ICCCM-JOURNAL OF SOCIAL SCIENCES AND HUMANITIES
2026; 5(sp): 34-40

doi: https://doi.org/10.53797/icccmjssh.v5isp.4.2026
e-ISSN 2811-4469

Study of Drying Techniques on Various Types of Fruits, Vegetables, and Herbs

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To Cite This Article:
Neama, A. S., Kadr, M. A., Abdelhady, A. O., & Basant, M.A. (2026). Study of Drying Techniques on Various Types of Fruits, Vegetables, and Herbs. *ICCCM Journal of Social Sciences and Humanities*,5 Special Issue, 34-40. https://doi.org/10.53797/icccmjssh.v5isp.4.2026

Received 19 February 2026. **Revised** 25 February 2026, **Accepted** 13 March 2026, **Available online** 25 March 2026

Abstract: This study aims to investigate the effects of various drying methods on different fruits, vegetables, and herbs in terms of chemical composition, sensory characteristics, and overall quality. Drying acts as a crucial preservation method that extends shelf life and reduces food wastage, contributing to sustainable development objectives the research addresses the issue of food loss due to the perishability of short-shelf-life foods, highlighting drying as a sustainable preservation method. Materials such as apricots, grapes, potatoes, moringa, and beets were analyzed using drying techniques including solar drying, microwave drying, and traditional methods. The results show significant impacts of the drying methods on moisture content, antioxidant activity, and phenolic and flavonoid compounds, along with substantial improvements in shelf life and sensory properties. This study provides valuable insights into optimizing drying processes in alignment with sustainable development goals and food waste reduction. Drying ranks among the most prevalent techniques employed for preserving food by lowering moisture levels, which discourages the development of microorganisms and prolongs shelf life. This research examines different drying techniques utilized for fruits, vegetables, and herbs, emphasizing their effectiveness in reducing waste while preserving product quality

Keywords: Solar dryer, drying methods, physicochemical, nutritional, bio-drying

1. Introduction

Owing to growing awareness regarding food sustainability and security among consumers and food producers, the enhancement of food products has garnered considerable attention from researchers aiming to broaden product varieties, including those derived from by products (Galanakis, 2024). As stated in the United Nations Environment Programme's Food Waste Index Report 2021, food wastage amounts to 931 million tons annually. To adhere to the UN Sustainable Development Goals, which target a 50% reduction in food waste by 2030, it has become essential to diminish food wastage particularly for perishable fruits and vegetables by converting them into stable, value-added products.

1.1 Meaning of Drying

Drying is a mass transfer process that removes water or another solvent by evaporation from a solid, semi-solid, or liquid. It is often used as a final production step before selling or packaging products (Mujumdar &U Devahastin, 2000). The sustainability and stability of food production for human consumption pose significant challenges, with increasing agricultural produce availability and controlling population growth being solutions to the increasing demand and shortage of agricultural produce. The Food and Agriculture Organization (FAO) states that famine is a major challenge, and rapid population growth and food waste management can increase the effects of this crisis by approximately 1.3 billion tons, resulting in 30% of global manufactured nutrition being wasted.

Post-harvest shortfalls in underdeveloped nations are smaller than those in developing nations due to their economic cultivation structures, improved shipping foundation, enhanced farm organization, and sufficient storing and handling capabilities (Goletti & Samman, 2002). In low-income nations, pre-collection management, handling, public storage services, and marketplace resources are either not offered or unsatisfactory. Regional data shows that all regions lose at least 20% of their fresh produce, with extreme losses of 45%-50% reported in Africa and Asia. Drying reduces the moisture content of crops, which is crucial for safeguarding agricultural crops and preventing spoilage. Dryers are used

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for the preservation of a broad assortment of crops, but the high price of electricity and natural fuels has led to increased concern on the use of sustainable supplies, particularly solar energy (Kimaro et al., 2024).

Fruits, particularly climacteric or ethylene dependent fruits, have a short shelf-life after harvest, leading to conservation problems (Zhang et al., 2017). These fruits are highly perishable and can be stored for less than 10 days at room temperature, making them unfit for consumption. Various processing technologies exist to address this issue, including drying, an ancient food preservation technique.

Drying is an interesting and practical alternative, especially in rural areas, as it allows for partial or complete removal of liquid impregnating a solid, extending product shelf life. Thermal treatment can induce changes in chemical composition, affecting the bioavailability and content of chemo preventive compounds and antioxidant activity in fruits.

Thermal processes in the food industry, such as baking, roasting, frying, sterilization, or microwave heating, can affect food positively or negatively. However, negative effects of thermal processing include the formation of process contaminants, such as mutagenic, carcinogenic, or cytotoxic compounds. These contaminants can have long-term health effects, such as cancer.

Toxic compounds formed during thermal processing include heterocyclic aromatic amines, nitrosamines, polycyclic aromatic hydrocarbons, 5-hydroxymethylfurfural, furan, and acrylamide (AA). Minimizing the formation of these toxins during industrial food-processing and consumer food preparation is crucial, as home-cooking choices can significantly impact acrylamide levels. Technological development and the use of both industrial and home-cooking techniques have increased knowledge of applying thermal treatment to achieve specific food qualities

1.2 Open-sun Dehydration

Solar dehydration is a feasible and regionalized thermal use of solar energy, commonly used in developing nations. Solar radiation energy is considered an alternative energy source and can be applied as a complete dehydrating processor in combination with other systems. It can be used as a complete dehydrating processor in combination with other dehydrating systems, reducing fuel energy requirements. Research has shown that different drying methods affect the quality attributes of beetroot slices, potato varieties, and nutritional quality of Moringa oleifera leaves.

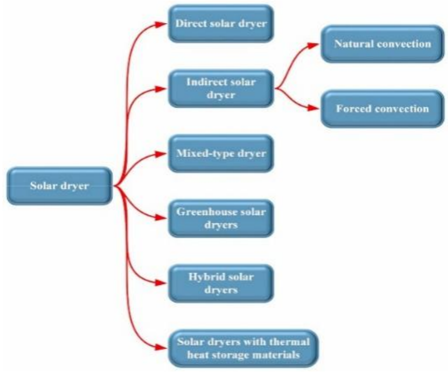

Fig. 1 - Classification of solar dryer types

This figure illustrates the main classification of solar drying systems based on the method of heat utilization. The primary categories include direct solar dryers, indirect solar dryers, mixed-type dryers (combining direct and indirect methods), greenhouse solar dryers, hybrid solar dryers, and solar dryers with thermal heat storage materials. In indirect solar dryers, the airflow mechanism is further divided into natural convection and forced convection. This classification highlights the various technological approaches used to enhance drying efficiency by utilizing solar energy.

1.2.1 Solar dryers

Solar dryers absorb solar radiation and transfer heat energy to products for dehydration. They increase dehydrating temperature and reduce humidity, lowering moisture content. Solar dryers have a dedicated structure to regulate dehydration and protect products from damage. This results in better quality products compared to sun-dehydrated ones. They can be categorized into direct, indirect, mixed-type, greenhouse, hybrid, and energy storage systems.

a. Direct Solar Dryers

Direct solar dehydration is the conventional procedure of dehydrating agricultural and food products. In this solar drying technique, a transparent cover is used to reduce heat losses and protect the food material from dust and rain [Hii, et al., 2012; Chaouch, et al., 2018; Ogheneruona & Yusuf, 2011) generic guidelines**.** Skip hyphenation at the last line. Symbols which denote vectors and matrices must be written in bold. Names of the scalar variable will usually appear in italics. Refer to the SI unit when describing weight and measures. Provide with a glossary or specified when first stated for all of non-standard abbreviations or symbols.

b. Working principle of direct solar dryers

Figure 2 presents the basics of the direct solar dehydration approach. A certain amount of solar energy on the transparent cover is reflected, and the remaining is transmitted within the box dryer. Moreover, the amount of solar energy is manifested by the food surface. The material's temperature increases, and the material dehydrates. The moisture in the food material is eliminated by the air blown into the cabin dryer [Singh et al., 2018; Karathanos & Belessiotis, 1997).

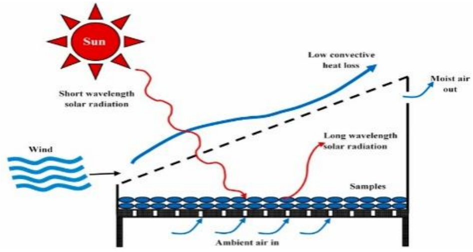

Fig. 2 - Schematic diagram of the solar drying process

This figure illustrates the working principle of a solar dryer. Short-wavelength solar radiation from the sun penetrates the transparent cover and is absorbed by the material (samples), converting it into heat. The heated surface then emits long-wavelength radiation, which is partially trapped inside the drying chamber, increasing the internal temperature. Ambient air enters the system, is heated, and flows across the samples, facilitating moisture evaporation. The moist air is then removed from the chamber, aided by airflow and low convective heat loss, thereby enhancing the overall drying efficiency.

1.2.2 Drying in Microwave Ovens

Over the past 30 years, microwave ovens have been used in households to heat food, affecting temperatures and bacterial destruction. Factors such as product mass, density, specific heat, ionic content, and dielectric properties play a significant role in these effects. Microwaves inactivate microbes by thermal effects alone, raising concerns about food safety. thermal treatment offered by microwave heating, potential temperature abuse, and the risk of pathogen survival in foodservice cook/chill foods have led to concerns (Fung & Cunningham, 1980). Most studies focus on foodborne pathogens like Listeria monocytogenes, Staphylococcus aureus, and Salmonella spp. The practical implications of these findings are examined. The microwave oven's popularity has increased significantly since its introduction in 1946, with 70% of American households owning them. Future applications include vacuum and freeze drying, pasteurizing, sterilizing, baking, roasting, and blanching.

Understanding microwave heating's advantages and limitations is crucial for understanding its impact on m Over the past two decades, there has been a growing interest in microwave drying to reduce drying time and increase water removal from agricultural products. This technology offers advantages such as higher drying rates, shorter drying times, decreased energy consumption, and better quality of dried products. However, a single technique cannot achieve this goal alone. A combination of existing drying techniques should be considered. Microwave-convective drying of fruit has shown success in obtaining high-quality dried products with low specific energy consumption. One primary advantage of microwave heating is that the temperature and moisture gradients are in the same direction, aiding each other.

Several studies have investigated the drying of grapes, such as thin-layer drying of seedless grapes, Iranian seedless white grapes, and hot air drying of sultana grapes. Results showed that microwave dried raisins were lighter in color and superior to hot air dried samples. Convective drying was found to be highly energy-intensive, but microwave drying achieved lower specific energy consumption.

The main objective of this study is to investigate the drying behavior of combined microwave oven/hot air cabinet drying methods compared to hot air-drying methods alone and their effects on drying characteristics and quality of grapes, biological safety.

1.2 Importance of Drying Fruit

Drying converts perishable foodstuffs into stabilized products with water activity below 0.65. Its benefits include extending product life, reducing food mass and volume for easier packaging, transport, and storage, and providing a specific presentation. Modern drying techniques should be popularized in rural communities to reduce post-harvest losses and transport losses.

1.2.1 Effect of Drying on Fruits

Drying can significantly alter a product's texture, shape, taste, or nutritional qualities (Guiné, 2018). Studies have shown that drying time significantly affects the color of dried mango slices at different temperatures. However, pre-treatment of dried mangoes can retain nutrients, making them healthy and nutritious. The antioxidant capacity of dried mangoes decreased by 18.4-54.6% compared to fresh mangoes, with the highest phenolic content in microwave-dried samples at 350W and lowest in hot-air dried at 80°C. Vitamin C content was not significantly affected by freeze-drying for 48 to 72 hours, and freeze-dried mango had lower β-carotene content than fresh mango.

Dried fruits are more concentrated in polyphenolic compounds and have greater antioxidant activity compared to fresh fruits due to concentration. Drying can also lead to losses in total polyphenolic compounds and changes in ratios of free to total polyphenolics. Margaris and Ghiaus (2007) conducted experiments on hot air drying of sultana grapes, using Thin-layer model and Page's equation. Tulasidas et al. (1997) developed a semi-theoretical model of microwave drying of grapes, which predicted the drying rate well but was similar to Page's model. This study aims to investigate the drying behavior of combined microwave oven/hot air cabinet drying methods compared to hot air drying methods alone and their effects on drying characteristics and quality of grapes.

1.2.2 Effect of drying on some fruits, vegetables and herbs: Banana (Musa spp.)

Bananas are a popular fruit crop in the tropics, known for their flavor, texture, and convenience (Giuggioli et al., 2024). They are rich in Vitamin A, C, and B6 content, and are an important source of energy for sportspeople. Banana farming has grown rapidly, leading to improvements in post-harvest practices. Conventional drying methods often result in poor color, flavor, texture, and rehydration qualities. Microwave drying has become increasingly popular due to its accuracy, penetration into fruit tissues, and shorter processing times.

Microwave drying provides low process temperatures and faster water evaporation, offering shorter drying times and higher quality dried products. However, the process can have high costs. Pre-treatments prior to microwave drying can decrease drying time and costs. Osmotic dehydration is an efficient way to remove up to 50% of initial moisture.
Apricots, a member of the Armeniaca section of Rosaceae, are economically important fruit trees cultivated worldwide and in temperate regions. They are used to extend the shelf life of apricots, which are considered healthy food and desirable ingredients for fruit-based snacks. Colour is a crucial quality attribute of dried apricots, as it affects consumer acceptance and retains pigment nutrients. Microwave (MW) processing reduces the time needed to reach the set point temperature and drying period. This study investigates the effectiveness of microwave plants compared to hot-air drying systems in terms of time of process, color changes, degradation of β-carotene, and inhibition of DPPH scavenging activity during apricot drying.

a. Grapes

   Grapes are deciduous fruit from the Vitis genus, used for various products like wine, jam, juice, and oil. Cultivation began 6,000-8,000 years ago in the Near East, with the oldest known winery in Armenia dating back to 4000 BC. By the 9th century AD, Shiraz produced some of the Middle East's finest wines.

b. Potatoes

   Potatoes, originally from the Andes, have become a global food consumed by millions worldwide. European colonization in the 16th century connected potatoes to Andean people, who rely on potatoes for their nutritional value. Potatoes, part of the Solanum genus, contain solanine in their aerial parts. Properly grown and stored potatoes produce minimal glycoalkaloids, but exposure to light can make them toxic.

c. Beet Plant

   Beetroot, a taproot portion of a beet plant, is commonly known as beets in North America, and can be roasted, boiled, canned, pickled, spiced, or served in a sauce.

d. Moringa Oleifera

   Moringa oleifera is a fast-growing, drought-resistant tree native to the Indian subcontinent and widely grown in South and Southeast Asia. It has thirteen species, including moringa borziana, moringa rivae, moringa peregrine, moringa concanensis, moringa longituba, moringa hildebrandtii, moringa arborea, moringa pygmaea, moringa ovalifolia, moringa drouhardii, moringa stenopetala, and moringa ruspoliana.

   Moringa leaves are commonly used as traditional medicine due to their nutritional content and metabolites such as glucosinolates, flavonoids, and phenolic acids. They can be used fresh or dried powder. To reduce biological damage during storage, moringa leaves are dried using various methods, including sun drying, chemical drying, oven-assisted drying, and microwave drying. Sun drying is less efficient due to weather conditions and is less efficient than chemical drying, which uses chemicals like silica sand, glycerin, and calcium chloride. Microwave drying is one of the fastest methods for reducing water content in materials and can reduce drying time by up to 50% compared to conventional drying. It is more environmentally friendly and can minimize microwave conductivity and exhaust gas production. Mathematical modeling is used in the advanced stage of moringa leaf drying to evaluate drying data produced by microwave drying. Popular thin layer models include the Verma model, Logarithmic model, Page model, Two-Term Exponential model, Midilli model, Henderson and Pabis model, Lewis model, and Modified Page model.

   In moringa leaf drying, mathematical models help describe drying mechanisms, optimize process parameters, predict drying data, process control, and model mass and heat transfer. Energy consumption efficiency is crucial during the drying process, and specific energy consumption (SEC) is an important parameter for calculating energy consumption. This research aims to evaluate moringa leaf drying using fourteen mathematical models and analyze energy consumption, CO2 emissions, and specific energy consumption (SEC) in moringa leaf drying by oven and MD methods.

e. Selecting and Pretreating Fruits
   Select fresh, fully ripened fruits for drying, as immature produce lacks flavor and color. Thoroughly wash and clean fruits, discarding decay, bruises, or mold. Pretreating fruits before drying helps prevent light-colored fruits from darkening and speeds up drying for tough skined fruits. Research shows that pretreating with an acidic solution or sodium metabisulfite dip also enhances the destruction of harmful bacteria. Ascorbic acid (vitamin C) is an antioxidant that prevents fruit from darkening and enhances bacteria destruction during drying. Commercial antioxidant mixtures are less effective but are more readily available.

2. Materials and Methods

2.1 Materials

2.1.1 Beets

(Beta vulgaris vulgaris) were obtained from Atlanta State Farmer's Market from Victory Farms (Hudsonville, MI). Whole beets were chopped into 1-mm chunks using a bowl chopper (Model 33, Schneidmischer,Wallau/Lahn, Germany) with 1% ascorbic acid (w/w)to minimize enzyme activity. Ascorbic acid was purchased from Prinova US LLC (Carol Stream, IL).

2.1.2 Apricot

Research was conducted on the following plum varieties: (Subkhoni Yubileynyy Navoi) (control), Lolacha Bukharsky, and Sholakh. The following were studied for the selected varieties: Biochemical composition of the selected varieties was analyzed [7-10]; Apricots were dried and analyzed in three ways: whole, split into two, and seedless.

2.1.3 Potato

The agricultural crop used in determining the dry rates is Potato (Solanum tuberosum). Similar weights of 200 g were used for continuous and intermittent drying methods. The Potatoes were obtained from Main Market, Birnin Kebbi, Kebbi State, Nigeria within the month of March, 2015. The equipment used include: Calibrated oven thermometer, Digital weigh balance, and Venire caliper. The samples were selected at random and extra care was ensured not to select bad potato so as to avoid obtaining incorrect results Narsi, 2006 study (as cited in [9]).

2.1.4 Moringa

Leaves are raw materials used for drying experiments. Moringa leaves used are the size of 3.2 × 2.3 cm with an average moisture content of 73.65–74.10%. Moringa leaves were taken from plantations in Kebondalem Village, Madurejo, Prambanan District, Sleman Regency, Yogyakarta Special Region Province, Indonesia (7◦47′22″S 110◦28′25″E). Moringa leaves used are ensured to be of good quality and do not experience leaf damage such as rot and yellowish color.

2.1.5 Grape (Vitis vinifera L.)

Total weight of grapes- 5 kg Variety: Fresh Thompson seedless grapes will be used due to its good variety - Moisture content: The moisture content of Thompson seedless grapes is between 75 to 85%.

2.2 Methods

2.2.1 Drying Beets

Beets were stored at -40°C, thawed for 24 hours, and added to beet samples at different levels of maltodextrin to aid in dehydration and reduce hygroscopicity. Vacuum belt drying was used for drying.

2.2.2 Drying Apricot

The study focuses on determining the duration and organoleptic evaluation of apricot fruits in whole, split, and seedless states, as well as their drying duration and organoleptic assessment.

2.2.3 Drying Potato

Potatoes were cleaned, peeled, and washed before being sliced into 5 cm thick slices. Drying experiments were conducted at 100oC, with moisture loss recorded. Samples were withdrawn and weighed at ten-minute intervals. The intermittent drying method involved removing samples from the oven and placing them in a ventilated area for 15 minutes. The data collected were analyzed using the SPSS 21 package.

2.2.4 Drying Moringa

This study used Electrolux Microwave Ovens 20 L - EMM20K18GW, imported from China, to dry 10 g of moringa leaves. The microwave was powered by 800 W and had a voltage of 220 V and frequency of 50 Hz. A digital analytical balance was used to calculate the mass of the leaves. Thermo scientific oven with Heratherm type OGS60 was also used.

2.2.5 Drying Grapes

Procurement of grapes, the berries were sorted, washed, and their characteristics like diameter, total soluble solids, skin thickness, moisture content, acidity, and pH were determined from the fresh grapes.

a. Preparation of dipping solution
b. Grapes were soaked in a solution of ethyl oleate and potassium carbonate anhydrous in 50 liters of water for 2 minutes, then removed
c. Open dryingGrapes are sun-dried on a platform, absorbing solar radiation to generate heat and moisture evaporation. The process takes 6-9 days, depending on weather, and stops when the grape reaches 15-16% moisture content.

d. Shade drying
   Shade drying is a natural method used for grape drying, requiring pre-treated grapes to be placed on a rack with a capacity of 500kg. This method produces better color and takes 12-15 days, depending on weather conditions.
e. Controlled shade drying
   The controlled shade drying process uses sensors with heaters and air hoods to regulate temperature and humidity. The cabinet measures 250x150x30 cm' and has a 500kg capacity. The drying time ranges from 10 to 13 days, with grapes stopped when 15-16% moisture content is reached.
f. Tray drying
   The drying tray drier, consisting of three sections, was used to dry grapes. The trays were placed perpendicularly to the airflow, and the samples were weighted at regular intervals. The drying runs were carried out at a constant temperature and air velocity.
g. Dry bulb temperature
   Thermometer temperature (T) indicates air heat content and is directly proportional to air molecules' mean kinetic energy.

3. Results

3.1 Chemical Composition of Raw Apricots and Fresh Grapes

The chemical composition of raw apricots and fresh grapes is an important parameter in determining their suitability for drying processes and evaluating the quality of the final product. As presented in Table 1 and Table 2, both materials exhibit distinct physicochemical characteristics, particularly in terms of moisture content, macronutrients, and bioactive compounds. Raw apricots are characterized by relatively high moisture content and the presence of phenolic, flavonoid, and antioxidant compounds, which contribute to their nutritional and functional value. Meanwhile, fresh grapes show a high moisture level along with measurable amounts of carbohydrates, sugars, organic acids, and ascorbic acid. These compositional differences play a crucial role in influencing drying behavior, energy requirements, and the preservation of nutrients during the solar drying process.

Table 1 - Chemical Composition of Raw Apricots

Parameter	Raw (Apricots/Kernels)
Moisture Content	85-87%
Fatty Acid Content	0.1-0.2%
Phenolic Content	1-2 mg GAE/g DW
Antioxidant Content	0.02-0.03 mmol TE/g DW
Flavonoid Content	0.4-0.7 mg QE/g DW
Oil Content	0.1-0.2%

Table 2 - Chemical Composition of Fresh Grapes

Parameters	Fresh Grapes
Moisture Content	82.00 ± 0.24
Crude Fat (%)	0.19 ± 0.04
Crude Protein (%)	0.77 ± 0.18
Crude Fiber (%)	4.71 ± 0.33
Ash (%)	0.35 ± 0.06
Carbohydrate (%)	16.79 ± 0.08
Total soluble solid (Brix)	22 ± 0.30
Total sugar (%)	11.71 ± 0.04
Acidity (%) as tartaric acid	0.50 ± 0.03
Ascorbic Acid (mg/100 gm)	12.79 ± 0.17

3.2 Chemical Composition Moringa

The chemical composition of Moringa (*Moringa oleifera*) is summarized in Table 3, which presents key parameters used to evaluate its nutritional and functional properties. These parameters include moisture content, protein, fat, fiber, ash, and various bioactive compounds that play an important role in determining the quality and stability of Moringa during processing and drying.

Table 3 - Chemical Composition Moringa

Parameter	Shade Drying	40°C Oven Drying	50°C Oven Drying	60°C Oven Drying	70°C Oven Drying
Crude Protein (g/100g)	28.44	26.75	24.92	22.13	19.89
Fat (g/100g)	2.69	2.58	2.53	2.50	2.46
Ash (g/100g)	4.55	4.80	4.95	5.10	5.20
Fibre (g/100g)	16.33	16.70	16.98	17.32	17.66
Carbohydrate (g/100g)	32.75	45.10	48.45	50.85	52.30
Beta-Carotene (mg/100g)	5220.20	5100.00	5000.00	4900.00	4946.20
Vitamin C (mg/100g)	27.39	26.80	26.20	25.90	25.70
Minerals	Increase	Increase	Increase	Increase	Increase

3.3 Sensory Characteristics

The sensory evaluation of the developed products was conducted to assess their acceptability based on key attributes, including color, taste, and smell, as presented in Table 4. The results indicate that beetroot juice achieved higher scores across all sensory parameters, particularly in color (8.9), taste (8.5), and smell (8.4), resulting in a final evaluation score of 8.6. In comparison, potato flour obtained slightly lower scores, especially in aroma (7.4), with an overall evaluation of 8.2. These findings suggest that beetroot juice is more favorable in terms of sensory acceptance, which may be attributed to its natural color intensity and distinctive flavor profile. Overall, sensory characteristics play a crucial role in determining consumer preference and the potential marketability of the products.

Table 4. Sensory Characteristics

Evaluation of 10	Color	Taste	Smell	Final Evaluation
Beetroot Juice	8.9	8.5	8.4	8.6
Orange Flour	7.4	6.6	7.3	7.1
Potato Flour	8.8	8.4	7.4	8.2
Cup cake with Potato Flour	9.1	9.2	8.8	9.0

4. Conclusion

In this study, the uses and roles of various drying methods for the valorization of fruits, vegetables, and their by-products were analyzed and contrasted. The research evaluated the drying parameters applied in different agricultural and food items and their effects on the quality of the final product. The results indicate that drying serves as an efficient technique for the valorization of agricultural goods. Certain drying techniques, especially hybrid drying, can maintain vital bioactive compounds that are advantageous to health. This leads to a notable decrease in food waste, thus enhancing economic results and tackling food scarcity. Nevertheless, issues such as elevated energy expenses and operational effectiveness must be resolved, particularly for large-scale production, to render these technologies commercially feasible and attractive to food producers. Furthermore, food waste from by-products of fruits and vegetables may undergo bio-drying. Aspects like airflow rate affect the efficiency of bio-drying, and adding bulking agents during the process aids in managing moisture levels and airflow. Future studies ought to investigate the incorporation of bio-drying into drying methods to minimize waste from unused fruits and vegetables. This is in line with the sustainability objectives within the food sector. Additional innovations in hybrid drying techniques can improve energy efficiency, decrease carbon emissions, and broaden green waste management strategies.

Acknowledgement

The authors would like to thank the fellow authors and organizations whose intellectual properties were utilized for this study.

Conflict of Interest

The authors declare no conflicts of interest.

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