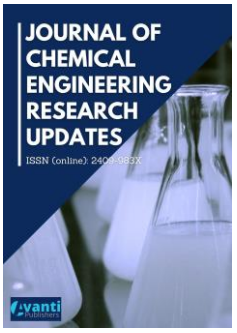
Published by Avanti Publishers

Journal of Chemical Engineering Research Updates

ISSN (online): 2409-983X



Validation of Solar Dehydrator for Food Drying Applications: A Granny Smith Apple Study

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ARTICLE INFO

Article Type: Research Article

Keywords:
Solar dehydrator
Food dehydration
Granny Smith apples
Psychrometric chamber

Timeline:
Received: May 16, 2022
Accepted: June 21, 2022
Published: July 22, 2022

Citation: Ingham J, Kanungo M, Beauchamp B, Korbut M, Swedish M, Navin M, Zhang W. Validation of Solar Dehydrator for Food Drying Applications: A Granny Smith Apple Study. J Chem Eng Res Updates, 2022; 9: 13-21.

DOI: https://doi.org/10.15377/2409-983X.2022.09.2

ABSTRACT

Food loss is a global issue that may be alleviated with effective dehydration strategies. Solar dehydration, rather than traditional sun-drying, is one method that could allow for the safe, efficient preservation of food materials. In this study, passive solar dehydration was achieved using a psychrometric chamber to model the environment of sub-Saharan Africa, where the temperature was the major focus (24.3 °C to 29.4 °C). A mass decrease of 88.56% was achieved within 9 hours. Microbial testing (total aerobic bacteria, Gram-negative bacteria, and total yeasts and molds) demonstrated no difference (all negative) between food stored at 4 °C and dehydrated food, indicating that the dehydrator introduced no new contamination. A 16.0% decrease in vitamin C (VC) concentration was observed due to the lability of VC. Insight into the visual appeal of the food samples was provided by measuring browning values, where it was found that dehydrated green apples are significantly less brown than the sample exposed to air for the same length of time. Passive solar dehydrators could provide a simple method to reduce food waste and maintain nutritional content and visual appeal.

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1. Introduction

Food loss and waste (FLW) is a pervasive issue threatening food security, environmental sustainability, and the global economy. Annually, approximately 1/3 of the food worldwide falls into the category of FLW, enough to feed two billion people [1]. Food loss is the unintended decrease in food quantity (mass) or quality prior to consumption, and it is primarily associated with post-harvest and processing stages [2,3]. Food waste is when food produced for human consumption is deliberately or non-deliberately discarded [2,3]. In underdeveloped countries, like sub-Saharan Africa (SSA), food loss accounts for up to 95% of the FLW. Poor preservation methods—which fail to inhibit microbiological growth and maintain sensory properties—contribute significantly to food spoilage. Dehydration is a preservation method based on the removal of water, and it involves two key components: (1) a reliable heat source and (2) the ability for moisture to be drawn and removed from the food. While dehydration is a simple and effective remedy to poor preservation, the process can degrade nutrients and fail to prevent spoilage caused by microorganisms.

Food dehydration is achieved through a variety of methods. Osmotic dehydration is a process in which water is transferred from the food material to a hypertonic solution due to a difference in osmotic pressure [4]. In microwave (MW)-assisted drying, microwave radiation is used to penetrate the material, and its conversion to thermal energy enables moisture removal [5]. Freeze-drying uses sublimation to remove ice from food material that has experienced freezing and a reduction in pressure [6]. Fluidized bed drying is a procedure in which water is removed through heat and mass transfer between moist solid particles and a hot air stream in which the particles are suspended [7]. The disadvantages to these industrial techniques are that they require a great amount of energy and are not economical in underdeveloped areas like sub-Saharan Africa [8]. Sun-drying is a method in which food material is directly exposed to solar radiation (part of which is used to evaporate water from the food), wind, and other ambient environmental factors. While this has been offered as a solution for issues arising from industrial designs, sun-drying still presents problems with microbial contamination and encroachment by insects, birds, and rodents, leading to high product losses. Solar dehydration is faster than sun-drying, yields products with better sensory properties, and is more hygienic [9]. Solar dehydration uses convective heat transfer between hot air and the food material to achieve dehydration and can mitigate many of the aforementioned concerns [10]. Specifically, there are two modes of solar dehydration: passive and active. In passive solar dehydration, air circulation is achieved through natural convection, as compared to its active counterpart, which employs forced convection (e.g., using fans), requiring more energy. Thus, passive solar dehydrators are more environmentally sustainable.

Additional concerns arise when considering the marketability of dehydrated foods, especially regarding the visual appeal of the food material. Sulfur dioxide (SO_2) is commonly used to preserve the vibrant color of fresh produce during dehydration, as it prevents both enzymatic and non-enzymatic browning. There is also evidence that sulphuration could reduce the total microbial load of dehydrated food [11,12]. Despite these advantages, sulfur dioxide treatment leads to an unappealing taste and potential adverse health effects. The Food and Drug Administration (FDA) estimates that 1% of the population is sulfite-sensitive, and 5% of asthma patients are sulfite sensitive [13]. Alternatives, like ascorbic acid treatment, have been explored to combat this issue, but they often affect the product's flavor.

In this study, the effectiveness of passive solar dehydration was investigated by determining microbial load, water loss, nutrient decomposition, and visual appeal. The environment of SSA (specifically temperature) was used to mimic solar dehydration in similar areas. The dehydration process was studied using Granny Smith (green) apples (GAs) because they are considered a "target fruit" for fruit preservation studies [14]. The nutritional value, microbial load, and sensory properties were evaluated. Vitamin C (VC) was chosen as an indicator of nutritional content because of its thermal and oxidative lability [15]. Evaluation of Gram-negative bacteria was conducted because nearly 69% of the food-borne bacterial disease cases in the United States are attributed to Gram-negative bacteria [16]. The findings of this study indicate that solar dehydration is a promising method for food preservation, especially in environmentally-conscious and developing regions.

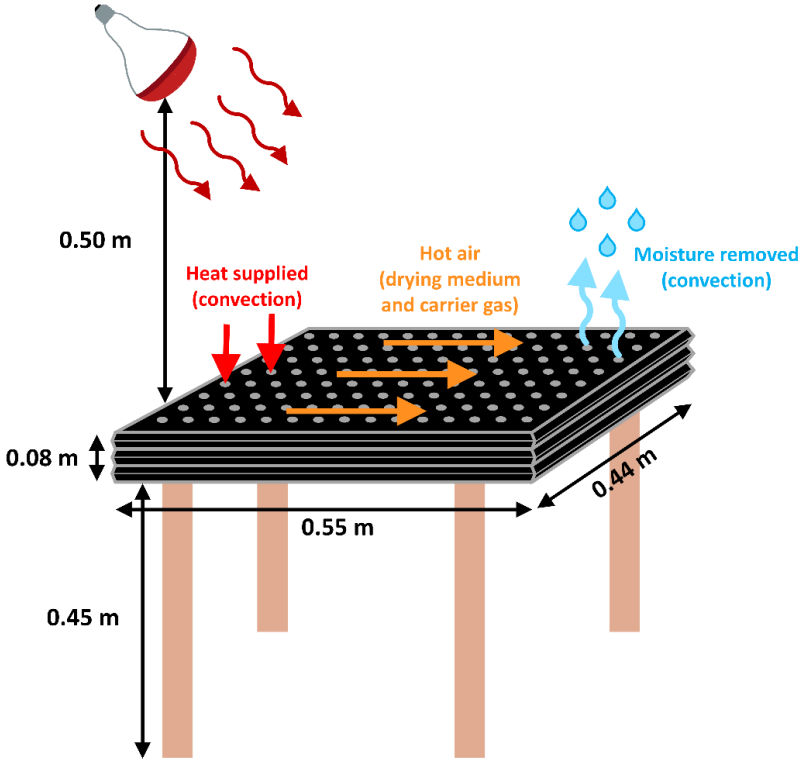
2. Materials and Methods

2.1. Materials

Granny Smith apples (GAs) were purchased from local grocery stores and refrigerated at 4 °C. A solar dehydrator was acquired from Agricycle© (Milwaukee, WI, USA). Heat lamps (Woods) were purchased. For microbiological analysis, standard plate count agar (PCA; #CM0463; Oxoid Limited, Hampshire, UK) and MacConkey agar (#784480; Carolina Biological Supply Company, Burlington, NC, USA) plates were poured per the manufacturer's instructions, while potato dextrose agar (PDA) plates (#470180-690, Ward's Science, Rochester, NY, USA) were used as obtained.

2.2. Food Preparation and Dehydration Setup

GAs were rinsed with water, sliced to a thickness of 3 mm using a mandolin slicer, and placed on dehydrator trays approximately 2.5-5 cm apart. Three dehydrator trays were stacked in the psychrometric chamber at 0.45 m above the ground on a stand, and an infrared lamp was placed at 0.5 m above the topmost dehydrator tray. An infrared lamp was used because infrared light accounts for approximately 50% of solar energy [17,18], and multiple solar simulator designs focus on mimicking infrared radiation [19,20]. This portion of solar energy is responsible for thermal radiation, a major component of the dehydration process [21]. The setup of the dehydration apparatus is shown in Schematic 1. Dehydration was performed in a psychrometric chamber (design detailed in a previous work [22]) for approximately 9 hours (less than the conventional solar drying time of 32 hours [23]) to mimic the average length of daylight in SSA and follow the recommendation provided by the dehydrator manufacturers. Temperature and humidity were monitored through the chamber control panel.



Schematic 1: Dehydrator setup.

2.3. Water Loss Measurements

The cumulative mass of slices in each tray was measured hourly using an analytical balance. Water loss was normalized to percentage weight loss using Equation (1),

$$\% \text{ weight loss} = \frac{\text{initial mass} - \text{final mass}}{\text{initial mass}} \times 100\%, \quad (1)$$

where the initial mass corresponds to the dehydrated sample prior to dehydration and the final mass corresponds to the sample post-dehydration.

2.4. Microbiological Analysis

Fruit extract was made aseptically by blending 5 g of the food material in 100 mL 1X phosphate buffer solution (PBS) for 45 s. The mixture was centrifuged (4000 RPM; 5 min; 4 °C) to produce the extract (supernatant). Plate count agar (PCA), MacConkey agar, and potato dextrose agar (PDA) plates were inoculated with 500 µL apple extract to quantify total aerobic bacteria, Gram-negative bacteria, and total yeasts and molds, respectively. *Escherichia coli* (#470176-528, Ward's Science, Rochester, NY, USA) and *Saccharomyces cerevisiae* (Red Star Yeast Company, Milwaukee, WI) were used as positive controls.

2.5. Determination of Vitamin C Content

The concentration of vitamin C (VC) in the undehydrated and dehydrated GAs was analyzed using iodometric titrations [24,25]. In short, 10 mL of fruit extract, 1 mL of 1 M HCl (H0013; Flinn Scientific, Batavia, IL, USA), 1 mL of 0.6 M potassium iodide (#746428; Millipore Sigma, St. Louis, MO, USA), 0.2 mL of 0.5% starch (#S25582; Fisher Scientific, Rochester, NY, USA), and 33 mL of DI water were mixed in a flask. The mixture was titrated with 0.002 M potassium iodate (#A16162; Tewksbury, MA, United States), and the endpoint was indicated by the first permanent trace of a blue-black color.

2.6. Measurement of Browning Intensity

The absorbance of Granny Smith apple extract, a blended and filtered mixture of 5 g sample and 100 mL 1X PBS, was determined at 420 nm using a UV-Vis spectrophotometer (Genesys™ 150; Thermo Fisher Scientific, Waltham, MA, USA) [26,27]. The negative control was an extract of fresh apples of the same batch, while the positive control was an extract of sliced apples exposed to air at room temperature for the same timeframe as dehydration.

2.7. Residual Water Measurement

The measurement was conducted according to the standard method [28,29]. Oven-drying was conducted at 105 °C, with a mass measurement conducted every 30 minutes until the sample mass remained constant. The samples taken from the drying oven were weighed immediately to avoid further dehydration. The residual water content of the dehydrated food was calculated by mass difference, according to Equation (2),

$$\text{water content} = \frac{\text{mass after dehydration} - \text{final mass}}{\text{initial mass} - \text{final mass}} \times 100\% \quad (2)$$

3. Results and Discussion

3.1. Dehydration Process

During dehydration, the temperature and relative humidity remained relatively stable, with temperatures ranging from 24.3 °C to 29.4 °C and relative humidity values ranging from 8.2% to 23.0% (Figure **1**). The mass of GAs began to decrease almost immediately after being placed in the dehydrator, mainly due to water loss. During dehydration, 88.56% of the initial mass was lost, as depicted in Figures **2**(a and b). This loss in mass is attributed to the natural convection mechanism, which involves heat and mass transfer. Heat is transferred to the food material through conduction and convection [30]. Simultaneously, water (mass) is transferred from the interior of the food material to its surface *via* diffusion and removed by the hot air [30]. The mass values plateaued when nearing complete dryness due to a decrease in the difference of temperature and water concentration between the apple slices and their surrounding environment [30].

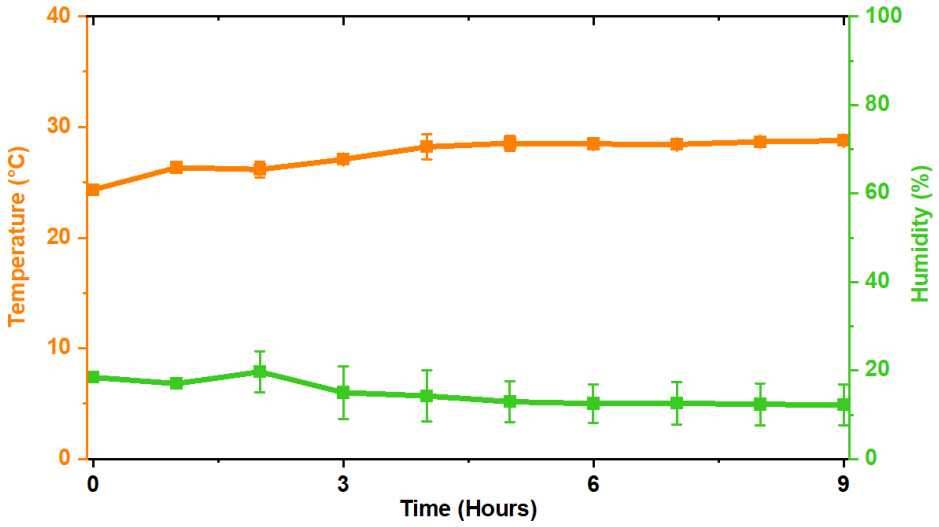


Figure 1: Temperature and humidity changes inside psychrometric chamber throughout food dehydration for a typical run for GAs.

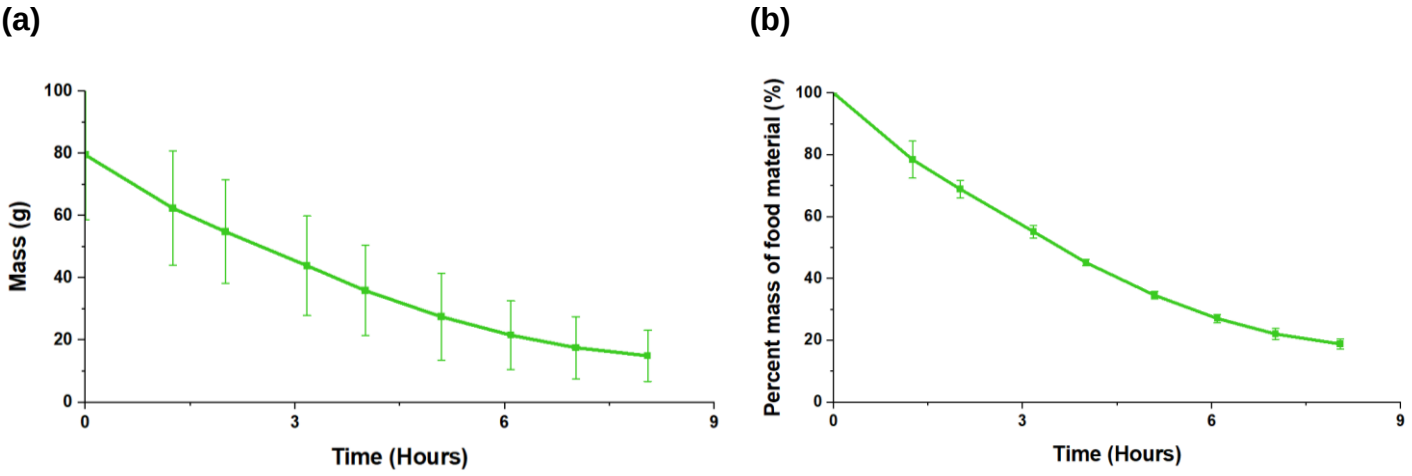


Figure 2: Mass change in GAs mass during passive dehydration in grams (a) and percent (b).

3.2. Microbiological Analysis

Both the GAs that were stored at 4 °C and the GAs that were dehydrated had a value of 0 CFU/g for total viable aerobic microorganisms, Gram-negative bacteria, and total yeasts and molds (Figure **3**). This indicates that dehydration did not introduce microbial contamination. Additionally, the low pH of the Granny Smith apples (pH = 3.56) may have inhibited the proliferation of microorganisms. Gram-negative bacteria are especially susceptible to high pH environments because they have a thinner (2-3 nm) peptidoglycan (PTG) layer than Gram-positive bacteria (30 nm). The thin PTG layer is weakened by high pH and can eventuate in the solubilization of plasma membrane proteins and saponification of plasma membrane lipids. This allows the plasma membrane to expand and burst [16].

3.3. Vitamin C Content Quantification

Vitamin C (VC) is often used as an overall indicator of nutritional quality due to its vulnerability to various conditions (such as heat and light) and processes [33]. Undehydrated green apples stored at 4 °C had a VC concentration of 0.0352 ± 0.0049 mg VC/g sample, while dehydrated samples had a VC concentration of 0.0296 ± 0.0000 mg VC/g sample, a loss of 16.0% (Figure **4**). Other studies have demonstrated 10-50% losses during infrared drying of apple slices [34]. The loss in VC is primarily ascribed to the drying time rather than temperature

because the drying temperature is relatively low. This aligns with previous studies that demonstrate the impact of drying time on VC degradation [35,36]. The decrease in VC may be associated with oxidation during lengthy drying periods [37,38].

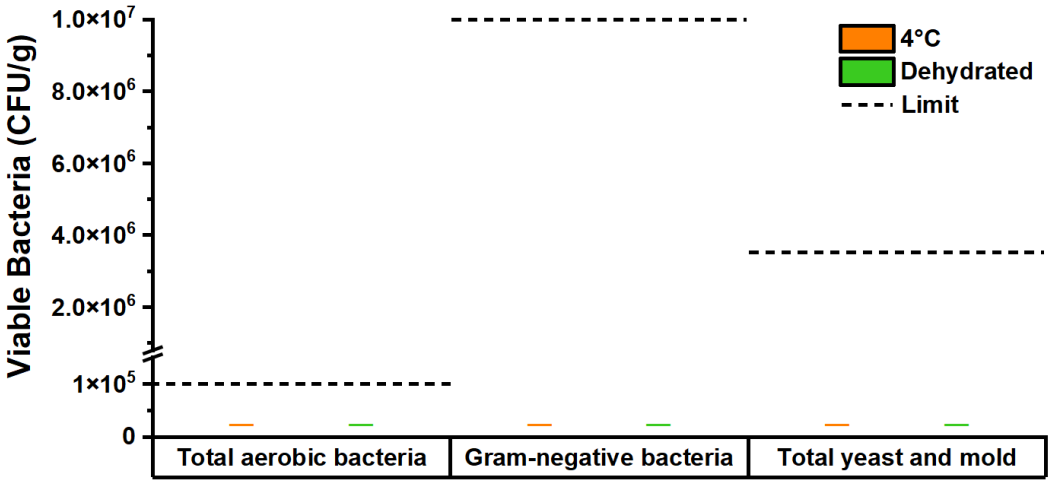


Figure 3: Microbiological content of refrigerated (4 °C) and dehydrated GAs. The dashed line for total aerobic bacteria indicates government limits, while the dashed lines for Gram-negative bacteria and total yeasts and molds indicate values at which spoilage occurs, according to literature [31,32].

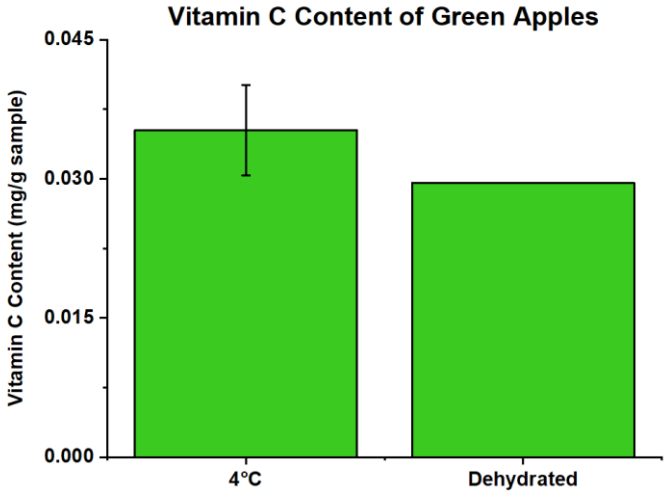


Figure 4: Vitamin C content of refrigerated (4 °C) and dehydrated GAs.

3.4. Browning Intensity

Color retention is a crucial factor in the marketability of food products, as there is a clear correlation between consumer interest and the color of the purchased food item [39]. Browning appeared at the surface of apple slices due to wounding, indicating the oxidation of polyphenolic compounds. The relative browning intensity of the dehydrated samples, represented by spectrophotometric absorbance, was greater than that of fresh samples but less than that of the positive control (as shown in Figure **5** and Figure **6**). The dehydration process likely inhibits some enzymatic browning through a decrease in water content. Some enzymatic browning occurs during dehydration because polyphenols are oxidized by polyphenol oxidase (PPO). GAs have many phenolic substrates, and O_2 is transported to phenolic substrates by PPO, catalyzing enzymatic browning reactions [14]. The oxidized polyphenols increase the rate of deterioration and nutrient degradation and take the form of brown pigments, such as melanin, that affect sensory characteristics [40].

Conversely, the heat present at the surface of the apple slices during dehydration degrades VC and phenolic compounds, which accelerate non-enzymatic browning reactions [41]. The temperature used during dehydration may have inactivated phenolases, preventing browning reactions. A previous study also found that within the first hour of drying apples, there was a 90% decrease in PPO activity, but drying does not entirely inactivate this enzyme, which is why some browning occurs [42].

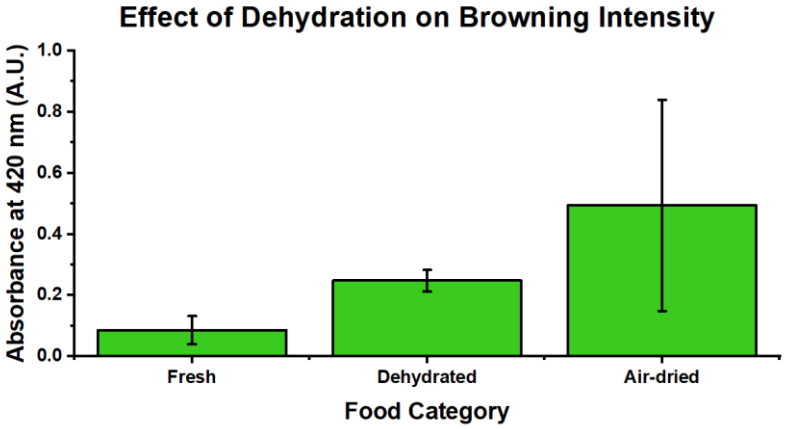


Figure 5: Relative browning intensity of fresh, dehydrated, and browned GAs.

Figure 6: Pictures of samples before (left) and after (right) dehydration.

4. Conclusion

Passive solar dehydration demonstrates the potential for food preservation in food-insecure regions, with the benefits of color retention (without sulfur dioxide), high vitamin C retention, and minimized microbial contamination. For dehydration, sub-Saharan Africa's environment was modeled using a psychrometric chamber to maintain temperatures between 24.3 °C to 29.4 °C. Within 9 hours, the initial mass of the food material decreased by 88.6% due to the removal of water. Investigation into the microbial load of GAs stored at 4 °C and dehydrated GAs showed no presence of total aerobic bacteria, Gram-negative bacteria, and total yeasts and molds. The VC concentration of GAs decreased by 16.0%, which is lower than losses observed when using other conventional dehydration methods. Regarding sensory qualities, the browning value for the dehydrated GAs fell between that for undehydrated GAs and GAs that had been exposed to ambient air conditions during the dehydration period. Future research could involve quantifying sensory properties (e.g., dissolved solids content). Additionally, the nutritional value of dehydrated products could be measured by analyzing vitamin A and iron content.

Credit Authorship Contribution Statement

Jude Ingham, Muskan Kanungo, Brandon Beauchamp, Michael Korbut, Michael Swedish, and Michael Navin conducted the experiments. Jude Ingham, Muskan Kanungo, Brandon Beauchamp, and Michael Korbut performed data analysis and wrote the manuscript. Wujie Zhang advised the project. All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

The authors declare no conflict of interest.

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