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Impact of Different Drying Methods on The Quality Attributes of Bilimbi (*Averrhoa bilimbi* L.) Fruits

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ABSTRACT

Bilimbi (*Averrhoa bilimbi* L.), a sour tropical fruit, is underutilized but has significant export potential. Drying, a key preservation method to increase the shelf-life of the bilimbi fruits. Therefore, this study evaluated the effects of sun, dehydrator, microwave oven, and electric oven drying on the physicochemical, proximate, antioxidant, and sensory properties of bilimbi fruits. Using AOAC methods, the physical and nutritional properties were analyzed, while antioxidant activity was measured via DPPH radical scavenging, total polyphenol content, and total flavonoid content assays. Results were statistically compared using one-way ANOVA with Tukey's test. Sensory analysis, conducted by 30 semi-trained panelists using a 7-point hedonic scale, was analyzed using the Kruskal-Wallis test. The dehydrator-dried bilimbi sample exhibited the highest rehydration ratio (3.97±0.02), crude protein (5.50±0.15%), crude fat (3.64±0.01%), and crude fiber (8.939±1.26%), along with the lowest water activity (0.48±0.002). The microwave oven-dried sample had the highest ash (17.1±3.14%), vitamin C (4.46±1.26 mg/g), and total polyphenol (71.96±1.27 mg GAE/g) content, with the lowest moisture content (5.17±0.08%). The oven-dried sample exhibited the highest DPPH radical scavenging activity (10.66±0.10 µg TE/g) and the best surface structure. Overall, dehydrator drying proved to be the best method for preserving the sensory and nutritional qualities of bilimbi fruit.

Keywords: Bilimbi fruits, dehydration, physical properties, nutritional properties, sensory properties, antioxidant properties

INTRODUCTION

Bilimbi fruit (*Averrhoa bilimbi* L.) which is belong to the family Oxalidaceae is an underutilized fruit commonly found in home gardens and small orchards in tropical regions. The tree is relatively hardy and can thrive in a variety of soil types, though it prefers well-drained, sandy loam soils. It is typically propagated through seeds and vegetative propagation methods such as grafting and budding (Rao and Reddy, 2019). The fruit of bilimbi is elongated, cylindrical, and resembles a small, green cucumber. The fruit's skin is thin and glossy, and its flesh is juicy, with a tart, acidic flavor due to its high oxalic acid content. When ripe, the fruit turns a yellowish-green color.

Bilimbi fruit is widely used in culinary traditions across Southeast Asia, India, and the Caribbean. Due to its sharp, sour taste, it is often used as a flavoring agent in various dishes. In Malaysia and Indonesia, bilimbi is commonly added to sambals and curries to provide a tangy twist (Pino et al., 2004). In India, it is used in chutneys, pickles, and as a souring agent in traditional dishes like fish curry (Raghavan, 2007). The fruit is also used in the preparation of refreshing drinks and preserves. In some regions, bilimbi is candied or used to make jams and jellies. Moreover, bilimbi fruit can be used in the production of vinegar, wine, pickles, and as a substitutes of lime and tamarind.

Bilimbi fruit is low in calories and rich in nutrients, making it a healthy addition to the diet. It is an excellent source of vitamin C, providing strong antioxidant benefits (Kumar et al., 2013). The fruit also contains smaller amounts of vitamins A and B, as well as minerals such as potassium, calcium, and iron (Lim, 2012). Bilimbi is high in oxalic acid, which contributes to its sour taste, and has been noted for its potential benefits in reducing urinary calcium and preventing kidney stones (Rao and Reddy, 2019). Additionally, the fruit contains dietary fiber, which aids in digestion and promotes gut health. Moreover, in traditional medicines, bilimbi fruit is used for cough mumps, pimples and to cure scurvy like conditions (Wong and Wong, 1995).

Bilimbi fruit can be value-added through drying, and the dried product serves as an excellent souring agent for dishes and curries. However, despite its significant potential for economic gain, bilimbi is largely overlooked (Rao and Reddy, 2019). Small-scale producers could prepare it for local or export markets, yet this opportunity remains underutilized. Drying is a common preservation method that can significantly extend the shelf life of bilimbi, allowing it to be enjoyed year-round and reducing post-harvest losses (Lim, 2012). However, the choice of drying technique can markedly influence the fruit's quality in terms of its nutritional content, flavor, texture, and color (Kumar et al., 2013). Therefore, evaluation of the effect of different drying techniques on the quality of bilimbi fruit is crucial for optimizing both its nutritional and sensory attributes. By systematically assessing the impact of sun drying, microwave oven drying, dehydrator drying, and oven drying, researchers and producers can determine the most effective method to retain the desirable qualities of bilimbi (Lim, 2012; Kumar et al., 2013).

Sun drying, a traditional and cost-effective method, utilizes natural sunlight to remove moisture from the fruit. This technique is energy-efficient and accessible in regions with ample sunlight. However, it poses challenges such as long drying times and exposure to environmental contaminants, which can affect the safety and quality of the dried product (Chauhan and Kumar, 2016). Microwave oven drying is a more modern technique that employs microwave radiation to rapidly remove moisture. This method is known for its speed and efficiency, potentially preserving more nutrients due to shorter drying times. However, it can also cause uneven drying and possible scorching if not properly controlled (Vadivambal and Jayas, 2007). Dehydrator drying uses controlled temperature and airflow to dehydrate the fruit, offering a balance between efficiency and quality preservation. Dehydrators are designed to provide consistent drying conditions, which can help maintain the nutritional and sensory qualities of bilimbi more effectively than sun drying. This method is particularly relevant for small-scale and commercial producers seeking reliable and repeatable results. Oven drying, another widely used method, involves using conventional ovens to dry the fruit at controlled temperatures. This technique offers the advantage of being accessible and easy to regulate, allowing for consistent drying conditions. However, it can be energy-intensive and may require longer drying times compared to microwave drying (Kumar et al., 2014).

Evaluating the effects of different drying techniques on bilimbi is essential for identifying the most suitable method to preserve its quality. Each technique has distinct advantages and limitations that can affect the nutritional content, safety, and sensory properties of the dried fruit. By understanding these impacts, producers can make informed decisions to optimize drying processes, ultimately enhancing the value and appeal of bilimbi in both domestic and international markets. Therefore, this research aimed to examine the changes of physicochemical, nutritional, antioxidant, and sensory properties of bilimbi fruit under different drying techniques in order to recommend the most effective drying technique that can preserve textural and nutritional properties.

MATERIALS AND METHODS

Sample preparation

Fully matured green colored fresh bilimbi fruits (*Averrhoa bilimbi* L.) were plucked from the home gardens in Weerakatiya, Hambantota, Sri Lanka (Latitude: 6.1476° N and Longitude: 80.7634° E). Preliminary experiments were conducted to optimize the pre-treatment methods, drying temperature, and time combination for different drying techniques which were sun drying, dehydrator drying, microwave oven drying, and oven drying techniques. The summary of the optimized conditions for each drying method is shown in Table 1.

Fresh bilimbi samples were pre-treated and dried according to the methods described in Table 1 until their moisture content reached 2-5% in dry weight basis. The dried samples were then packed in high-density polyethylene (HDPE) bags and stored at room temperature until further use.

Determination of physico-chemical properties of dried bilimbi

Development of drying characteristic curves

Drying characteristic curves were developed using the method described by Datta (2018) with modifications. Samples were cut into pieces, and 5 g of sample were transferred to a moisture can for moisture content determination using the AOAC (2000) standard method. Weight measurements were taken at 5-minute intervals. The data were used to calculate moisture content (MC_i), moisture fraction (X_i) and drying rate (DR) using the equations given below.

$$MC_i = \frac{m_i - m_f}{m_f} \times 100$$

where, MCi is the dry-basis moisture content (g H_2O/100 g dry solid) at ith time interval; m_i is the sample weight at ith time interval and m_f is the final mass of dry solid in the sample.

$$X_i = \frac{MC_i}{100}$$

$$DR = \frac{dx}{dt} = \frac{X_{i-1} - X_i}{t_i - t_{i-1}}$$

where, X_i is moisture fraction (g of water/g of dry solid) at ith time interval; DR is drying rate (g of water g of dry solids^{-1} min^{-1}) between (i−1)th and ith time (t) intervals (Datta, 2018).

Determination of color

The color parameters (L*, a*, and b* values) of the dried bilimbi samples were determined using a colorimeter (BCM-200, China). The L* value represents brightness (100 for white, 0 for black), a* value indicates red-green axis, and b* value denotes yellow-blue axis.

Determination of rehydration ratio

The rehydration ratio of dried bilimbi samples were calculated using the method described by Ranganna (2001) with some modifications. One gram of the dried sample was mixed with 10 mL of distilled water and immersed for 1 hour and 40 minutes at room temperature. After filtration, the weight of the rehydrated sample was recorded. The rehydration ratio was calculated by dividing the mass of rehydration sample by the mass of dehydration sample.

Determination of water activity

Water activity of the dried samples was measured using a water activity meter (Lab-Touch aw, Switzerland). One gram of the sample was placed in the designated cup of the meter, and the data were recorded.

Determination of texture profile

Texture profiles (hardness, springiness, chewiness, gumminess) were measured using a Brookfield CT3 texture analyzer with a TA41 cylindrical probe, 5 g trigger load, and 50,000 g load cell at 1 mm/s test speed.

Observation of microstructure of dried bilimbi

Scanning Electron Microscope (SEM) images were taken by using the SEM instrument. Dried bilimbi samples were mounted on the aluminium mount sand affixed using double carbon tape. The sample prepared is placed in SEM chamber. Then SEM chamber achieved high vacuum and images were captured.

Determination of proximate composition of dried bilimbi

Proximate composition such as moisture, ash, crude fiber, crude protein, and crude fat contents of dried bilimbi samples was assessed using AOAC (2000) standard methods.

Determination of bioactive properties of dried bilimbi

Preparation of sample extract

The amount of 1 g of dried bilimbi sample was mixed with 10 mL of methanol and mixture was vortexed. Then it was centrifuged at 5000 rpm for 20 min and the supernatant was collected as the extract for analyze the bioactive properties.

Determination of total flavonoid content

The flavonoid content of the extract was determined using the method outlined by Saha et al. (2023) with some modifications. The volume of 1 mL of the sample extract or standard (quercetin) was combined with 0.3 mL of a 5% $NaNO_2$ solution, followed by the addition of 0.3 mL of a 10% $AlCl_3$ solution and 2 mL of a 1M NaOH solution. After allowing the mixture to react for 6 minutes, it was diluted to a final volume of 10 mL with distilled water and then incubated for 1 hour in the dark. The absorbance of the mixture was then measured at 510 nm using a spectrophotometer (HACH DR 3900, Germany). The total flavonoid content of the sample was calculated using the standard curve equation derived from various concentrations of quercetin and expressed in µg of Quercetin Equivalents (QE) per gram.

Determination of total polyphenol content

The polyphenol content was estimated using the Folin-Ciocalteu method described by Chandra et al. (2014) with some modifications. In brief, a standard solution was prepared by dissolving 10 mg of gallic acid in 1 mL of ethanol and then diluting it to 100 mL with distilled water. Then, 2 mL of the sample or standard solution was mixed with 2 mL of a 10% (v/v) Folin-Ciocalteu solution and 2 mL of 7.5% (w/v) Na_2CO_3, and the volume was adjusted to 10 mL with distilled water. The mixture was incubated in the dark for 120 minutes, and the absorbance was measured at 760 nm. The total polyphenol content of the sample was calculated using the standard curve equation developed from different concentrations of gallic acid and results were expressed in mg of Gallic Acid Equivalents (GAE) per gram.

Determination of DPPH radical scavenging activity

The antioxidant activity of the dried bilimbi extract was assessed using the DPPH-radical scavenging method, as described by Fernando et al. (2022), with some modifications. To prepare the standard solutions, 25 mg of Trolox was dissolved in 25 mL of ethanol and then diluted to a total volume of 100 mL. A volume of 0.4 mL sample or standard solution was mixed with 4 mL of a 0.1 mM DPPH radical solution and incubated in the dark for 30 minutes. The absorbance of the mixture was then measured at 415 nm. The antioxidant activity of the sample was determined using a standard curve equation developed from various concentrations of Trolox and results were expressed as µg of Trolox Equivalents (TE) per gram.

Determination of Ascorbic acid content

Ascorbic acid content of dried bilimbi samples was determined using DI regent method described by Baker and Flatman (2007) with some modifications. The preparation of the ascorbic acid standard solution involved dissolving 100 mg of ascorbic acid in 100 mL of distilled water. For the DI reagent, 100 mL of distilled water, 0.4 g of $NaHCO_3$, and 0.5 g of 2, 6-Dichlorophenolindophenol (DCPIP) were mixed and diluted to 1000 mL with distilled water. The dried bilimbi sample extract was prepared by mixing 1 g of dried bilimbi sample with 10 mL of 10% (v/v) acetic acid and centrifuged at 2100 rpm for 20 minutes at 15 °C. The supernatant was filtered, and the filtrate was used for titration. During titration, the filtrate was titrated with the DI reagent until a light pink color was achieved, with the dye in the burette and the extracted solution in a conical flask. The volume used for the titration was recorded, and the ascorbic acid percentage in the sample was calculated.

Determination of sensory properties of dried bilimbi samples

Sensory evaluation of the dried bilimbi samples was conducted using 30 semi-trained panelists using 7-point hedonic scale. Dried bilimbi was used in a form of pickle for sensory analysis and the same amount of chili powder, pepper powder, and sugar were added to make pickles from the bilimbi fruits dried using different techniques. Sensory attributes such as appearance, color flavor, aroma, taste, and texture (hardness) were analyzed.

Data analysis

All the data are presented as mean ± standard deviation of three replicates. Sensory Data was analyzed using Kruskal-Wallis non-parametric One-way ANOVA method using Statistix software Version 10 for Windows. One way ANOVA with Tukey's Post-hoc multiple comparison test using MINTAB software version 17.0 for

Windows was used to compare the results of different drying techniques.

RESULTS AND DISCUSSION

Comparison of Physical Properties of dried bilimbi fruits obtained from different drying methods

The physical properties such as drying curves, color, rehydration ratio, water activity, texture, and surface structure changes of the bilimbi fruits obtained from different drying methods were tested. Preparation of drying curves is important to get an idea about the drying efficiency of different drying methods (Zielinska and Markowski, 2018). In the present study, two types of drying curves were developed such as the variation of dry basis moisture content with time (Figure 1A) and variation of drying rate with dry basis moisture content (Fig. 1B). As shown in Figure 1A, microwave drying shows the steepest initial moisture decline, reflecting extremely fast removal of moisture while sun drying displays the slowest and most gradual decline in moisture content and it takes significantly longer time to reach constant moisture compared to the other methods, Results showed that the moisture content started to be constant at 300 min, 120 min, 70 min and 30 min for sun drying, dehydrator drying, oven drying and microwave drying, respectively. In Figure 1B, the drying rates peak at very high at the beginning with showing slightly constant rates of drying in microwave and oven drying methods. Then it shows an unsteady decline of the drying rates, suggesting the falling rates in bilimbi fruit in all drying methods due to unequal moisture migration between the inside and outside of water body in the food. It was found that the drying process of most of the fruits including apple, grapes and banana occurred mainly in the falling rate period due to quick surface drying at the beginning and creating a partial barrier that resists free moisture movement (Borah et al., 2015: Togrul et al., 2004). It is clear that microwave drying is the most efficient, maintaining the highest drying rate over a range of moisture contents while sun drying is the least efficient, with the lowest drying rate and prolonged drying time.

Color is one of the most important quality parameters of dried fruits and vegetables. The color of the dried products mainly depends on the drying temperature and exposes time of the product for drying (Karam et al., 2016). L* values depict the lightness (where 100 signifies white and 0 represents black) of the products whereas a* and b* values represent the color redness and color yellowness, respectively. The colour values of the dried bilimbi samples obtained from different drying methods are shown in Table 2. The highest L* value was received by the dehydrated dry bilimbi (42.10±7.27) while the lowest L* value was obtained by the microwave oven dry bilimbi. However, there were no significant differences ($P>0.05$) among the drying methods for L* and a* values of the dried samples. Overall, dehydrator-dried bilimbi samples showed highest value for all L*, a* and b* values and thus, having acceptable lightness color.

The rehydration ratio is a term that quantifies the proportion of water required to restore a dehydrated food item, typically expressed as a ratio of the weight of the dried ingredient to the amount of water needed for rehydration. Rehydration of dried products is correlated with loose and porous structures which can be formed during drying process (Krokida and Zacharias, 2001). In the present study, the rehydration ratio of the different samples ranged from 2.88 to 3.97. The dehydrator-dried bilimbi showed the highest rehydration ratio (3.97±0.02) while the sun-dried bilimbi showed the lowest value (2.88±01). The reasons for showing different rehydration ratios may be the heat applied efficiency for the dying, drying temperature, and time. Considering the heat applied efficiency dehydrator provides uniform heat during the time than sun drying and thus, cell changes happen rapidly in dehydrator-dried fruits.

Water activity is a crucial parameter for dried products as it indicates the amount of water accessible for chemical reactions and microbial growth in food products (Barbosa-Cánovas et al., 2020). The water activity of the dried fruits should be less than 0.6 and the results of the present study are aligned with the recommended values (Ozcelik et al., 2020). The lowest water activity of 0.48±0.002 was shown by dehydrator-dried bilimbi samples while the highest water activity of 0.56±0.006 was shown by the sun-dried samples. The reason for this could be the higher drying temperature employed in the dehydrator drying method and it causes faster water evaporation. Other than that drying time, particle size, humidity, and drying temperature also lead to water activity differences. Moreover, studies have indicated that maintaining a water activity level below 5% leads to decreased browning, hydrolytic reactions, lipid oxidation, auto-oxidation, and enzymatic activity in dried products (Shahari et al., 2015).

The texture profile of the dried bilimbi samples was tested using the texture profile analyzer and results are shown in Table 2. Texture profiles such as hardness, gumminess, chewiness, and springiness are important parameters to assess the quality of the food product after drying. The texture of fruits can be affected by factors such as the composition of cell walls, the proportion of essential constituents within cells, fruit maturity, and moisture content. Water content, drying method, temperature and time of drying, pre-treatment processes, and fruit type are other factors that can influence the final texture profile of the dried products. Fruits containing abundant water typically exhibit soft and juicy textures with low hardness. However, the removal of water is linked to the formation of dried products that are harder and more brittle (Dhara et al., 2023). In the present study, there were significant differences ($P<0.05$) can be seen among the hardness of the dried bilimbi obtained from different drying methods. This may be due to the variation of drying temperature, exposure time, and air velocity used in different drying methods. However, there were no significant differences ($P>0.05$) can be seen in the springiness, gumminess, and chewiness of the dried samples obtained from different drying methods. Overall, microwave-dried bilimbi samples showed the best texture profile compared to the other drying methods.

In addition, the microstructure of dried bilimbi samples was observed under the scanning electron microscopy (SEM) method, and images are shown in Fig.2. SEM analysis of the dried product is essential for a comprehensive understanding of their microstructure, quality, and the impact of processing parameters which contributed to improved product development and manufacturing processes (Wickramarachchi and Ranamukhaarachchi, 2005). Compared to the fresh bilimbi samples, the principal changes that can be seen in dried samples were cracks and fractures, surface roughness, and structural changes such as cell disruptions, and shrinkages. The rapid increase in vapor pressure in the cells during the drying and shrinkage after water removal can cause internal stress in cell structure and it alters the surface tension (Ngamwonglumlert and Devahastin, 2018). The rapid removal of water at high temperatures causes to create large amount of stress and exceeds the natural capacity of fruit tissue result the cracks and fractures (Dhara et al., 2023). In dehydrator-dried sample showed more cell rupture and destruction compared to the samples obtained from other drying methods. In contrast, oven-dried samples showed the best microstructure after drying and it may be due to the presence of comparatively high moisture content (6.87±0.11%) in the dried samples compared to the other dried bilimbi samples. Because of the undesirable color changes within a short period of time, and oven-dried sample was kept less time in the oven than others.

Comparison of proximate composition of dried bilimbi fruits obtained from different drying methods

The proximate composition of dried bilimbi fruits using different drying methods is summarized in Table 3. The proximate composition gives valuable information about the basic nutritional components present in a particular food product. This helps to evaluate the nutritional quality, shelf-life stability, and potential applications of the food product. The moisture content of the fresh bilimbi used in the present study was 88.92±0.56% and dehydrator-dried bilimbi fruits showed the lowest moisture content (5.02±1.10%), while the electric oven-dried bilimbi fruits showed the highest value (6.87±0.11%). The reason could be the less drying temperature and time applied in electric oven caused less evaporation of water compared to the other drying methods. According to Nilugin and Mahendran (2016), the moisture content of the dried product should be less than 3.5% and if not, it may cause to reduce shelf-life of the dried product. However, the moisture content of the dried bilimbi samples in the present study showed slightly higher value than the recommended value.

There was a significant difference ($P<0.05$) of the fat content among the dried bilimbi obtained using different drying methods. A study conducted by Ratti (2001) mentioned that the lipid oxidation happens during the drying process may be the reason for showing differences in the fat content of the samples. Moreover, varying intensity of heat, light, and radiation may cause an increase of lipid oxidation rate under different drying methods.

There was no significant difference ($P>0.05$) in the fiber content of dried bilimbi yield from different drying methods. Fiber is a measurement of the quantity of indigestible cellulose, pentosans, and lignins present in foods (Nilugin and Mahendran, 2016). The fruit drying process generally concentrates their fiber content, as the water content decreases during the drying process. This result is due to the presence of higher percentage of fiber per unit weight in the dried fruits compared to the fresh products (Ratti, 2001).

The highest protein content (5.50±0.10%) was shown by dehydrator-dried bilimbi fruits while the lowest protein content (4.191±0.14%) was shown by sun-dried bilimbi fruits. The fluctuating protein content could be attributed to protein degradation occurring during heat application, which weakens the three-dimensional structure of protein cells. This can result in protein loss under different drying conditions (Ratti, 2001).

There was no significant difference ($P>0.05$) in the ash content of the different dried bilimbi. However, microwave-dried bilimbi showed the highest ash content (15.76±1.79%), while sun-dried bilimbi showed the lowest (7.015±0.02%) ash content among the samples. The reason for showing different ash content among the samples could be the degradation of minerals under different thermal conditions and exposure time during the drying of the samples (Ratti, 2001).

Overall, the findings indicated that drying can markedly change the nutritional composition, influenced by factors such as food type, drying method, treatment intensity, and operational parameters.

Comparison of functional properties of dried bilimbi fruits obtained from different drying methods

The functional properties such as total polyphenol content, flavonoid content, total antioxidant content, and Vitamin C content of dried bilimbi samples were assessed and results are summarized in Table 3. As per the results, the microwave-dried bilimbi showed the significantly highest (P<0.05) total phenolic content (71.96±0.27 mg GAE /g), while the sun-dried bilimbi showed the lowest value (49.26±0.81 mg GAE/g). The reason for this could be the uncontrol drying temperature and prolong time to removal of water under sun drying condition than dehydrator dried sample (Dhara et al., 2023). According to the present study, microwave-dried bilimbi exposed to low time for drying and therefore, showed the highest phenolic content compared to the samples obtained from other drying methods.

Considering the flavonoid content, oven-dried bilimbi showed higher total flavonoid content (193.74±0.21 μg QE/g) than other dried bilimbi samples. According to Zainol et al., (2009), stability of flavonoid compounds may vary depending on the time/ temperature conditions provided under different drying conditions. Therefore, the variation of the flavonoid content of the samples could be observed.

Interestingly, sun-dried bilimbi showed the significantly highest antioxidant content (10.05±0.007 μg TE /g), while oven-dried bilimbi showed the lowest (9.51±0.003 μg TE /g) antioxidant activity. This could be mainly due to the aforementioned explanation of the stability of bioactive compounds under different thermal and operating conditions.

Vitamin C content of the microwave-dried bilimbi showed the highest value (4.46±1.26 mg/g), while dehydrator-dried bilimbi showed the lowest (1.60±0.25 mg/g) value. This is mainly due to degradation of thermal liable vitamin C at high temperatures (Ratti, 2001).

Comparison of Sensory Properties of the dried bilimbi fruits obtained from different drying methods

The results of the comparison of mean scores of the sensory attributes of four pickles made out from the differently dried bilimbi are shown in Table 4. According to the sensory results, there was no significant difference (P>0.05) among the samples for appearance, color, texture, and overall acceptability. However, dehydrator-dried bilimbi samples showed significantly higher acceptance (P<0.05) for appearance and colour among the other samples. Overall, dehydrator-dried bilimbi fruit showed the highest mean rank values for all the sensory attributes tested in the study. The reason for this may be equal heat applied for the short time period that saved the sensory properties of the dried fruits. Moreover, use of hot air application in dehydrator may contribute to minimize the overheat of the surface of the fruits (Ratti, 2001).

CONCLUSION

This study comprehensively evaluated the impact of various drying techniques i.e. sun drying, dehydrator drying, microwave oven drying, and electric oven drying on the physicochemical, proximate, antioxidant, and sensory properties of bilimbi fruits. The results of this study highlighted that there was significant impact of different drying techniques on the aforementioned properties of bilimbi fruits. Accordingly, dehydrator drying emerged as the most effective method for preserving the nutritional and sensory qualities of bilimbi. This method provided the highest rehydration ratio, crude protein, crude fat, and the lowest water activity, making it a superior technique for maintaining the quality and extending the shelf-life of bilimbi fruits. Microwave drying also showed promising results, particularly in retaining high levels of phenolic compounds and vitamin C, though it affected the texture and sensory attributes differently. The findings of the present study underscore the importance of selecting appropriate drying methods to enhance the utilization and marketability of underutilized fruits like bilimbi. Future research could explore the further optimization of drying parameters and investigate the economic feasibility of adopting these techniques on a larger scale. Overall, the study contributes valuable insights into the preservation of bilimbi fruits, offering practical recommendations for small-scale producers and potential applications in the food industry.

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Table 1. Optimized Drying Conditions for Bilimbi Fruits

Drying method	Pre-treatment method	Drying Temperature	Time/100 g Sample
Sun Drying	Soak in 1% salt solution for 5 min	55-60 °C	3 hr
Dehydrator Drying	Soak in 1% salt solution for 5 min	55 °C	1 hr
Microwave Oven Drying	Soak in 1% salt solution for 5 min	Low heat	35 min
Oven Drying	Soak in 1% salt solution for 5 min	100°C	40 min

Table 2. Results of the physical properties of Bilimbi Fruit under different drying methods

Physical Parameter	Drying methods			
	Sun drying	Dehydrator drying	Microwave drying	Electric Oven-drying
L* value	30.61±1.82[a]	42.10±7.27[a]	42.03±7.50[a]	30.16±3.29[a]
a* value	7.19±2.47[a]	9.79±1.26[a]	7.26±1.12[a]	6.167±0.45[a]
b* value	9.58±1.19[b]	16.73±2.20[a]	13.32±4.26[ab]	10.24±2.08[ab]
Rehydration Ratio	2.88±0.01[a]	3.97±0.02[a]	3.10±0.02[a]	2.96±1.33[a]
Water Activity	0.56±0.01[a]	0.48±0.002[b]	0.52±0.002[b]	0.55±0.03[a]
Texture profile				
Hardness (g)	1025±156.00[a]	320±21.20[b]	212.5±53.00[bc]	567.5±38.90[c]
Gumminess (g)	562±205.00[a]	281±90.50[a]	188.5±9.19[a]	448±12.02[a]
Chewiness (mJ)	64.0±31.10[a]	52.5±13.44[a]	35.1±25.20[a]	58.75±6.01[a]
Springiness (mm)	11.43±01.55[a]	8.32±0.93[a]	19.5±544[a]	13.55±1.06[a]

The values are mean ± SD of three replicates and the comparison done within the row. Means with different superscripts on the same row are statistically different (p<0.05).

Table 3. Proximate composition and functional properties of dried Bilimbi fruits (Wet Weight Basis)

Composition (%)	**Drying methods**			
	Sun Drying	**Dehydrator Drying**	**Microwave Oven Drying**	**Electric Oven Drying**
Moisture	5.52±0.40^a	5.02±1.10^a	5.17±0.18^a	6.87±0.11^a
Crude Fat	3.28±0.01^b	3.64±0.01^a	3.63±0.33^a	3.30±0.03^b
Crude Fiber	7.40±0.17^a	7.85±0.08^a	7.45±0.59^a	7.42±0.56^a
Crude Ash	7.02±0.02^a	15.08±5.62^a	15.76±1.79^a	9.60±0.41^a
Crude Protein	4.19±0.14^c	5.50±0.10^a	5.12±0.01^b	4.56±0.02^c
DPPH Assay (µg TE/g)	10.05±0.01^a	9.94±0.00^b	9.62±0.003^c	9.51±0.003^d
Total Phenolic Content (mg GAE/g)	49.26±0.81^d	62.82±0.68^c	71.96±0.27^a	66.76±0.27^b
Total Flavonoid Content (µg QE/g)	104.20±0.42^b	97.53±0.00^b	101.47±6.43^b	193.74±0.21^a
Vitamin C Content (mg/g)	2.14±0.50^a	1.60±0.25^a	4.46±1.26^a	2.32±0.75^a

The values are mean ± SD and the comparison done within the row. Means with different superscripts on the same row are statistically different ($p<0.05$).

Table 4. Mean rank values of sensory attributes of pickles made from dried bilimbi fruits

Parameter	**Drying methods**			
	Sun Drying	**Dehydrator Drying**	**Microwave Drying**	**Oven Drying**
Appearance	59.48±1.58^b	85.97±1.45^a	56.74±1.35^b	47.81±1.49^b
Color	57.38±1.56^b	84.63±1.39^a	52.73±1.38^b	47.25±1.45^b
Flavor	64.17±1.72^a	62.88±1.54^a	57.60±1.25^a	57.35±1.60^a
Aroma	60.60±1.42^a	58.08±1.52^a	64.08±1.38^a	59.23±1.30^a
Taste	53.10±1.35^a	65.85±1.59^a	54.75±1.54^a	68.30±1.34^a
Texture	62.90±1.10^a	68.13±1.31^a	55.95±1.21^a	55.02±1.33^a
Overall Acceptability	60.55±1.35^a	73.20±1.48^a	56.28±1.10^a	51.97±1.56^a

The values are mean ± SD of 30 semi-trained panelists and the comparison done within the row. Means with different superscripts on the same row are statistically different ($p<0.05$).

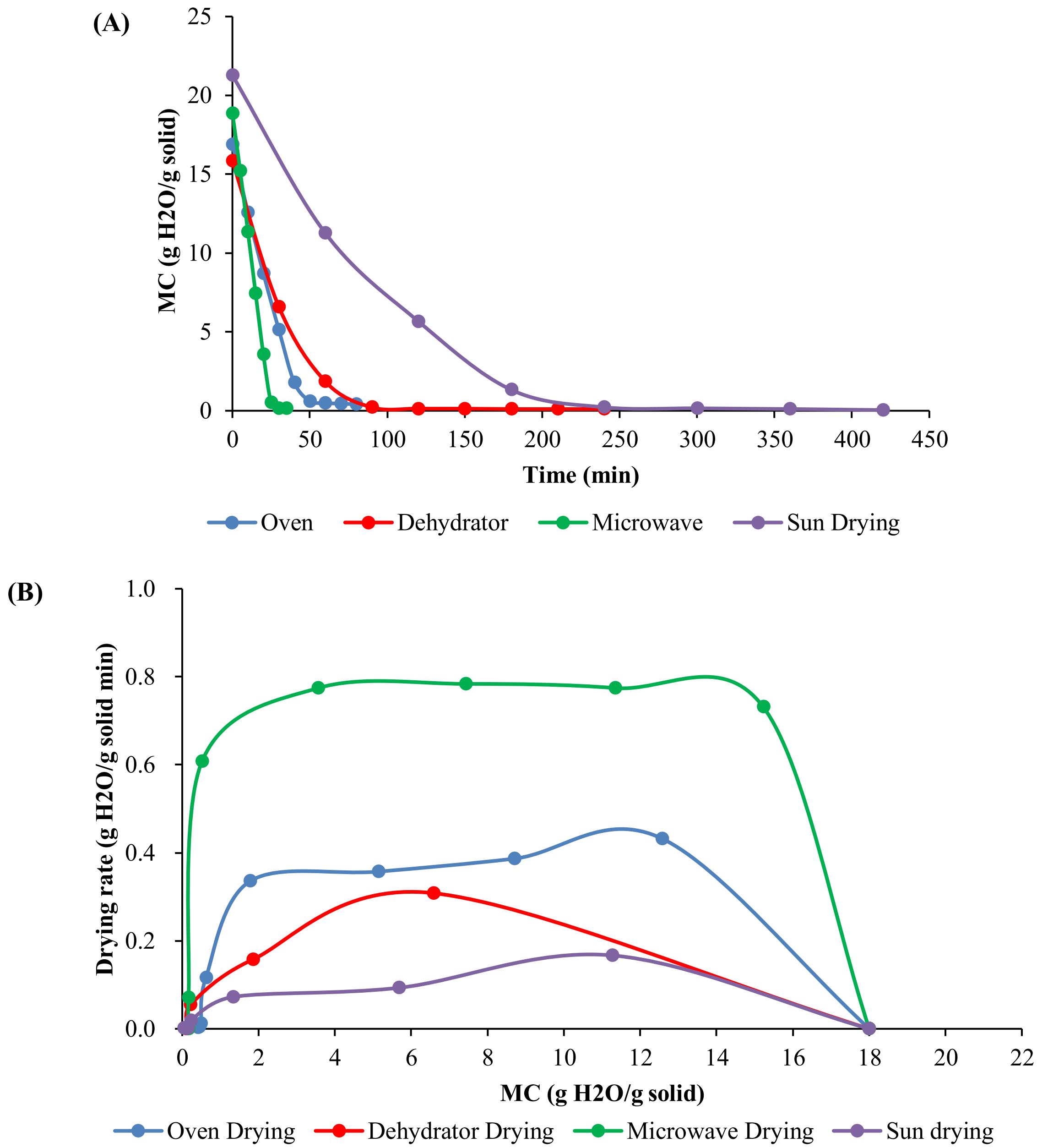
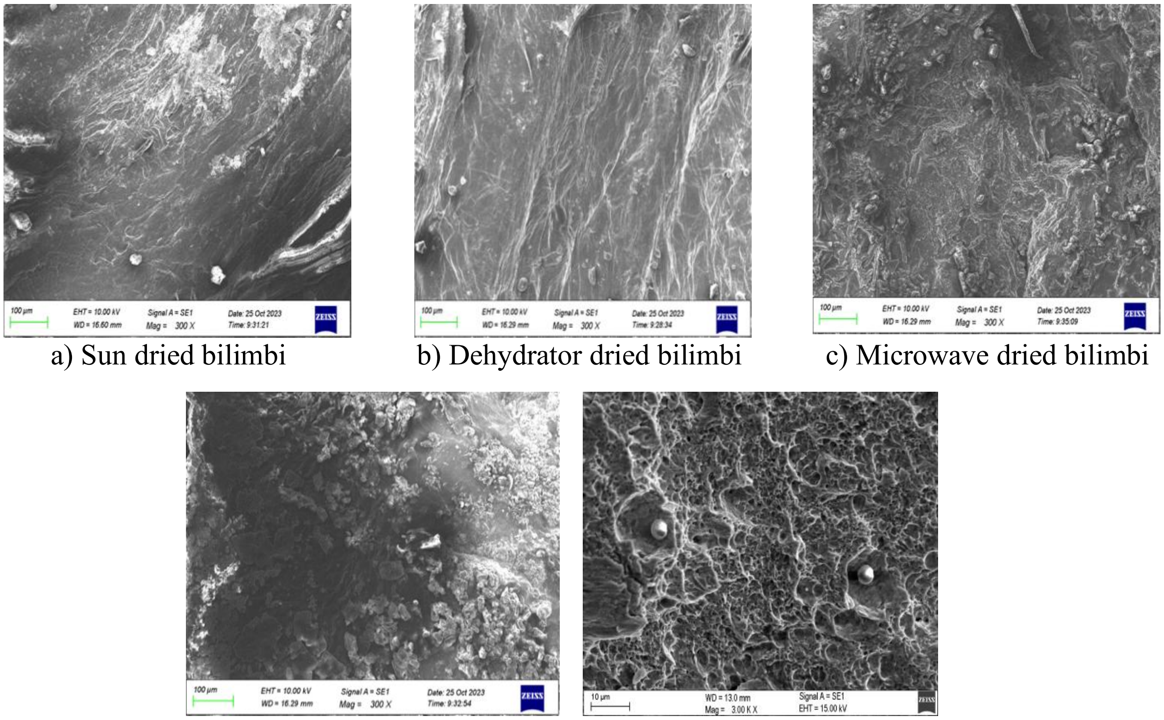


Figure 1. Drying curves of bilimbi fruit (A) Dry basis moisture content of bilimbi fruit and (B) Drying rate with the dry basis of moisture content.



a) Sun dried bilimbi b) Dehydrator dried bilimbi c) Microwave dried bilimbi

d) Oven dried bilimbi e) Fresh bilimbi

Figure 2. SEM images of bilimbi (a) Sun-dried bilimbi (b) Dehydrator-dried bilimbi, (c) Microwave-dried bilimbi, (d) Oven-dried bilimbi (e) fresh bilimbi fruit (obtained from Dhara et al., 2003).