For collecting the data used in discussion, the processes were divided by two big groups: OPU Laboratory Process and Food Laboratory Process. The OPU Laboratory was utilized specifically for the making of the freeze-dried powder of ungurahui by the next steps:

Weighing Ungurahui Fruit:
The first step involves weighing the ungurahui fruit on a precision scale. To ensure accuracy, the scale must be calibrated, and it is important not to overload it. The expected result is a weight of 667.99 grams, which represents the initial weight of the raw material. This task is carried out by the laboratory team and takes approximately 5 minutes.

Washing the Fruit in a Chlorine Solution:
The fruit is washed in a solution of water and chlorine to eliminate contaminants. For safety, gloves must be worn when handling chlorine to avoid skin and eye contact. The washing process lasts for 30 minutes, with the solution consisting of 3 drops of bleach per liter of water. The result is clean, contaminant-free fruit, prepared for further processing.

Manual Removal of Seeds:
After washing, the seeds are manually removed from the fruit. The procedure takes 20 minutes, and care must be taken to avoid injury. The result is the complete removal of seeds, which is then ready for the next stage.

Initial Moisture Test:
The moisture content of the pulp is measured using a moisture balance. The test should be carried out without opening the balance during the drying process to prevent errors. The process lasts about 52 minutes, with the balance set at a temperature of 105°C. The initial moisture content is found to be 47.8%.

Blending the Fruit with Osmotized Water:
The pulp is then blended with osmotized water in a blender. It is important to ensure the blender is securely closed before use. This step takes approximately 10 minutes and results in a thick, purple juice with the correct consistency.

Dividing the Juice into Samples and Weighing:
The blended juice is divided into individual samples, and each sample is weighed using a precision scale. Care must be taken to handle the flasks carefully to avoid spills. After 15 minutes, eight samples weighing a total of 327.18 grams are prepared for freezing.

Freezing the Samples in a Refrigerated Bath:
The samples are frozen using a refrigerated bath with medicinal-grade alcohol at -40°C. Safety glasses and gloves must be worn during this process. The freezing step takes 5 minutes, ensuring uniform freezing of the samples.

Lyophilization of the Samples:
The frozen samples are then subjected to lyophilization using a freeze-dryer. The process lasts 24 hours, with the lyophilizer set at -45°C and 0.9 mbar pressure. The result is dry ungurahui powder.

Dehumidification and Vacuum Sealing:
The dried powder is then dehumidified and vacuum-sealed to reduce moisture content. The sealing process is done with a vacuum sealer, ensuring that the bags are properly sealed before final closure. After 10 minutes, the product has a final moisture content of 0.97%, and it is ready for storage.

Nutritional and Sensory Analysis:
The final step involves conducting nutritional and sensory analysis of the ungurahui powder. This includes testing various nutrients and assessing the organoleptic characteristics such as taste, color, and texture. The analysis results help assess the product's quality and suitability for consumption.

Figure 3. Ungurahui in freeze-drying machine

Then we take the lyophilized powder to the nutritional and sensory analysis in the Food Laboratory Process, followed by the next steps:

Separation and Weighing of Freeze-Dried Ungurahui Samples:
This first step involves accurately weighing freeze-dried ungurahui samples using an analytical scale. Each sample weighed 15 mg. The samples are labeled as control, sample 1, sample 2, and sample 3 for further analysis. This step takes approximately 5 minutes.

Covering Tubes and Adding Reactants for Antioxidant Testing:
Reactants are added to the samples for antioxidant testing. The samples are protected from light, and care is taken to avoid direct contact with the chemicals. The process involves adding 1 mL of methanol, 1.5 mL of acetic acid, and 2 mL of ultrapure water to each sample. This process lasts for 10 minutes and ensures proper homogenization of the samples.

Preparation of the Folin-Ciocalteu Reagent:
The Folin-Ciocalteu reagent is prepared by carefully measuring and mixing the required quantities. This step takes 5 minutes, ensuring that the reagent is at the proper concentration for testing. The reagent is then stored in a vial covered with aluminum foil.

Thermal Process of Samples in a Water Bath:
The samples undergo a thermal process in a water bath at 80°C for 20 minutes. The samples are checked to ensure the bath is properly calibrated. After this step, the samples are ready for resting until the following day.

Absorbance Measurement Using Spectrophotometry:
The absorbance of each sample is measured using a spectrophotometer at a wavelength of 517 nm. Calibration is performed before use, and the absorbance data is recorded for each sample. This process takes approximately 15 minutes.

Stirring and Addition of Reactants in Phenolic Compounds Testing:
Reactants are added to the samples to test for phenolic compounds. Each sample is agitated for 5 minutes, and the required reactants are added. The result is a homogeneous mixture, ready for centrifugation.

Centrifugation for Separation of Solids in Phenolic and Solubility Tests: The samples are centrifuged for 15 minutes at a speed of 2500 rpm to separate solids. Proper calibration and balancing of the centrifuge are essential for accurate results. The samples are then prepared for further drying or analysis.

Drying of Solids in a Forced-Air Oven: The solids are dried in a forced-air oven at a consistent temperature for 24 hours. After drying, the weight of the samples is measured to determine solubility or material that is not soluble.

Density Calculation of Freeze-Dried Ungurahui: The density of the freeze-dried ungurahui is measured using a graduated cylinder. The volume and mass are recorded, and the density is calculated. The samples should maintain a constant density of 2 g/mL across all measurements.

5. Results and Discussion

5.1 Numerical Results

After data collection, we calculate the results based on the research objectives.

Freeze-Drying Performance:
The performance of the freeze-drying process can be calculated using the water lost in the fruit during the freeze-drying process. Considering the following data:

- Initial weight of the fruit = 667.99 g
- Initial moisture content of the fruit = 47.8%
- Final moisture content of the fruit (after freeze-drying) = 0.97%

First, we calculate the amount of water removed, as follows:

$$Water\ removed\ (g)\ =\ Initial\ weight\ of\ fruit\ (g)\ \times\ (\frac{Initial\ moisture(\%)\ -\ Final\ moisture(\%)}{100})$$

$$Water\ removed\ (g)\ \ =\ 667.99\ g\ \times\left(\frac{47.8\%\ -\ 0.97\%}{100}\right) =\ 312.13\ g$$

Then, calculate the freeze-drying efficiency (performance) as the amount of dry fruit obtained (after freeze-drying) based on the initial weight and the amount of water removed. The formula would be:

$$Freeze-drying\ performance\ (\%)\ =\ \frac{Final\ weight\ of\ the\ fruit\ (g)}{Initial\ weight\ of\ the\ fruit\ (g)}\times\ 100 = \frac{355.86\ g}{667.99\ g}\times\ 100\ =\ 53.30\ \%$$

The freeze-drying process achieved a yield of 53.3%, meaning that more than half of the fruit's initial weight was retained after water removal. This yield is crucial for commercial viability, as it influences production efficiency and cost-effectiveness. Additionally, maintaining a high retention rate helps preserve the fruit's bioactive compounds, ensuring that its nutritional properties remain intact. However, variations in process conditions may affect final product quality, highlighting the need for further optimization to enhance consistency and maximize both nutrient preservation and market potential.

Antioxidant Testing Capacity:
After results from the spectrophotometry, the absorbance and antioxidant concentration results are summarized in the table below:

Table 6. Absorbance Real and Concentration Results

Sample	Absorbance (Abs)	Absorbance Control	Absorbance Real	Concentration (mg Trolox/L)
1	0.497	1.0705	$1.0705 - 0.497 = 0.5735$	98.27
2	0.182	1.0705	$1.0705 - 0.182 = 0.8885$	152.82

The equations used for Absorbance Real and Concentration of antioxidants are the ones followed:

$$Absorbance\ Real\ (Abs) = Absorbance\ Control\ (Abs) - Absorbance\ Sample\ (Abs)$$
$$Antioxidant\ Concentration\ (mg\ Trolox/L) = k \times Absorbance\ Real\ (Abs)$$
**where k is the calibration constant (specific to Trolox)*

Given these results, the higher absorbance values indicate greater antioxidant capacity. Sample 2 had the highest real absorbance (0.8885), corresponding to the highest antioxidant concentration of 152.82 mg Trolox/L. Sample 1 showed a lower antioxidant capacity with a concentration of 98.27 mg Trolox/L. There appears to be implications for the freeze-drying process, it can retain a significant amount of antioxidant compounds, but variations between samples may result from differences in phenolic compound concentration. Even so, samples with higher absorbance and concentrations are better at neutralizing free radicals, indicating superior nutritional quality and potential value in functional food markets.

Solubility Test
The solubility of the freeze-dried ungurahui powder was analyzed by measuring insoluble solids. These were calculated as follows: *Insoluble Solids (g) = Weight before Drying (g) - Container Weight (g)*
Then, solubility was determined using the formula: *Solubility (%) = (1g- Insoluble Solids (g)) ×100*

Table 7. Solubility Test results

Sample	Weight before drying (g)	Container weight (g)	Insoluble solids (g)	Solubility (%)
1	24.23	23.24	0.99	1.00%
2	24.78	23.79	0.99	1.00%
3	25.25	24.28	0.97	3.00%

The solubility test revealed a relatively low solubility percentage across all samples, with a homogeneous performance for Samples 1 and 2 (1%) and a slightly higher value for Sample 3 (3%). These results indicate that a small portion of the freeze-dried powder remains insoluble in water, potentially due to the powder's structural properties. Specifically, the high fiber and fat content of the fruit may contribute to this low solubility. Insoluble dietary fiber tends to absorb water without fully dissolving, forming a network that retains water but does not disperse in aqueous solutions. Additionally, the significant fat content could create a hydrophobic barrier, further reducing the ability of the powder to dissolve. These structural characteristics suggest that the freeze-dried powder is more suitable for use in dry mixtures or as a topping, like how granola or chia are consumed, such as sprinkled over yogurt.

5.2 Graphical Results

The freeze-drying process of ungurahui effectively reduces its water content while preserving over 50% of its dry weight, highlighting its potential as a sustainable and nutrient-rich powder. This balance between moisture removal and retention of the fruit's key components ensures a high-quality product suitable for long-term storage and diverse applications, maximizing its value in health-focused markets

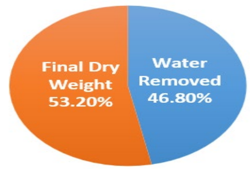


Figure 4. Freeze-Drying Process Weight distribution

The following bar chart clearly demonstrates the significant reduction in moisture content of ungurahui powder after undergoing the lyophilization process. Initially, the moisture content of the ungurahui pulp was 47.8%, indicating a high water content. However, after the lyophilization process, this value dropped drastically to 0.97%. This substantial reduction in moisture is a key indicator of the effectiveness of lyophilization in preserving the quality and enhancing the shelf-life of the powder, making it a stable and concentrated product for future use.

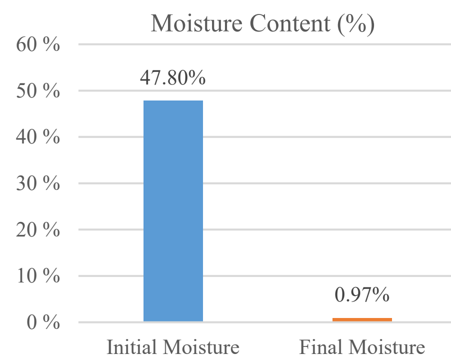


Figure 5. Reduction of Moisture Content in Ungurahui Powder during the Lyophilization Process

For the antioxidant capacity, the next chart illustrates the antioxidant capacity of the freeze-dried ungurahui samples, represented by two key metrics: real absorbance (orange line) and antioxidant concentration in mg Trolox/L (blue bars). Sample 2 exhibited the highest real absorbance value of 0.8885, corresponding to an antioxidant concentration of 152.82 mg Trolox/L, demonstrating its superior ability to neutralize free radicals. In contrast, Sample 1 had a lower real absorbance of 0.5735 and an antioxidant concentration of 98.27 mg Trolox/L. These results confirm a positive correlation between real absorbance and antioxidant concentration, emphasizing the potential of freeze-drying to preserve the nutritional quality of ungurahui.

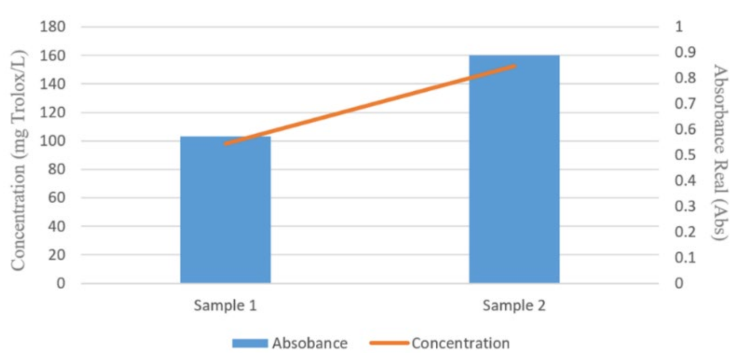


Figure 6. Absorbance and Concentration for Antioxidants in Samples after Spectrophotometry

For the sensory evaluation of the lyophilized ungurahui powder used as a topping, a five-point hedonic scale was employed to assess color, aroma, taste, texture, and global impression. The scale was defined as follows1 – Strongly dislike, 2 – Dislike, 3 – Neutral, 4 – Like, 5 – Strongly like. The survey was conducted with a total of 30 participants, and the results were as follows:

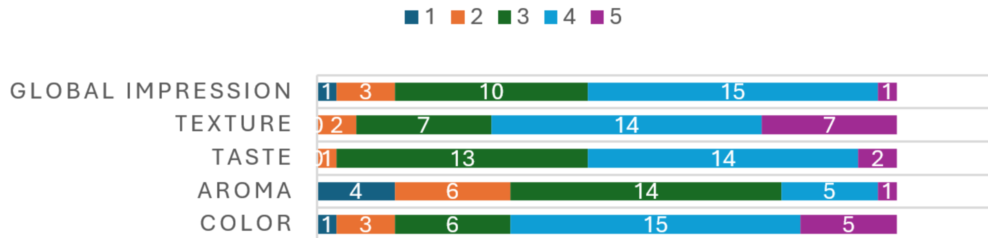


Figure 7. Sensory Test for Lyophilized Ungurahui Powder

The sensory evaluation results indicate that the lyophilized ungurahui powder was generally well received by the participants. Most ratings for color, aroma, taste, texture, and overall impression fell within the "like" (4) and "strongly like" (5) categories, suggesting a positive perception of the product. However, some participants rated certain attributes neutrally (3) or negatively (1–2), highlighting areas for potential improvement, particularly in texture and aroma.

5.3 Proposed Improvements

One critical adjustment made during the development of freeze-dried ungurahui powder was optimizing the temperature of the lyophilizer. Initially, the temperature was set at -40°C, which resulted in residual moisture levels of approximately 2.5% in the final product. By lowering the temperature to -50°C, the dehydration process improved significantly, reducing the final moisture content to 0.97%, as shown in the table below:

Table 8. Optimization of Freeze-Drying Temperature

Parameter	Initial Temperature (-40°C)	Optimized Temperature (-50°C)
Final Moisture Content (%)	2.50%	0.97%
Freeze-Drying Time (hours)	18	20

This improvement ensured a more stable product with better preservation of its antioxidant properties. In conjunction with temperature adjustment, extending the freeze-drying time by 2 hours (from 18 to 20 hours) further reduced residual moisture. While the longer drying time increased energy usage slightly, the trade-off was justified by improved product quality and shelf stability.

In the OPU laboratory, another improvement involved controlling the sample thickness on the trays. Initially, samples were spread unevenly, leading to inconsistent dehydration rates. By standardizing the thickness to 5 mm, moisture removal became more uniform, enhancing the reproducibility of the process.

5.4 Validation

The freeze-dried powder of ungurahui underwent spectrophotometric analysis using the DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging assay to quantify its antioxidant activity. This method was chosen for its precision in measuring free radical neutralization potential. The results consistently demonstrated high antioxidant activity, with values exceeding those of comparable products in the market. This reinforces the efficacy of the freeze-drying process in preserving bioactive compounds.

In addition, total polyphenol content was assessed as a complementary metric, given its strong correlation with antioxidant capacity. Using the Folin-Ciocalteu assay, the polyphenol content in the final product was significantly higher than in raw material controls, validating the enhanced concentration of antioxidants in the processed product.

The process was fine-tuned to maximize antioxidant retention. Key parameters, such as freezing rate and drying temperature, were optimized to minimize the degradation of sensitive bioactive compounds. Replicated trials confirmed the consistency of antioxidant values across production batches, highlighting the reproducibility and reliability of the method. The validation stage strongly supports that the antioxidant capacity, as the cornerstone of this project, was not only preserved but also enhanced through meticulous process development. These findings align with the project's overarching goal of creating a high-value, health-promoting product from ungurahui.

6. Conclusion

The study successfully evaluated the state of the art of ungurahui and the freeze-drying process in Peru, highlighting the limited use of advanced conservation technologies for this fruit and emphasizing a significant opportunity for growth in the local agro-industry. A detailed freeze-drying process for ungurahui was developed in the Operations and Unit Processes Laboratory at the University of Lima, optimizing critical variables such as temperature, pressure, and drying time to preserve the fruit's nutritional content and sensory attributes. Comprehensive analyses of the powdered ungurahui confirmed the retention of its antioxidant compounds, showcasing its potential as a high-value ingredient in the health and wellness market. Additionally, the project contributes to scientific knowledge on tropical fruit processing through advanced preservation technologies, positioning ungurahui powder as an innovative product that aligns with the growing demand for functional foods and sustainable food practices.

However, some limitations remain, such as the powder's low solubility and the need for further optimization of the freeze-drying parameters to enhance its efficiency. Future research could focus on improving solubility through stabilizing agents or modifications in the drying process, as well as assessing its large-scale commercial feasibility. Additionally, exploring its incorporation into different food matrices could expand its applications in the functional food industry, further increasing its market potential.

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