ISBN 978-1-960740-06-9

DRYING TECHNOLOGY – CURRENT RESEARCH AND INDUSTRIAL APPLICATIONS

Editors

Muhammad Imran

Department of Food Science, Faculty of Life Sciences, Government College University, Faisalabad, Pakistan

Amna Javed

Department of Nutrition and Dietetics, The University of Faisalabad, Faisalabad, Pakistan

Book Publication Date

December 28, 2023

doi: 10.5281/zenodo.14823289

Scientific Knowledge Publisher (SciKnowPub), USA

info@sciknowpub.com

CONTENTS

Scientific Knowledge Publisher (SciKnowPub), USA
info@sciknowpub.com

ISBN 978-1-960740-06-9

DRYING TECHNOLOGY – CURRENT RESEARCH AND INDUSTRIAL APPLICATIONS

Editors

Muhammad Imran & Amna Javed

Review Based Book Chapter

INFLUENCE OF VARIOUS FACTORS IN DRYING PROCESS ON QUALITY OF FINISHED PRODUCT

July 19, 2023

doi: 10.5281/zenodo.10245217

Scientific Knowledge Publisher (SciKnowPub), USA

info@sciknowpub.com

REVIEW BASED BOOK CHAPTER

INFLUENCE OF VARIOUS FACTORS IN DRYING PROCESS ON QUALITY OF FINISHED PRODUCT

Amna Javed[1], Rahima Amjad[1], Muhammad Saad Hashmi[2,3], Uzma Javaid[4,5]

[1]Department of Nutrition and Dietetics, The University of Faisalabad, Faisalabad, Pakistan
[2]Institute of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan
[3]Punjab Food Authority, Pakistan
[4]Department of Anatomy, Sargodha Medical College, Sargodha, Pakistan
[5]University of Sargodha, Sargodha, Pakistan

For Correspondence
amna.javed@tuf.edu.pk

Abstract

The drying process is critical in the food industry for the preservation and processing of various food items while many optimized drying operations are using response surface methods, resulting in higher product quality. Understanding the elements influencing drying processes is essential for improving product quality, shelf life, and energy efficiency in the food business. It also focusses the important aspects to govern drying process that include food material qualities such as moisture content, composition, and physical structure. Furthermore, the effect of process factors such as temperature, airflow rate, drying time for better drying efficiency and food product quality has been investigated along external influences on the drying process, such as pressure, and the inclusion of additives or pre-treatments. The interconnections between these parameters and their consequences on drying kinetics, product quality features (e.g., color, texture, and nutritional content), and energy consumption are affecting the end product in multiple ways. Breakthrough technology and creative techniques to improve drying processes in the food business such as freeze-drying, microwave drying, and vacuum drying are optimizing drying operations to make it more sustainable.

Keywords
Drying Technology, Processing Operations, Drying Kinetics, Drying Factors

1. Introduction

The process of drying is an essential stage in the various techniques applied within the food industry. It is utilized to draw moisture out of food, which inhibits the proliferation of bacteria and other microbes that shorten the shelf life of food goods, causing spoilage. Foods that have been dried are easier to store and transport whilst retaining their flavor, texture, and nutritional content [1, 2]. Drying is known as the removal of moisture from a substance through heating, cooling, or exposure to air or other gases. In the food sector, drying is a frequently employed technique that is used to turn a surplus crop into shelf-stable produce. In the food industry, food products are dried to lower their moisture content to a level suitable for storage and transportation. The food industry utilizes a variety of drying techniques, each with particular advantages and disadvantages [3, 4].

Drying processes and techniques are essential in the food sector as they are employed to maintain the integrity and security of food products, control deterioration, and minimize waste. Food goods can be made more cost-effective to transport and store by reducing their weight and volume through drying methods. Additionally, drying can improve the flavor, texture, and nutritional content of foods, increasing their consumer appeal. Several drying methods have undergone successful testing to see if they may be used in food preparation. For instance, a high-efficiency drying technique that has the potential to be utilized within the food industry is the microwave-assisted thermal process [5, 6].

2. Significance of Drying Process

According to previous documented research, using innovative drying technologies can enhance the quality of food products by maintaining their nutritional value, color, and consistency. Vacuum drying, for example, may significantly reduce the drying process as well as improve the ability of fruits and vegetables to rehydrate [7, 8], while freeze-drying can preserve the nutritional content of food products, such as vitamins and antioxidants [9]. Several cutting-edge methods have been proposed and researched for their possible application in the food sector, including Elliot and symmetric Elliot extreme learning machines, artificial neural networks, spray-drying of bioactive components, and freeze-drying methods [6, 7]. These methods seek to preserve the nutritional value of food while improving product quality and lowering energy costs. Furthermore, advanced drying techniques can raise the standard of food product safety. For instance, by removing the requirement for physical handling of the product, spray-drying can lower the risk of contamination [10]. To decrease the possibility of microbiological contamination and prolong the shelf life of their products, McCormick

& Company, a leader in the world of flavor manufacturing, employed a vacuum belt dryer [11]. The need of novel drying method has been presented in Figure 1.

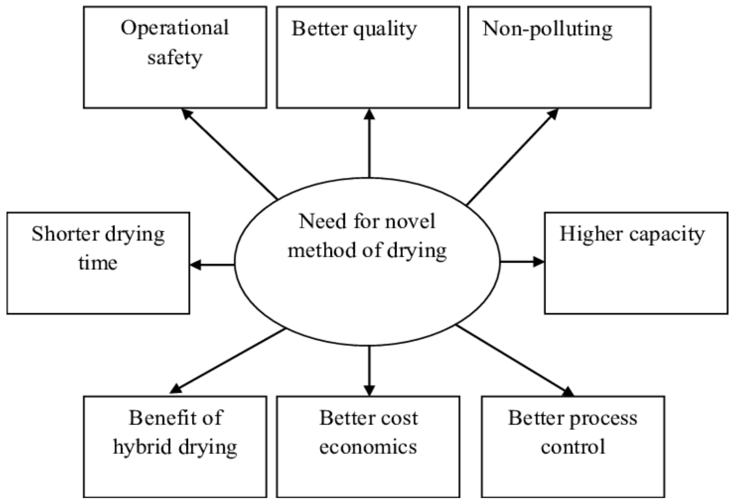

Figure 1 Advantages of novel drying methods [48]

In this chapter, we will discuss about the various factors and elements which affect the processing and production of food products, specifically during the process of drying. We will also look at the various applications of drying processes and technologies within the food industry, and what is the affect of drying on various food products as well as the stage of production at which drying is needed. The challenges pertaining to drying processes at an industrial level will also be discussed along suggested solutions.

3. Factors Affecting Drying Processes in the Food Industry

Following are certain factors which have certain affects upon the drying processes in the food industry:

3.1. Temperature

Drying is a major operation in the food business, and temperature is a critical aspect that can dramatically affect the efficiency and quality of the process. To maximize the production of premium dried food items, it is imperative to comprehend how temperature affects drying processes. In this section, the impact of temperature on drying operations in the food industry will be investigated, specifically looking into how temperature impacts the rate of moisture removal during drying by pinpointing the best temperatures for various drying processes, and assessing how temperature impacts the quality and shelf life of dried food products. By delving into these issues, we intend to offer a thorough understanding of the function that temperature plays in the process of drying and provide suggestions for how to produce dried food products of the highest caliber.

3.1.1. Affect on Rate of Moisture Removal

Temperature is a key drying element that influences moisture removal during drying processes. Temperature and relative humidity are the two key factors that affect the evaporation rate. It is commonly known that heat can accelerate evaporation, which raises the amount of liquid that the air can hold while lowering relative humidity [12]. Temperature can be changed to achieve distinct drying behaviors, and changing the drying parameters over time can also result in varied drying behaviors. With the use of low heat sources to promote moisture evaporation, intermittent or non-isothermal drying techniques have been claimed to be more effective than traditional continuous drying methods. The influence of temperature on moisture removal during drying processes has been investigated through drying tests at various temperatures and step-down temperature settings, with fixed air velocity. It has been noted that the drying temperatures now in use demand lengthy drying durations of up to 24 hours and use a significant amount of energy. Therefore, it is necessary to create innovative drying techniques that raise output and energy efficiency while preserving a satisfactory level of product quality. The development of computational techniques to forecast the temporal and geographical changes in temperature and moisture during processing can aid in the optimization of the dry process. For non-isothermal drying of leafy products, a model for simultaneous heat and mass transmission has been presented, and numerical findings have been verified using dehydration experiment curves. It has also been discovered that the drying properties of walnuts are greatly impacted by the non-uniformity of the drying circumstances around the product, specifically the air temperature and humidity along the column heights [13, 14].

3.1.2. Optimal Temperature

The selection of the appropriate temperature to achieve the best drying duration while maintaining the physicochemical, nutritional, and sensory qualities of the food product while drying, is critical. Higher temperatures ought to be avoided since they might cause food to cook rather than dry. The drying process takes place at temperatures ranging from 15°C to 37°C, with 140°F being the ideal temperature for food. The drying process shouldn't be accelerated by raising the temperature in order to reach the specified moisture content of 10% (on a wet basis) [15, 16]. For example, the generalized method for drying orange peels is done under sunlight for 48 hours at temperatures ranging from 30°C to 37°C in the morning and 15°C to 20°C at night. Low-temperature drying processes are advised for meat products to prevent microbiological and biochemical decomposition. High temperatures may shorten drying times but can cause heat-sensitive components to degrade, lose color quality, become more difficult to rehydrate and shrink at higher rates. Regardless of the drying technique, it's critical to pick a drying temperature that doesn't degrade the end product's quality and offers a respectable drying time [16, 17].

Freeze-drying can be done using an ultralow-temperature freezer that can reach up to 80°C and the drying process may be sustained at 80°C for 24 hours. The size of the dried powder obtained during freeze-drying is dependent on the granulometry operating conditions. The recommended temperature range for spray drying is between 110°C and 140°C; however, no evidence has been found on the best range for drying using alternative techniques. The vacuum spray drying process maintains an interior dryer temperature of 40°C to 50°C [16].

3.1.3. Affect on Quality and Shelf-life

In order to maintain the quality and shelf life of dried food products, temperature control is an essential feature. Based on the nature and sensitivity of the food material being dried, the ideal temperature range is determined. To maintain stability, it is advised to keep temperatures for heat-sensitive materials between 10-35°C. Although higher temperatures speed up the drying process, they can also induce material collapse and pore structure degradation. As a result, the right selection of shelf temperature should be determined based on the balance of input and the required heat. For instance, in the secondary stage of freeze-drying, greater temperatures might hasten the drying process. However, too high temperature may cause ice to melt during sublimation, resulting in structural changes such as shrinkage. The drying time for conventional freeze-drying has been demonstrated to be significantly reduced by over 50% with an increase in process temperature [18].

Case hardening, in which food seems dry from the exterior but is actually moist inside, can occur as a result of an increase in shelf temperature. High heat can also cause food to cook on the exterior before drying inside, which can lower the product's overall quality. The majority of dried fruits have a storage life of one year at 60°F and six months at 80°F. The storage duration shortens as the temperature rises. Vegetables also have a shorter shelf life than fruits, and beef jerky should be kept in a freezer or refrigerator for best results. The optimal conditions for storing dried food are below 60°F since low temperatures can increase the shelf life of dry food products. Room temperature, on the other hand, can cause dried food to degrade if not consumed within a particular duration, and exposure to moisture can also reduce the shelf life of dry food. The texture and mechanical resistance during transit of freeze-dried items are also greatly impacted by the mechanical stiffness of the product, which increases dramatically with greater shelf temperature. To maintain the highest possible quality and shelf life, the shelf temperature should be adjusted based on the individual food materials [15, 18].

Overall, the current study gives useful insights into the impact of temperature in drying processes and emphasizes the need of optimizing drying parameters to obtain optimal quality and shelf life of dried food items. Future studies in this field may examine how temperature affects various food components and create inventive drying methods to improve the quality and shelf life of dried food products.

3.2. Humidity

Humidity, in particular, may have a considerable influence on the drying process and the subsequent product quality. As a result, the purpose of this section is to investigate the influence of humidity on drying operations in the food business. We will specifically look at how humidity affects drying, determine the ideal conditions for drying food goods, and assess the difficulties in regulating humidity during drying. Understanding these characteristics allows the food business to improve its drying operations, improve the quality of its goods, and boost its efficiency.

3.2.1. Effect on Drying Process

Humidity greatly impacts the drying processes within the food industry. Low humidity can cause moisture to migrate from food to the air, resulting in flavor and texture loss. High humidity in the early stages of drying, on the other hand, may enhance the drying pace of some fruits, such as apricots. However, for fruits and vegetables including apricots, crambe seeds, carrot cubes, and onions, changing the relative humidity of the drying air might dramatically alter product quality and drying speed. For example, a moderate relative humidity of 30% to 50% resulted in improved product quality, but lower and higher relative humidity reduced the quality of the product or decreased drying speed [19, 26].

A step-by-step regulation of relative humidity can successfully avoid crusting and conserve energy. The adaptive hot air-drying system with temperature and relative humidity monitoring and control capability can optimize the stepwise control of relative humidity via a fuzzy logic controller designed to automatically adjust the relative humidity for optimal product quality and accelerated drying speed. Additionally, production is increased with humidity control equipment by reducing the time required for water to dry [19, 20]. The effect of relative humidity on microwave drying speed and product quality was studied, and it was discovered that low relative humidity increased the drying rate while high relative humidity slowed it [20, 21]. Low relative humidity, however, can lead to low-quality color and vitamin C content. Furthermore, moisture exposure can cause mold and bacterial development in dry goods, reducing their shelf life. Even in immaculate environments, moisture encourages the growth and spread of microbes, which can taint the finished product if not adequately managed. Therefore, in order to assure quality, efficiency, and safety throughout the drying process, humidity management is crucial in the food sector [19, 20].

3.2.2. Optimal Conditions

Specific temperature and humidity levels are necessary for optimal drying conditions for food products in order to guarantee that moisture is removed from the food without cooking or an external degree of hardness. Food should be dried at a temperature not more than 140°F to avoid burning the food instead of drying it. In order to avoid case hardening, the drying process should never be accelerated by increasing the temperature. Case hardening can happen when food cooks on the exterior and moisture cannot escape. Water travels from the food to the surrounding air during drying; therefore, low humidity is ideal for drying food products, and drying will be inhibited if the surrounding air is humid [22, 27].

During the drying process, air flowing over the food removes moisture; therefore, ideal circumstances call for a balance of temperature and humidity-warm temperatures, low humidity, and air current. Drying eliminates moisture from food, preventing the growth of bacteria, yeasts, and molds; however, enzyme function is delayed rather than inactivated throughout the process. The optimal drying method depends on factors such as climate, equipment availability, and food type [22, 23].

While room drying at room temperature works only if heat, humidity, and air movement are sufficient, sun drying is problematic in places with high humidity. Sun drying is best used in dry climes. Modern food dehydrators or convection ovens, which combine low heat with a fan to circulate the air, are excellent methods for drying food in the oven at a temperature of 140°F to 150°F (60°C to 65°C). It is critical to ensure that food is dried equally on both the interior and exterior, and vegetables are regarded as optimally dried when they are brittle, while fruits are considered optimally dried when they feel like leather. After drying, items should be allowed to cool for 30-60 minutes before being packed into clean, dry, insect-proof containers. The containers for dried meals should be packed as securely as possible without crushing the food in order to prevent insect contamination and moisture reabsorption. Dried foods must be appropriately packaged and stored right away [21-23].

3.2.3. Challenges Associated with Controlling Humidity

Controlling humidity throughout the drying process may be challenging. An excessive amount of humidity can cause drying processes to take longer, increased energy use, and reduce productivity. Humidity can also impact the drying process, lowering product integrity and damaging items and processing equipment as a result of moisture. This is crucial for processing hygroscopic food products or other objects that naturally collect moisture from their environment. Humidity control strategies need to be implemented by manufacturers during drying processes to prevent such issues [24, 25].

Relative humidity, or the difference between the quantity of moisture in the air at a particular temperature and the maximum amount that may exist at that same temperature, must be monitored for effective humidity control. Minor changes in humidity might result in costly and time-consuming procedure changes in industrial processing facilities. It may not be possible to maintain appropriate humidity levels for equipment functioning and product integrity with just air conditioning. A specific dehumidification system is required to remove unnecessary moisture to maintain the optimum room air temperature [25].

Uncontrolled air leakage can cause condensation and other moisture-related difficulties, but building a specialized continuous air barrier can help alleviate these challenges. Insufficient humidity levels during the drying process can result in problems such as cracking, fragility, and product deterioration. Excess moisture during the drying process might impair the product's quality and shorten its shelf life. During the hot summer months, manufacturers struggle to maintain constant humidity levels in their facilities because warm air currents bring more Gulf moisture to northern regions during these months, making it harder to regulate humidity levels during the drying process [24, 25].

3.3. Air Velocity

Air velocity is another significant factor in the food drying process because it impacts the rate of moisture removal from the food product. According to research, increasing air velocity increases the rate of water evaporation from food. The gradient of evaporation rate, however, changes with temperature while rising with velocity. To get the necessary quality and efficiency, it is crucial to choose an appropriate air velocity for a particular food product. Furthermore, optimizing process parameters such as air velocity is required to achieve the desired drying efficiency and food product quality [29, 30, 33].

3.3.1. Role of Air Velocity

The drying process is significantly influenced by air velocity, which also has an impact on drying efficiency and product quality. The rate of water migration and the heat stability of the chemical composition should be considered when determining air velocity during HAID (Hot Air Impingement Drying) [28]. The drying kinetics of lumber in the food industry is immediately impacted by higher air velocity because it accelerates evaporation during the drying process [29, 30]. The drying rate is increased throughout the constant drying rate phase as well as during the transition and falling rate periods by gradually raising air velocity from 0.5 m/s to 3.5 m/s. However, as the air velocity approaches 1.5 m/s, the influence on the drying rate is modest due to the balanced heat transfer rate and enthalpy change. The influence of velocity is substantial throughout this period, especially at high velocities. Air velocity also has an impact on the critical moisture content (CMC), with increased velocity being correlated with lower CMC and pushing it towards FSP. At high air velocities, the impact of temperature is less noticeable since the drying rate is not considerably affected by additional increases in air velocities due to reduced heat and mass transfer rates [29]. Furthermore, wood stacking may block the airflow channel and minimize turbulence at the air-lumber contact, leading to the substantial influence of velocity. Therefore, in order to optimize the drying process in applications for the food industry, experimental setups may be utilized to investigate the impact of air velocity on wood drying [30, 31].

3.3.2. Impact of Air Velocity on the Quality of the Dried Food Product

The effect of air velocity on the quality of dried food has been studied in food science and has a pivotal role. The maximum values of enzymatic response were achieved when samples were dried at 65°C with an air velocity of 6 m/s, according to a research. However, high air velocity might cause a long-term non-enzymatic response and reduce lightness owing to prolonged drying time. Therefore, it's crucial to choose an air velocity that strikes a compromise between the necessity to effectively dry the product and the need to preserve its color quality. In fact, increasing air velocity can enhance the color quality of dried items. Compared to other drying techniques, ovens with built-in fans for air movement have faster rates of moisture removal, and higher air velocities at the start of drying can improve overall efficiency and the quality of the finished product. As a result, careful consideration of air velocity is required to ensure the quality and efficiency of the dried food product [28].

3.4. Surface Area

The surface area of food items is critical in the drying process. Due to enhanced moisture transport, drying rates rise with surface area. Slicing, shredding, or grinding are methods used in the food business to increase the product's surface area. According to a previous publication [38], increasing the surface area of kiwifruit slices resulted in a faster drying rate and a shorter drying time when compared to whole kiwifruit. Similar results were found in another [39], which found that smaller potato cubes dried faster and more quickly than bigger potato chunks.

3.4.1. Affect on Drying Rate of Food Products

The surface area of food goods is a significant aspect in influencing drying rate. Food slices that are thin have more surface area, which speeds up the elimination of moisture during drying. This is because moisture may escape more quickly from the surface of the food. Comparatively speaking, thinner slices dry up faster than broader ones [35]. This is due to the fact that thinner slices have a greater surface-to-volume ratio, which means they dry more quickly as moisture has a shorter distance to travel from the food's surface to the air, where it may evaporate. Therefore, it is advised to cut food goods into thinner pieces to enhance their surface area in order to accomplish faster drying periods. Moisture removal is influenced by temperature as well. Increasing the temperature of food causes moisture to evaporate, but a balance of temperature and humidity is required for optimal food drying.

3.4.2. Increasing the Surface Area of Food Products

Various methods are used throughout the drying process to improve the surface area of food goods. Three of these important procedures are: (1) ultrasonic vacuum (USV), (2) vacuum dryer (VD), and (3) freeze dryer (FD). The content does not focus particular procedures for increasing surface area, although it does discuss various minced beef drying processes. Cabinet drying, for example, tends to diminish the material's surface area and permeability. Adding a hard coating to the food's surface, on the other hand, might result in less moisture escape and a longer drying time [36]. Ultrasound treatment, on the other hand, can cause micro channels and tissue breakdown, resulting in increased porosity and intercellular gaps in the dry product [39]. In research comparing USV and VD drying processes on minced beef samples, the USV approach produced a more open structure and more porosity than the VD technique. In comparison to VD and USV procedures, freeze-drying yields minced beef samples with greater porosity and open structure because it sustains less damage at low temperatures. Accordingly, depending on the particular requirements of the product being dried, these various drying techniques may be used to enhance the surface area of food items throughout the drying process [32, 34, 37].

3.5. Type of Food Product

The drying process in the food sector is greatly influenced by the kind of food product. Table 1 shows the various processing temperatures and drying periods needed for various foods [40]. Drying is a cheap and effective technique of preserving food, but it can have a negative impact on the end product's quality and safety. Fruits and vegetables include substances that make it simpler for microorganisms to survive the dehydration process, whereas certain sugars and amino acids can boost the survival rate of bacteria during preservation techniques [41].

Foods to be dried	Processing temperature and time
Fruits	
Cherries	70 °C for 2–3 h; 55 °C until dry
Coconuts	45 °C until dry
Pineapples	70 °C for 1–2 h; 55 °C until dry
Persimmons	60 °C for 1–2 h; 55 °C until dry
Pears (Asian)	60 °C
Vegetables	
Asparagus	60 °C for 2–3 h; 55 °C until dry
Beans, green	60 °C for 2 h; 55 °C until dry
Mushrooms	25–30 °C for 2–3 h; increase to 50 °C until dry
Onions	70 °C for 1–2 h; 55 °C until dry
Parsley	30 °C to 50 °C; may be room dried
Fish	
Carp	4 °C under high pressure for 15–20 min
Prawn	70 °C for 30 min
Meat	
All	80 °C for 2 h

Table 1 Processing temperature and time for different food products

To tackle this, many methods that inactivate microorganisms during the drying process have been developed. Acidic fruits with a low pH are particularly efficient in damaging microbes after drying [41]. However, drying can cause flavor, fragrance, and useful ingredients in some foods, such as vitamin C, thiamin, protein, and fat, to be lost. Despite these disadvantages, drying provides a number of benefits, including as lowering food weight and volume for simpler storage, packing, and transportation. Any sort of food may really be thoroughly dried out by spray drying, extending its shelf life at ambient temperature without refrigeration [40, 42].

Pathogens adhered to the surface of white cabbage, such as Salmonella spp., can be inactivated at different rates depending on the drying process used. For example, the decrease of microbial growth in vacuum microwave drying and the atmospheric pressure microwave processing combination method varies depending on the food product, but it has been demonstrated to be successful in decreasing microbial growth in freshly shredded carrots and parsley. Finally, as dry food containers can be opened and closed several times without the contents changing, they are a great strategy for minimizing food industry waste. To prevent infection, canned goods must be consumed right away after being opened [41].

3.5.1 Characteristics of Food Products that Affect the Drying Process

The drying of food products is a complicated process that is influenced by a number of variables. The initial moisture level of the product is one of the most important aspects since it impacts the drying process and duration. The outcome of the drying process is significantly influenced by the chemical makeup of the food. For instance, the drying time and rate are impacted by the presence of natural or added chemicals such as sugars, acids, and salts. The size and form of the food product also have an influence on the process, since bigger or irregularly shaped goods might take longer to dry [43]. The food's structure can also affect how quickly and how long it takes to dry. For instance, the density and porosity of food items are natural qualities that influence the drying process. Additionally, the process is impacted by the material's ability to develop pores as it dries, and poor temperature management can result in unintended structural changes to the material [43, 44].

Low humidity, low heat, and sufficient air circulation are only a few of the other requirements for successful drying [45]. The drying of numerous food items, such as fruits, vegetables, and dairy components, is covered in the Special Issue. The Special Issue may also cover the analytical techniques used in the drying operations [43]. Finally, understanding the features of food items that impact the drying process is critical for achieving optimal drying results. It is possible to increase shelf life while maintaining nutritional quality, texture, and sensory characteristics by regulating elements such as initial moisture content, chemical composition, and structural qualities.

3.5.2. Different Drying Methods Used in Food Industry

Depending on the kind of food product being dried and the intended end product quality, the food business uses a variety of drying techniques, such as sun drying, oven drying, spray drying, freeze drying, and vacuum drying. It is important to select the right drying technique for each product since it might affect the functional qualities and nutritional value of the food product. There are around 50 distinct types of dryers used for drying food items, and new drying technologies are being widely researched to evaluate their influence on the chemical and metabolic changes that occur throughout the dehydration process. Drying can improve material quality and provide value-added chemicals in spices, medicinal plants, herbs, bioactive enzymes, and nuts. It is critical to adopt an appropriate drying process for each product since various food items may require different drying methods to optimize drying parameters and assure product quality. Traditional drying techniques are more prone to physical and chemical deterioration in the finished product, which should be minimized by using an appropriate drying technique [46].

The drying techniques employed, such as sun drying, which is a natural process, while dehydrating with heat from a fire or other dryers is an artificial process, affect the physical characteristics of the drying process [47]. Intermittent drying can help preserve bioactive chemicals by reducing browning effects, hydro-thermomechanical stress, and chemical reactions in samples. Innovative or combination methods must provide high-quality dried goods while also taking the environment and energy efficiency into account. To remove water from food items, the food industry uses a variety of drying procedures, including mechanical dewatering, osmotic dehydration, and thermal drying [46].

Figure 2 Factors to be considered for dryer selection [49]

In Figure 2, some factors have been discussed regarding the selection of an appropriate dryer during various drying processes. One of the main factors when selecting a dryer is the type of food product to be dried and the optimum temperature need by the product such as vacuum drying is considered to be a good option for fruits and fruit related products.

4. Conclusion

Drying process is an important stage in the food industry working with various parameters, including air velocity, surface area, and developing technology, have considerable influence on the quality and shelf life of food items along an impact on the drying process's efficiency and sustainability. These parameters have significant influence on nutrient and flavor retention, as well as the environmental and economic consequences of drying techniques while significant insights for boosting the efficiency and sustainability of the drying process in the food sector can be achieved by giving case studies that illustrate effective optimization of drying operations using the response surface technique. Current research findings and practical ideas consolidates fundamental concepts of heat and mass transport processes; however, further investigations are needed to lead the creation of efficient and sustainable drying processes, allowing manufacturing of high-quality food items with prolonged shelf life.

Author Contributions
Conceptualization, A.J.; validation, M.S.H. and U.J.; writing—original draft preparation, A.J. and R.A; writing-review and editing, and..; visualization, U.J.; R.A; M.S.H.

Acknowledgments
The authors are highly obliged to their departments and institutes for access to journals, books and valuable database

Conflicts of Interest
The authors declare no conflict of interest

References

1. Food and Agriculture Organization of the United Nations. (2018). Drying of Foods. Retrieved from http://www.fao.org/3/X5731E/x5731e03.htm
2. Wray, D., Ramaswamy, H. (2015). Novel Concepts in Microwave Drying of Foods. Drying Technology, 7(33), 769-783. https://doi.org/10.1080/07373937.2014.985793.
3. Goula, A. M., & Adamopoulos, K. G. (2013). A review of new technological developments for the production of dried food products. Drying Technology, 31(14), 1539-1557. doi: 10.1080/07373937.2013.814266.
4. Li, Z., Chen, J. (2022). Recent Application of Artificial Neural Network in Microwave Drying of Foods: A Mini-review. J Sci Food Agric, 14(102), 6202-6210. https://doi.org/10.1002/jsfa.12008.
5. Kumar, S., & Mishra, H. N. (2017). Drying technologies for foods: Fundamentals and applications. Hoboken, NJ: John Wiley & Sons.
6. Salmeron, J., Ruiz-Celma, A. (2018). Elliot and Symmetric Elliot Extreme Learning Machines for Gaussian Noisy Industrial Thermal Modelling. Energies, 1(12), 90. https://doi.org/10.3390/en12010090
7. Zhang, M., Mujumdar, A. S., & Yang, H. (2020). Advances in drying of food materials: A review. Journal of Food Engineering, 277, 109885.
8. Karim, M. A., Rahman, M. S., & Joardder, M. U. H. (2018). Vacuum drying technique for food preservation: A review. Journal of Food Process Engineering, 41(2), e12638.
9. Santos, D. T., Ribeiro, A. P. B., & Telis, V. R. N. (2017). Freeze-drying of fruits and vegetables: A review. Journal of Food Engineering, 193, 46-57.
10. Koc, B., Kaya, A., & Gecgel, U. (2017). Recent advancements in spray drying technology for effective food processing: A review. Journal of Food Processing and Preservation, 41(1), e12866.

11. Kumar, R., & Sun, J. (2019). Vacuum belt drying technology for high-quality dried foods. Food Engineering Reviews, 11(1), 1-16.
12. Drying – The Effect of Temperature on Relative Humidity. (n.d.) Retrieved June 18, 2023, from techblog.ctgclean.com
13. Effect of step-down temperature drying on energy consumption and product quality of walnuts. (n.d.) Retrieved June 18, 2023, from www.sciencedirect.com
14. Drying food at home | UMN Extension. (n.d.) Retrieved June 18, 2023, from extension.umn.edu/preserving-and-preparing/drying-food
15. Drying Foods. (n.d.) Retrieved June 18, 2023, from hgic.clemson.edu/factsheet/drying-foods/
16. Impact of the Drying Techniques on the Functional Properties of Citrus sinensis (Sweet Orange) Fruit − A Review: International Journal of Nutrition, Pharmacology, Neurological Diseases. (n.d.) Retrieved June 18, 2023, from journals.lww.com
17. Effects of Different Drying Methods on Drying Kinetics, Microstructure, Color, and the Rehydration Ratio of Minced Meat. (n.d.) Retrieved June 18, 2023, from www.ncbi.nlm.nih.gov/pmc/articles/PMC6617532/
18. Foods | Free Full-Text | The Freeze-Drying of Foods—The Characteristic of the Process Course and the Effect of Its Parameters on the Physical Properties of Food Materials. (n.d.) Retrieved June 18, 2023, from www.mdpi.com/2304-8158/9/10/1488
19. www.sciencedirect.com. (n.d.) Retrieved June 20, 2023, from www.sciencedirect.com
20. 3 Ways Too Much Humidity Affects Food Processing and Warehousing. (n.d.) Retrieved June 20, 2023, from www.polygongroup.com
21. Drying food at home | UMN Extension. (n.d.) Retrieved June 20, 2023, from extension.umn.edu/preserving-and-preparing/drying-food
22. Drying Foods. (n.d.) Retrieved June 20, 2023, from hgic.clemson.edu/factsheet/drying-foods/
23. Let's Preserve: Drying Fruits and Vegetables (Dehydration). (n.d.) Retrieved June 20, 2023, from extension.psu.edu
24. Solving Humidity Issues in Manufacturing Facilities. (n.d.) Retrieved June 20, 2023, from www.ien.com
25. Solving Humidity Issues in Manufacturing Processes. (n.d.) Retrieved June 20, 2023, from www.dehumidifiercorp.com
26. Mojola, O. (1987). Solar crop drying in a low humidity environment. International Journal of Energy Research. https://doi.org/10.1002/ER.4440110304.

27. Chen, Y., Choong, E., & Wetzel, D. (1996). A numerical analysis technique to evaluate the moisture-dependent diffusion coefficient on moisture movement during drying. Wood and Fiber Science.
28. Foods | Free Full-Text | Hot Air Impingement Drying Enhanced Drying Characteristics and Quality Attributes of Ophiopogonis Radix. (n.d.) Retrieved June 21, 2023, from www.mdpi.com/2304-8158/12/7/1441.
29. Influence of Air Temperature and Velocity for Drying Process ☆. (n.d.) Retrieved June 21, 2023, from www.sciencedirect.com/science/article/pii/S1877705817311980
30. Chanpet M, Rakmak N, Matan N, Siripatana C. Effect of air velocity, temperature, and relative humidity on drying kinetics of rubberwood. Heliyon. 2020 Oct 8;6(10):e05151. doi: 10.1016/j.heliyon.2020.e05151. PMID: 33083612; PMCID: PMC7550925.
31. Drying food at home | UMN Extension. (n.d.) Retrieved June 21, 2023, from extension.umn.edu/preserving-and-preparing/drying-food
32. Food Dehydration. (n.d.) Retrieved June 21, 2023, from www.sciencedirect.com/topics/food-science/food-dehydration
33. Putra, Raka & Ajiwiguna, Tri. (2017). Influence of Air Temperature and Velocity for Drying Process. Procedia Engineering. 170. 516-519. 10.1016/j.proeng.2017.03.082.
34. Turkan, B., Canbolat, A., & Etemoğlu, A. (2019). Numerical Investigation of Multiphase Transport Model for Hot-Air Drying of Food. Journal of Agricultural Sciences. https://doi.org/10.15832/ankutbd.441925.
35. The Effect of Pre-Drying Treatment and Drying Conditions on Quality and Energy Consumption of Hot Air-Dried Celeriac Slices: Optimisation. (n.d.) Retrieved June 21, 2023, from www.ncbi.nlm.nih.gov/pmc/articles/PMC8394511/
36. Foods | Free Full-Text | Interaction of Different Drying Methods and Storage on Appearance, Surface Structure, Energy, and Quality of Berberis vulgaris var. asperma. (n.d.) Retrieved June 21, 2023, from www.mdpi.com/2304-8158/11/19/3003
37. Effects of Different Drying Methods on Drying Kinetics, Microstructure, Color, and the Rehydration Ratio of Minced Meat. (n.d.) Retrieved June 21, 2023, from www.ncbi.nlm.nih.gov/pmc/articles/PMC6617532/.
38. Khazaei, J., Kaveh, M., & Emam-Djomeh, Z. (2013). Effect of cutting methods on drying kinetics and quality attributes of kiwifruit. Journal of Food Processing and Preservation, 37(1), 105-113.
39. Krokida, M. K., Maroulis, Z. B., & Saravacos, G. D. (2001). Drying kinetics of some vegetables. Journal of Food Engineering, 49(1), 27-32.

40. A review on mechanisms and commercial aspects of food preservation and processing. (n.d.) Retrieved June 22, 2023, from agricultureandfoodsecurity.biomedcentral.com
41. The microbiological quality of various foods dried by applying different drying methods: a review. (n.d.) Retrieved June 22, 2023, from www.ncbi.nlm.nih.gov/pmc/articles/PMC8017434/
42. Drying Foods. (n.d.) Retrieved June 22, 2023, from hgic.clemson.edu/factsheet/drying-foods/
43. Implications of Drying Techniques on the Bioactive Components and Quality of Food. (n.d.) Retrieved June 22, 2023, from www.hindawi.com/journals/jfq/si/970864/
44. The Freeze-Drying of Foods—The Characteristic of the Process Course and the Effect of Its Parameters on the Physical Properties of Food Materials. (n.d.) Retrieved June 22, 2023, from www.ncbi.nlm.nih.gov/pmc/articles/PMC7603155/
45. Drying food at home | UMN Extension. (n.d.) Retrieved June 22, 2023, from extension.umn.edu/preserving-and-preparing/drying-food
46. Comparison of Traditional and Novel Drying Techniques and Its Effect on Quality of Fruits, Vegetables and Aromatic Herbs. (n.d.) Retrieved June 22, 2023, from www.ncbi.nlm.nih.gov/pmc/articles/PMC7554907/
47. Drying Method of Food Preservation with Types, Examples. (n.d.) Retrieved June 22, 2023, from microbenotes.com/drying-method-food-preservation/
48. Advantages of novel drying methods. (n.d.). ResearchGate. https://www.researchgate.net/figure/Advantages-of-novel-drying-methods-71_fig2_316507291.
49. Factors to be considered for dryer selection. (n.d.). ResearchGate. https://www.researchgate.net/figure/Factors-to-be-considered-for-dryer-selection_fig1_350519278.

ISBN 978-1-960740-06-9

DRYING TECHNOLOGY – CURRENT RESEARCH AND INDUSTRIAL APPLICATIONS

Editors

Muhammad Imran & Amna Javed

Review Based Book Chapter

SPRAY DRYING AND ENCAPSULATION – TECHNOLOGICAL ASPECTS AND APPLICATIONS

August 17, 2023

doi: 10.5281/zenodo.10246954

Scientific Knowledge Publisher (SciKnowPub), USA

info@sciknowpub.com

REVIEW BASED BOOK CHAPTER

SPRAY DRYING AND ENCAPSULATION – TECHNOLOGICAL ASPECTS AND APPLICATIONS

Marwah Sarwar[1]

[1]*Department of Food Science, Faculty of Life Sciences, Government College University, Faisalabad, Pakistan*

For Correspondence
marwahsarwar123@gmail.com

Abstract

Spray drying is increasingly gaining attraction in the food industry, demonstrating a growing prevalence in the fabrication of not only a vast spectrum of elements, but also functional foods, pharmaceuticals, and nutraceuticals, amongst various drying methods by providing microbiological stability and preventing chemical and biological deterioration. It also minimizes storage needs and shipping costs and leads to the creation of a product with unique features like quick solubility along color enhancing or concealing an astringent taste in food items as its one of the finest and most potent strategies to enhance the durability and sensory qualities of products is the spray-drying of liquid extracts. Its popularity in the industry stems from its efficiency in drying even the most challenging substances. The preference for spray drying encapsulation often stems from its economic efficiency relative to alternate encapsulation techniques. The resulting powder is extremely stable and immune to chemical and microbiological alterations (such as oxidation and hydrolytic reactions) due to its low moisture content and low water activity.

Keywords
Spray Drying, Spray Dried Powder, Encapsulation, Drying Technology, Powder Quality

1. Drying Technology: A Preservation Technique

Drying is an ancient preservation technique that is still widely used today. The process involves using heat to remove moisture from food, which helps keep it fresh for longer periods. Drying of food items can be categorized into two main types: a) in-air drying and b) in-vacuum drying, depending on the method of dehydration used. There are various heat application techniques for drying, including convection, conduction, radiation, microwave, radio frequency, and Joule heating. Drying materials can be in the form of wet solids, liquids, suspensions, or pastes, and they need to undergo downstream processing to enhance their value and extend their storage and transportation time. However, conventional hot air drying may harm the preservation of bioactive components in these heat-sensitive materials. High temperatures can lead to product deterioration, denaturation of active substances, case hardening, discoloration, and other negative effects [1]. The advantage of selecting dehydration as a method to conserve food lies not solely in its technical simplicity but also in its economic benefits. The expenses associated with processing, packaging, transporting, and storing dried commodities are less compared to those associated with canned and frozen goods. Generally, the food dehydration process is divided into three stages a) initial preparation before drying b) the drying process itself, and c) treatment after drying. The impact of these steps on the end product's quality hinges on the type of processing material utilized and the envisaged use of the final product [2-4].

Drying is an energy-intensive process in postharvest processing, used to reduce the water content of various fruits, vegetables, agricultural products, and herbs. By reducing the water activity to a level that inhibits microbial growth, enzymatic activities, and other deteriorative reactions, the shelf life of biologically derived items can be extended. Drying is especially important for herbs, as it allows the extraction of active chemicals. Moreover, dry products are lighter, resulting in lowering shipping costs. Biologically derived products have diverse physical, chemical, and biological characteristics. To meet different quality and price requirements, a wide range of dryers have been developed for dehydrating and preserving these items. While approximately 100 dryer types are available commercially, the technical literature describes over 500 dryer types. Dryer design varies due to differences in product characteristics, heat input methods, operating temperatures & pressures, and quality standards for the dried product. Traditional dryers typically operate at atmospheric pressure, use hot air as the drying medium, and rely solely on convection for heat transfer. Batch operation is preferred for systems with limited capacity and long drying times, such as solar dryers. Drying safeguards products by reducing moisture content, offering various advantages in food preservation. It allows for early harvest, reduces shipping weights and costs, minimizes the need for packaging, and extends shelf life [5-8].

2. Drying Methods: A General Overview

In the food industry, microcapsules are typically dried using the most common methods of freeze-drying and spray-drying. These are distinct procedures, each performed under different temperatures and durations, which result in unique morphological and particle size characteristics in the dried goods. An experiment that encapsulated bioactive elements from acerola pulp, followed by freeze-drying and spray-drying, was conducted to compare the properties of the microcapsules. The results indicated that the spray-dried product contained higher levels of bioactive substances and antioxidants [9].

Traditional thermal processes for drying encompass techniques such as hot air drying, vacuum drying, and freeze drying, among others. Each method has its own strengths, for instance, hot air drying utilizes simple, safe, and cost-effective machinery. Vacuum drying is suited for materials that are prone to oxidation. Microwave technology provides rapid drying rates and uniform product quality. However, due to the complexity and diversity of component characteristics, a single drying technique often falls short in meeting the quality standards of the final product. As a solution, innovative and eco-friendly combined drying technologies, such as heat pump drying, superheated steam drying, freeze drying, vacuum sealing, and microwave drying, are gradually replacing traditional drying methods. These combined technologies aim to decrease drying time and elevate product quality [6, 10].

Freeze drying and spray drying are not only used in the food industry but also in the chemical sector, for encapsulation and drying purposes. The first method aids in the transformation of liquid products into a powder form, thus extending their usable lifespan. Certain active biological components are encapsulated to facilitate their storage and distribution. Spray drying, another method, also converts liquid food into powder form. These procedures have been long implemented in the dairy industry and have recently found applications in the pharmaceutical sector, primarily for drug delivery. Freeze drying is an excellent choice for heat-sensitive materials, as it can preserve the color, taste, and nutritional value of the food. Freeze-drying, because of its steady state and lower temperature, is ideal for handling heat-sensitive substances. The freeze-drying technique integrates two pivotal stages: freezing and drying. Earlier, efforts were mainly focused on refining the drying stage, not fully considering the potential impacts of the freezing phase. As a solution undergoes freezing, it experiences several physical transformations, including reaching a supercooling state. The level of supercooling in a solution governs the characteristics of ice formation (its size, number, and form) during the freezing stage, which in turn affects the subsequent drying stage, such as resistance to the flow of water vapor. Therefore, varying levels of supercooling lead to diverse ice characteristics and subsequently, uneven drying outcomes [11, 12].

2.1. Spray Drying

The technique of spray drying, which transforms liquid meals into a powdered form, has been extensively utilized over the years to manufacture a range of products like milk powder, fertilizers, medicinal compounds with active properties, and laundry detergents [12-14]. Spray-drying offers benefits like rapid processing, flexibility, and the capacity to produce small droplets. Typically, spray drying suspensions that contain nanoparticles result in larger, hierarchically organized structures. Secondary particle shapes like dense, hollow, or even doughnut-shaped morphologies can be achieved by manipulating factors such as temperature, air flow speed, droplet size, viscosity, the size of the primary particle, the amount of solid content, and interactions between particles [15-17].

2.1.1. Working Principle of Spray Drying

The spray drying process primarily includes following steps:

1) Concentration
2) Atomization
3) Droplet interaction with air
4) Droplet drying
5) Separation

Spray drying is a method employed for transforming solid components into dry powder. It begins with a slurry, which is a mixture of liquid, solution, or suspension that is introduced into the spray dryer as a damp product. This slurry is atomized into tiny droplets, typically ranging in diameter from 10 to 500 micrometers. Due to the lack of atomizers capable of producing monodisperse droplets of very small sizes, the drying process has to accommodate a broad spectrum of droplet sizes, achieved through the use of heated gas. Unlike other drying techniques, spray drying allows for the reduction of significant accumulations of dry material downstream of the atomization zone since there is no necessity for wall contact within the spray dryer, and drying droplet collisions rarely occur. Spray drying stands out as one of the few drying techniques that can endure long viscous and sticky phases during the solidification process. Other drying procedures, such as spin flash, mill drying, or contact drying methods including mixing and kneader drying as well as one shaft and two shaft techniques, struggle with prolonged viscous stages. The success of spray drying relies on the wet product being of low enough viscosity to permit efficient atomization. This often means that the inflow concentration needs to be reduced compared to other drying methods, resulting in a higher required evaporation rate [17, 18].

Several factors, including the size of the dryer and the diameter of the droplets, allow spray drying to have quick drying times between 1 to 60 seconds. The high surface to volume ratio of small droplets facilitates rapid drying periods. For instance, a larger droplet with a diameter of one millimeter has a hundred times less specific surface area for an evaporating solvent compared to a smaller 10-micrometer droplet. Moreover, solidified droplets have longer diffusion lengths, which slows down the drying rates, especially during the "falling rate drying period," where the last of the solvent has to be eliminated through diffusion through the solid and the outer surface is dry. Hence, the drying periods in a spray drying process, which usually produces droplets sizes below 1mm, can be significantly reduced. The stickiness of the final dried and hot particles is an essential product quality in spray drying. Depending on the operational mode and the product's drying properties, exit temperatures can be reduced to 80-120°C, with lower temperatures achieved for certain products. However, spray drying might not be successful for products with inadequate glass transition temperatures. Despite the drawbacks, spray drying can serve as a cheaper alternative to freeze-drying for certain substances, such as blood plasma [19].

In spite of their high drying temperatures, spray dryers maintain a brief drying contact time with the core materials inside the drying chamber, often a few seconds. This typically involves an input air temperature of 150 to 250 °C and an exit air temperature of 50 to 80 °C [20]. The spray drying procedure involves atomizing liquid feed, often referred to as extracts, into the drying chamber. Here, the droplets traverse through a stream of hot-air or occasionally nitrogen. The small droplets, which enhance the surface-to-mass ratio and evaporate water rapidly, provide a larger contact surface, making the process both fast and aggressive. This minimizes heat damage to sensitive materials. The dry powder particles are then separated from the exhausted air in a separation cyclone and collected in a vessel [21-23].

The wall material used for spray drying includes sugars such as lactose and sucrose [24], gum arabic [25] and mesquite gum [26], in addition to milk proteins like sodium caseinate and whey protein [27]. However, pointed out that certain wall elements like gelatin, gum arabic, and sucrose is unsuitable for use in infant formula. Multiple wall substances are accessible, including starches such as maltodextrin, which are used for the microencapsulation of food components [28, 29].

3. Encapsulation Technique

The influence of consumer needs propels advancements in encapsulation technology for food uses. Bioactive chemical encapsulation has seen improvements due to novel dehydration methods. Encapsulation serves as a method to safeguard an extremely susceptible substance which forms micro or nano scale formations after enclosing a bioactive center in what is referred to as wall substances. The purpose is to boost the stability of bio actives for targeted, controlled or postponed release while shielding them from harsh elements such as light, moisture, and oxygen [30]. In relation to oils that have not undergone encapsulation, the encapsulation process bolsters the endurance and robustness of oils during their period of storage [31]. A successful encapsulation system should employ food-grade ingredients, preferably natural ones, seamlessly integrate bioactive compounds into food without altering organoleptic properties, provide enhanced physical stability, shield the encapsulated substances from heat, light, and pH changes, and enable maximum absorption of the bioactive compound [32].

3.1. Applications and Advantages

The growing demand for versatile, nutrient-rich oils in the realms of food, medicine, and cosmetics is undeniable, driven by their multifaceted utilities.

However, the high degree of unsaturation present in vegetable and marine oils introduces a risk for oxidative degradation and the onset of an unpleasant taste. Further complicating matters is the inherent instability of oils when subjected to processing and storage conditions, given their vulnerability to light and heat, which restricts their utility in the food sector. Consequently, measures to safeguard these oils are imperative to enhance their stability during management, processing, and storage [33, 34]. Such fluctuations negatively influence the product's shelf life, sensory attributes, and overall market acceptance [35]. Encapsulation, which is typically employed to resolve the problems stated earlier, is a hopeful approach that involves safeguarding the main elements from heat, light, and oxygen. It also facilitates stability, bioavailability, taste concealing, and controlled release, all while retaining the oils' functional attributes and improving their manageability [36-41].

Encapsulation of oil enhances the oxidative stability of lipids and safeguards the interior ingredients from external elements such as reactive substances, oils, flavorings, and vitamins. This is enabled by the core material's high solubility, ease of blending, and controlled release, pending the appropriate trigger. It also minimizes the evaporation of the volatile components in the core material, thereby decreasing or concealing any associated unfavorable tastes [42-45]. There are some key reasons for opting for oil encapsulation: (a) Encapsulation aids in bolstering lipid oxidation stability, a crucial element in the creation of powdered edible oil goods. This process helps in the conservation of oils by shielding them from oxidation [43] (b) It acts as a protective shield for the core ingredients against elements such as oxygen, light, and water. This is particularly relevant for vulnerable ingredients like oils, scents, and vitamins. Food oils are especially sensitive to irradiation, air, temperature, and light [46, 47] (c) Encapsulation facilitates the transformation of oils from a liquid state to a dry state, creating a powder derived from the primary components that blends easily and has high solubility. In the food industry, this conversion of liquid feeds (like flavors and edible oils) into powders with suitable handling characteristics is a critical encapsulation form [48] (d) It helps control the release of crucial contents, ensuring an appropriate delay for the correct stimulus. This characteristic, known as encapsulation, is a significant benefit in managing the release of active components in oil and flavor until they reach their intended target [49] (e) Encapsulation prevents the evaporation of volatile compounds present within the key ingredients. This results in a dry powder with superior oxidation stability and low volatility. Encapsulated oils create a dry powder with enhanced oxidation resistance and decreased volatility, making it easier to utilize in various end products such as cakes and beverages [50] (f) It helps to disguise or neutralize the unpalatable tastes of the core ingredient. Some edible oils, such as vegetable or marine oils, are highly desired in food items due to their nutritional value. Moreover, encapsulation can help solve primary problems associated with food containing 3 PUFA, like the undesired "fishy" smell of fish oil and the proneness of polyunsaturated fatty acids to oxidation, which can negatively impact food acceptance [51] and when compared to non-encapsulated oils, encapsulation improves the longevity and robustness of oils during storage [52].

4. Spray Drying Applications in Various Industries

Drying serves as a vital operation in the various sectors including pharmaceutical industry, biopharmaceutical industry, dairy industry, food industry and many more. Few of them are discussed below:

4.1. Pharmaceutical Sector

Spray drying has been an active area of technological progression over the past few decades, especially within the pharmaceutical industries. In pharmaceutical and biopharmaceutical sectors, spray drying being primarily used for the conversion of liquid drug formulations into solid states, all while preserving their therapeutic and pharmacological characteristics. This procedure, most commonly applied to remove solvents like water, is significant as it allows a drug in its solid form to stabilize both the active pharmaceutical ingredient and the additives. This stabilization considerably curtails pathways of chemical and physical degradation, such as hydrolysis, oxidation, isomerization, condensation, racemization, and interactions with other constituents present in the solution [53]. Spray drying also has been used in the delivery of pulmonary medications, including the manufacture of consistent and inhalable size particles for devices such as nebulizers, dry powder inhalers (DPI), and pressurized metered dose inhalers. Spray drying also assists in the development of mucoadhesive formulations that can effectively adhere to nasal passages, thus improving drug absorption and bioavailability. Innovations and patent submissions in spray drying technologies aimed at enhancing solubility are also underscored. Historically, the pharmaceutical industry has utilized spray drying for creating dry versions of plant-based active ingredients [54].

4.2. Food Industry

The potential of spray drying to generate a diverse array of food products, including powders from milk or soymilk, tomato pulp, dehydrated fruit juice and others, has been acknowledged. It can be employed for the encapsulation of substances like vegetable or fish oil, and dry creamer [55]. There's a growing health consciousness among contemporary consumers, leading to a surge in demand for foods fortified with bioactive or functional components, especially those derived from natural sources [54, 56].

Bioactive compounds, also referred to as nutraceuticals, are naturally occurring substances that are either essential or optional elements of our diets and positively impact human health [57, 58]. Certain bioactive compounds that enhance human health include polyunsaturated fatty acids, polyphenolic compounds, anthocyanin, and vitamins. However, their bioactivity and antioxidant properties can be compromised by various factors such as light, temperature, air, moisture, or the existence of unsaturated bonds. Therefore, encapsulation methods are employed to bolster the chemical or biological stability of these substances [59, 60]. In essence, researchers extensively review the primary use and recent advancements in spray drying and lyophilization processes for encapsulating bioactive ingredients within the food [56, 61]. Spray drying process enhances the management attributes of the items and bolsters oxidation stability by protecting the bioactive constituents, in encapsulating oils. The quality of the final product is significantly influenced by factors associated with oil encapsulation such as the temperatures at the point of entry and exit, total solids, and the wall materials utilized. Thus, this evaluation gives priority to understanding and refining the spray drying methodology for encapsulating oils used as food supplements [14, 62, 63, 64].

4.2.1. Dairy Products

The global production of dairy products has been progressively growing; for instance, from 2012 to 2016, the production rose by 5.47%, escalating from 771,262 to 815,965 thousand tonnes. Given this increased production, it's vital to preserve this higher quantity of milk for the benefit of people worldwide, particularly in regions where conditions are not conducive to dairy farming or might accelerate the spoilage of liquid dairy products. Consequently, the preference is to produce powdered products using spray drying [65]. Spray-drying is commonly employed in the dairy industry to create a range of products on a substantial commercial scale. The individual characteristics of each product depend on the ratio of protein to fat to carbohydrate, the specific type of protein, and, to a lesser extent, the process conditions applied. Due to their high moisture content, dairy products naturally have a short shelf life, despite their excellent nutritional value. To drastically decrease the microbial activity associated with moisture and to allow for cost-effective, global distribution due to reduced weight, a significant portion of the material derived from milk is dehydrated [66]. Owing to their high perishability, milk and its byproducts often undergo processes like spray drying to extend their usable lifespan [67]. Spray drying usually yields a free-flowing powder that's easier to transport, handle, and store, while also having an extended shelf life. This ease of use makes the powder an effortless addition to processed foods such as bread and sweets. The development of spray drying equipment and techniques has evolved over several years, from the 1870s until the early 20th century [68].

5. Spray Drying: Pros and Cons

A tried and tested, economical, and scalable drying method known as spray drying converts liquids directly into powders [69]. By employing the process of spray drying, bioactive elements drawn out from food wastes and byproducts can be reduced to powder form and reincorporated into the food supply chain. Spray drying has been identified as the most convenient, time- and energy-efficient approach, as it converts liquids directly into a stable powder that can be either stored for extended periods or effortlessly mixed with other substances. Even though spray drying has many advantages for different materials, it's not without its problems, some of which need attention in future development programs [70] a) minimizing scale for a more straightforward validation of new products, which often necessitates comprehensive testing b) The challenge of designing an atomization process that needs a diluted, low viscosity input and generates a broad size distribution, which may pose challenges during the drying phase c) The process of droplet recycling within the tower can lead to the accumulation on the spray tower wall and at the nozzles and can place excessive thermal stress on the product d) The shorter drying periods for larger droplet fractions can result in inconsistent drying and clumping of the final product.

6. Quality Characteristics of Final Spray Dried Product

The consistency in the quality and characteristics of the end product is crucial as these aspects are intrinsically linked with the bioactive component content, bulk density of the powder, particle size, moisture content, and a host of other physical and chemical properties [71, 72]. Many researchers also added several factors that influence the quality of the end product/powder, including atomizer speed, nozzle design, solvent used, concentration of the liquid feed, feed flow rate, inlet and outlet temperatures, airflow rate, aspirator rate, and temperature. This technique can yield particles of diverse sizes, from nanoparticles (210-280 nm) to agglomerates (2-3 mm) [14]. A low moisture content and a high bulk density are sought-after qualities in powder. Increased bulk density reduces packaging expenses while enhancing the flow of the powder. Moreover, a moisture content of less than 5% boosts product stability during storage [73-75].

Another advanced technique, nano-spray drying, is used to produce powders with particle sizes smaller than 100 nm. Reaching nanoscale dimensions is not feasible since the cyclone separator is unable to segregate extremely tiny particles during traditional spray drying [22]. Encapsulation enveloping each droplet or particle of a bioactive liquid or solid (core substance) within a polymerized shell. These small capsules can be round or irregular in shape and vary in size from micrometers to millimeters. The core elements can be solid substances, dispersions, or droplets [32, 77-80].

7. Conclusion

Spray-drying, due to its quick drying time, is frequently used to encapsulate heat-sensitive bioactive compounds. Consumers have exhibited heightened interest in food items abundant in bioactive components due to substantial research linking their intake to the prevention of chronic diseases. By decreasing the moisture content of the product, drying helps preserve the quality, inhibit microbial growth and chemical changes during storage. Both reduced water activity and content are responsible for longer shelf life of the product. The utility of spray drying in the creation of dry flavorings to maximize output and minimize flavor degradation, has played pivotal role in food industry. Spray drying is also predominantly employed in the commercial production of dry plant extracts. However, high temperatures used in the drying process can lead to heat degradation and an unstable state in thermally sensitive components. Hence, alternative drying methods and operative conditions need to be developed and standardize for multipurpose procedures.

Author Contributions

Conceptualization; validation; writing—original draft preparation, writing-review and editing, and..; visualization: M.S.

Acknowledgments

The author is highly obliged to university departments and institutes for access to journals, books and valuable database.

Conflicts of Interest

The author declares no conflict of interest.

References

[1] Chen HH, Huang TC, Tsai CH, Mujumdar AS. Development and performance analysis of a new solar energy-assisted photocatalytic dryer. Dry Technol. 2008(4); 503-507.
[2] Singh A, Van den Mooter G. Spray drying formulation of amorphous solid dispersions. Advanced drug delivery reviews. 2016; 27-50.
[3] Rahman K. Studies on free radicals, antioxidants, and co-factors. Clinical interventions in aging. 2007(2); 219-236.
[4] Lewicki PP. Design of hot air drying for better foods. Trends in Food Science & Technol. 2006(4); 153-163.
[5] Mujumdar AS, Law CL. Drying technology: Trends and applications in postharvest processing. Food and Bioprocess Technol. 2010(3); 843-852.
[6] Zielinska M, Zapotoczny P, Alves-Filho O, Eikevik TM, Blaszczak W. A multi-stage combined heat pump and microwave vacuum drying of green peas. J. Food Eng. 2013(3); 347-356.
[7] Sansone F, Mencherini T, Picerno P, d'Amore M, Aquino RP, Lauro MR. Maltodextrin/pectin microparticles by spray drying as carrier for nutraceutical extracts. J. Food Eng. 2011(3); 468-476.
[8] Laine P, Kylli P, Heinonen M, Jouppila K. Storage stability of microencapsulated cloudberry (Rubus chamaemorus) phenolics. J. Agric. Food Chem. J. 2008(23); 11251-11261.
[9] Rezende YRRS, Nogueira JP, Narain N. Microencapsulation of extracts of bioactive compounds obtained from acerola (Malpighia emarginata DC) pulp and residue by spray and freeze drying: Chemical, morphological and chemometric characterization. Food chemistry. 2018; 281-291.
[10] Barzegar M, Zare D, Stroshine RL. An integrated energy and quality approach to optimization of green peas drying in a hot air infrared-assisted vibratory bed dryer. J. Food Eng. 2015; 302-315.

[11] Assegehegn G, Brito-de la Fuente E, Franco JM, Gallegos C. The importance of understanding the freezing step and its impact on freeze-drying process performance. J. Pharm Sci. 2019(4); 1378-1395.
[12] Vehring, R. Pharmaceutical particle engineering via spray drying. Pharmaceutical research. 2008(5); 999-1022.
[13] Wang S, Langrish T. A review of process simulations and the use of additives in spray drying. Food Research International. 2009(1); 13-25.
[14] Gharsallaoui A, Roudaut G, Chambin O, Voilley A, Saurel R. Applications of spray-drying in microencapsulation of food ingredients. An overview. Food research international. 2007(9); 1107-1121.
[15] Zellmer S, Lindenau M, Michel S, Garnweitner G, Schilde C. Influence of surface modification on structure formation and micromechanical properties of spray-dried silica aggregates. J. colloid Interface Sci. 2016; 183-190.
[16] Vehring R, Foss WR, Lechuga-Ballesteros D. Particle formation in spray drying. J. Aerosol Sci. 2007(7); 728-746.
[17] Nandiyanto ABD, Okuyama K. Progress in developing spray-drying methods for the production of controlled morphology particles. From the nanometer to submicrometer size ranges. Advanced powder technology. 2011(1); 1-19.
[18] Patel RP, Patel MP, Suthar A M. Spray drying technology: an overview. Indian J Sci Technol. 2009(10); 44-47.
[19] Bellinghausen R. Spray drying from yesterday to tomorrow: An industrial perspective. Drying Technology. 2019(5); 612-622.
[20] Geranpour M, Assadpour E, Jafari SM. Recent advances in the spray drying encapsulation of essential fatty acids and functional oils. Trends in food science & technology. 2020; 71-90.
[21] Vidović SS, Vladić, JZ, Vaštag ŽG, Zeković ZP, Popović LM. Maltodextrin as a carrier of health benefit compounds in Satureja montana dry powder extract obtained by spray drying technique. Powder technology. 2014; 209-215.
[22] Arpagaus C, John P, Collenberg A, Rütti D. Nanocapsules formation by nano spray drying. In Nanoencapsulation technologies for the food and nutraceutical industries. Academic press. 2017; 346-401.
[23] Jafari SM, Arpagaus, Cerqueira MA, Samborska K. Nano spray drying of food ingredients.materials, processing and applications. Trends in Food Science & Technol. 2021; 632-646.
[24] Davidov-Pardo G, Arozarena I, Marín-Arroyo MR. Optimization of a wall material formulation to microencapsulate a grape seed extract using a mixture design of experiments. Food and Bioprocess Technology. 2013; 941-951.
[25] Tupuna DS, Paese K., Guterres SS, Jablonski A, Flôres SH, de Oliveira Rios A. Encapsulation efficiency and thermal stability of norbixin microencapsulated by spray-drying using different combinations of wall materials. Industrial crops and products. 2018; 846-855.
[26] Kandansamy K, Somasundaram PD. Microencapsulation of colors by spray drying-a review. International J. Food Eng. 2012; (2).
[27] Hosseini H, Ghorbani M, Jafari SM, Sadeghi Mahoonak A. Encapsulation of EPA and DHA concentrate from Kilka fish oil by milk proteins and evaluation of its oxidative stability. J. Food Sci. Technol. 2019; 59-70.
[28] Morin P, Jiménez-Flores R, Pouliot Y. Effect of processing on the composition and microstructure of buttermilk and its milk fat globule membranes. Int. Dairy J. 2007(10); 1179-1187.
[29] Tolun A, Altintas Z, Artik N. Microencapsulation of grape polyphenols using maltodextrin and gum arabic as two alternative coating materials: Development and characterization. J. Biotechnol. 2016; 23-33.

[30] Drosou CG, Krokida MK, Biliaderis CG. Encapsulation of bioactive compounds through electrospinning/electrospraying and spray drying: A comparative assessment of food-related applications. Drying technol. 2017(2); 139-162.
[31] Mohammed NK, Meor Hussin AS, Tan CP, Abdul Manap MY, Alhelli AM. Quality changes of microencapsulated Nigella sativa oil upon accelerated storage. Int. J. Food Prop. 2017(sup3); S2395-S2408.
[32] Đorđević V, Balanč B, Belščak-Cvitanović A, Lević S, Trifković K, Kalušević A, Nedović V. Trends in encapsulation technologies for delivery of food bioactive compounds. Food Engineering Reviews. 2015; 452-490.
[33] Di Giorgio L, Salgado PR, Mauri AN. Encapsulation of fish oil in soybean protein particles by emulsification and spray drying. Food Hydrocolloids. 2019; 891-901.
[34] Eratte D, Dowling K, Barrow CJ, Adhikari B. Recent advances in the microencapsulation of omega-3 oil and probiotic bacteria through complex coacervation: A review. Trends in food science & technology. 2018; 121-131.
[35] Ojagh SM, Hasani S. Characteristics and oxidative stability of fish oil nano-liposomes and its application in functional bread. J. Food Meas. Charact. 2018; 1084-1092.
[36] Fang Z, Bhandari B. Encapsulation of polyphenols–a review. Trends in food science & technology. 2010(10); 510-523.
[37] Aguiar J, Estevinho BN, Santos L. Microencapsulation of natural antioxidants for food application–The specific case of coffee antioxidants–A review. Trends in food science & technology. 2016; 21-39.
[38] Lozano-Vazquez G, Lobato-Calleros C, Escalona-Buendia H, Chavez G, Alvarez-Ramirez J, Vernon-Carter EJ. Effect of the weight ratio of alginate-modified tapioca starch on the physicochemical properties and release kinetics of chlorogenic acid containing beads. Food Hydrocolloids. 2015; 301-311.
[39] Amstad E. Capsules: their past and opportunities for their future. 2017
[40] Estevinho BN, Rocha F. Application of biopolymers in microencapsulation processes. In Biopolymers for food design. Academic Press. 2018; (pp. 191-222).
[41] Zuidam NJ, Nedovic V. Encapsulation technologies for active food ingredients and food processing (Vol. 410). New York, NY, USA: Springer. 2010.
[42] Zheng X, Wu F, Hong, Y, Shen L, Lin X, Feng Y. Developments in taste-masking techniques for traditional Chinese medicines. Pharmaceutics. 2018(3); 157.
[43] Ahn JH, Kim YP, Lee YM, Seo EM, Lee KW, Kim HS. Optimization of microencapsulation of seed oil by response surface methodology. Food Chemistry. 2008(1); 98-105.
[44] Jafari SM, Assadpoor EHeY, Bhandari B. Encapsulation efficiency of food flavours and oils during spray drying. Drying technology. 2008(7); 816-835.
[45] Kolanowski W, Ziolkowski M, Weißbrodt J, Kunz B, Laufenberg G. Microencapsulation of fish oil by spray drying--impact on oxidative stability. Part 1. European Food Research and Technology. 2006; 336-342.
[46] Bilia AR, Guccione C, Isacchi B, Righeschi C, Firenzuoli F, Bergonzi MC. Essential oils loaded in nanosystems: a developing strategy for a successful therapeutic approach. Evidence-based complementary and alternative medicine. 2014.
[47] Bakry AM, Abbas S, Ali B, Majeed H, Abouelwafa MY, Mousa A, Liang L. Microencapsulation of oils: A comprehensive review of benefits, techniques, and applications. Comprehensive reviews in food science and food safety. 2016(1); 143-182.
[48] Gupta S, Khan S, Muzafar M, Kushwaha M, Yadav AK, Gupta AP. Encapsulation: Entrapping essential oil/flavors/aromas in food. In Encapsulations. Academic Press. 2016; (pp. 229-268).
[49] Manaf MA, Subuki I, Jai J Raslan R, Mustapa AN Encapsulation of volatile citronella essential oil by coacervation: efficiency and release study. In IOP conference series: materials science and engineering (Vol. 358, No. 1, p. 012072). IOP Publishing. 2018, may.

[50] Encina C, Márquez-Ruiz G, Holgado F, Giménez B, Vergara C, Robert P. Effect of spray-drying with organic solvents on the encapsulation, release and stability of fish oil. Food chemistry.2018; 263, 283-291.
[51] Melgosa R, Benito-Román Ó, Sanz MT, de Paz E, Beltrán S. Omega–3 encapsulation by PGSS-drying and conventional drying methods. Particle characterization and oxidative stability. Food chemistry. 2019; 138-148.
[52] Mohammed NK, Meor Hussin AS, Tan CP, Abdul Manap MY, Alhelli AM. Quality changes of microencapsulated Nigella sativa oil upon accelerated storage. Int. J. Food Prop. 2017(sup3); S2395-S2408.
[53] Walters RH, Bhatnagar B, Tchessalov S, Izutsu KI, Tsumoto K, Ohtake S. Next generation drying technologies for pharmaceutical applications. J. Pharm. Sci. 2014(9); 2673-2695.
[54] Sollohub K, Cal K. Spray drying technique: II. Current applications in pharmaceutical technology. J. Pharm. Sci. 2010(2); 587-597.
[55] B Patel B, K Patel J, Chakraborty S. Review of patents and application of spray drying in pharmaceutical, food and flavor industry. Recent patents on drug delivery & formulation. 2014(1); 63-78.
[56] Marrelli M, Statti G, Conforti F. A review of biologically active natural products from Mediterranean wild edible plants: Benefits in the treatment of obesity and its related disorders. Molecules. 2020(3); 649.
[57] Boyano-Orozco L, Gallardo-Velázquez T, Meza-Márquez OG, Osorio-Revilla G. Microencapsulation of rambutan peel extract by spray drying. Foods. 2020(7); 899.
[58] Biesalski HK, Dragsted LO, Elmadfa I, Grossklaus R, Müller M, Schrenk D, Weber P. Bioactive compounds. Safety and efficacy. Nutrition. 2009(11-12); 1206-1211.
[59] Ozkan G, Franco P, De Marco I, Xiao J, Capanoglu E. A review of microencapsulation methods for food antioxidants. Principles, advantages, drawbacks and applications. Food chemistry. 2019; 494-506.
[60] Rezvankhah A, Emam-Djomeh Z, Askari G. Encapsulation and delivery of bioactive compounds using spray and freeze-drying techniques: A review. Drying Technol. 2020(1-2); 235-258.
[61] Kandasamy S, Naveen R. A review on the encapsulation of bioactive components using spray-drying and freeze-drying techniques. J. Food Eng. 2022(8); e14059.
[62] Marrelli M, Statti G, Conforti F. A review of biologically active natural products from Mediterranean wild edible plants: Benefits in the treatment of obesity and its related disorders. Molecules. 2020(3); 649.
[63] Pirbalouti AG, Mahdad E, Craker L. Effects of drying methods on qualitative and quantitative properties of essential oil of two basil landraces. Food chemistry. 2013(3); 2440-2449.
[64] Orphanides A, Goulas V, Gekas V. Drying technologies: Vehicle to high-quality herbs. Food Engineering Reviews. 2016; 164-180.
[65] O'Sullivan JJ, Norwood EA, O'Mahony JA, Kelly AL. Atomisation technologies used in spray drying in the dairy industry: A review. J. Food Eng. 2019; 57-69.
[66] Schuck P, Jeantet R, Bhandari B, Chen XD, Perrone IT, de Carvalho AF, Kelly P. Recent advances in spray drying relevant to the dairy industry: A comprehensive critical review. Drying Technol. 2016(15); 1773-1790.
[67] Ramaprasad TR, Baskaran V, Debnath S, Lokesh B. Shelf life of spray-dried milk formulations supplemented with n-3 fatty acids. J. Food Process. Preserv. 2006(3); 364-378.
[68] Saikia S, Mahnot NK., Mahanta CL. Effect of spray drying of four fruit juices on physicochemical, phytochemical and antioxidant properties. J. Food Process. Preserv. 2015(6); 1656-1664.
[69] Singh A, Van den Mooter G. Spray drying formulation of amorphous solid dispersions. Advanced drug delivery reviews. 2016; 27-50.

[70] Bellinghausen R. Spray drying from yesterday to tomorrow: An industrial perspective. Drying Technol. 2019(5); 612-622.
[71] Vladić J, Ambrus R, Szabó-Révész P, Vasić A, Cvejin A, Pavlić B, Vidović S. Recycling of filter tea industry by-products: Production of A. millefolium powder using spray drying technique. Industrial Crops and Products. 2016; 197-206.
[72] Kaderides K, Goula AM. Development and characterization of a new encapsulating agent from orange juice by-products. Food Research International. 2017; 612-622.
[73] Shishir MR I, Chen W. Trends of spray drying: A critical review on drying of fruit and vegetable juices. Trends in food science & technology. 2017; 49-67.
[74] Sinija VR, Mishra HN. Moisture sorption isotherms and heat of sorption of instant (soluble) green tea powder and green tea granules. J. food Eng. 2008(4); 494-500.
[75] Tan L. W, Ibrahim MN, Kamil R, Taip FS. Empirical modeling for spray drying process of sticky and non-sticky products. Procedia Food Science. 2011; 690-697.
[76] Tyagi VV, Kaushik SC, Tyagi SK, Akiyama T. Development of phase change materials based microencapsulated technology for buildings: a review. Renewable and sustainable energy reviews. 2011(2); 1373-1391.
[77] Fredes C, Becerra C, Parada, J, Robert P. The microencapsulation of maqui (Aristotelia chilensis (Mol.) Stuntz) juice by spray-drying and freeze-drying produces powders with similar anthocyanin stability and bioaccessibility. Molecules. 2018(5); 1227.
[78] Bah MG, Bilal HM, Wang J. Fabrication and application of complex microcapsules: A review. Soft Matter. 2020(3); 570-590.
[79] Norkaew O, Thitisut P, Mahatheeranont S, Pawin B, Sookwong P, Yodpitak S, Lungkaphin A. Effect of wall materials on some physicochemical properties and release characteristics of encapsulated black rice anthocyanin microcapsules. Food chemistry. 2019; 493-502.
[80] Javed, A., Imran, M., Ahmad, N., & Hussain, A. I. Fatty acids characterization and oxidative stability of spray dried designer egg powder. Lipids in health and disease, 2018 (17), 1-13.

ISBN 978-1-960740-06-9

DRYING TECHNOLOGY – CURRENT RESEARCH AND INDUSTRIAL APPLICATIONS

Editors

Muhammad Imran & Amna Javed

Review Based Book Chapter

DRYING TECHNOLOGY: APPLICATIONS AND CHALLENGES IN FOOD INDUSTRY

October 24, 2023
doi: 10.5281/zenodo.10251202

Scientific Knowledge Publisher (SciKnowPub), USA
info@sciknowpub.com

REVIEW BASED BOOK CHAPTER

DRYING TECHNOLOGY: APPLICATIONS AND CHALLENGES IN FOOD INDUSTRY

Amna Javed[1], Rahima Amjad[1], Muhammad Saad Hashmi[2,3], Uzma Javaid[4,5]

[1]Department of Nutrition and Dietetics, The University of Faisalabad, Faisalabad, Pakistan
[2]Institute of Food Science and Nutrition, Bahauddin Zakariya University, Multan, Pakistan
[3]Punjab Food Authority, Pakistan
[4]Department of Anatomy, Sargodha Medical College, Sargodha, Pakistan
[5]University of Sargodha, Sargodha, Pakistan

For Correspondence
amna.javed@tuf.edu.pk

Abstract

Drying process is a common food preservation technique that eliminates moisture from food goods to increase shelf life, stability, and convenience along countless applications in food sector. By reviewing of the basic ideas and mechanisms involved in drying processes, this chapter dives into the practical applications of drying techniques in a variety of food categories. It delves into the drying of fruits, vegetables, cereals, meats, dairy products, herbs, and spices, clarifying the special issues and obstacles connected with each food item. The notable impact of drying on the nutritional composition, sensory characteristics, and functional qualities of food items explored current trends, challenges and advances of drying technology in food sector. The processes such as energy consumption, cost-effectiveness, and sustainability of various drying procedures, offering insights into their overall viability and practicality in the food industry along reviewing the economic and environmental ramifications of drying processes. More innovative methods with accurate operative settings might enhance food preservation, quality, and market competitiveness by providing a greater understanding of the benefits and constraints connected with drying procedures.

Keywords
Drying Process, Food Preservation, Shelf Life, Dry Powder, Drying Methods, Industrial Challenges

1. Introduction

Drying processes are frequently employed in the food sector for a variety of applications, including dairy products, coffee, tea, flavors, powdered beverages, processed cereal-based meals, fruits, vegetables, and spices. Drying is employed in the manufacturing of malt, where the kilning procedure is utilized to remove water from wet germinated grain. This drying stage is critical in the malting process since it contributes to the ideal color and flavor of the malt. Drying fresh food products requires complicated processes such as energy transfer, unbound moisture evaporation, and water particle movement inside the cellular structure. Drying is a heat-driven process that results in solid-dried goods. Vaporizing bound water is critical for producing a safe and dry product. Drying fresh food goods reduces bacteria development and extends the product's shelf life. The drying method consists of eliminating unbound moisture followed by the removal of interior moisture. The drying process also has an impact on enzyme activity, sensory qualities, and microbial proliferation in food. Various drying processes have been widely researched for their chemical and biological changes in food items, and changed through time as advanced equipment and optimized drying parameters are developed [1, 2].

Sun drying, hot air drying, contact drying, infrared drying, freeze-drying, fluidized bed drying, and dielectric drying are some of the most prevalent drying processes used in the food sector. Furthermore, drying food has been utilized as a technique of food preservation for millennia and may be used as an alternative or supplement to canning and freezing procedures. Individuals may now dry numerous foods at home year-round with current food dehydrators, which are great for hiking, camping, and other outdoor activities due to their lightweight, compact design and lack of refrigeration. Intermittent drying is another technology created to address the constraints of convective drying by enhancing drying kinetics, product quality, and lowering energy usage in the food sector [2, 3, 4].

2. General Overview and Drying Methods

Each drying method has its own set of advantages and disadvantages. Pre-evaporation, for example, allows for an increase in the dry substance content of wet material without the need for additional equipment, which can be beneficial in terms of efficiency and energy consumption. This approach can also be used in conjunction with specific dewatering equipment, such as presses or centrifuges, to improve the dry material content while consuming less energy throughout the drying process. Cabinet-type dryers, also known as dehydrators, provide controlled heat and air circulation for drying food, making them a popular choice for home drying. Oven drying, on the other hand, requires the use of an oven to dry the food, which may limit its accessibility and convenience. Air drying, a more traditional method, can be done in a variety of settings, such as a shady porch or corner of the kitchen, offering flexibility and ease of use. This criterion includes various factors such as drying time, energy efficiency, protection from environmental elements, and the possible influence on the quality and appearance of the dried product [6, 7, 8].

2.1. Impact on Quality and Characteristics of Food Products

The drying process can have a considerable influence on the quality and features of food items. Dehydration procedures, for example, have been shown to preserve superior quality and nutritional content than sun drying. However, it is crucial to remember that drying processes in general might cause vitamin and nutritional loss in food items. Drying procedures might impact the water-holding capacity of food goods, particularly meat, where it may decrease. Cooking the items before drying helps to eliminate any bacteria that may be present and ensuring food safety. Lower temperatures can be employed in high-pressure drying (HPD) dryers to improve the overall quality of the dried product [5].

It is also important to note that the storage and treatment of dried foods play an important role in keeping their quality. Dried food containers may be opened and reopened repeatedly without affecting the contents, making them easy to store and use. Canned goods, on the other hand, should be consumed quickly after opening to avoid spoiling while drying processes differ from evaporation as they produce concentrated liquid products with different properties than the original food product. The primary goal of drying is to increase the shelf-life of foods by decreasing their water activity and limiting the growth of microbes and enzymes that cause deterioration and undesirable chemical changes. To guarantee proper drying, elements such as time, temperature, and pre-treatment of the food goods must be considered. Starting with high-quality ingredients is critical for getting optimum drying outcomes. Low humidity, low heat, and excellent air circulation are crucial for efficient drying since they help keep the natural flavor, nutritional content, and scent of the food goods. Drying at low temperatures can also minimize or eliminate the requirement for flavor and scent additions in food items [1, 6].

It should be noted that hastening the drying process by raising the temperature might have a detrimental impact on the quality and attributes of the food items. Higher temperatures might cause food to cook rather than dry, resulting in a lesser quality end product. This can also cause "case hardening," in which the food is cooked on the exterior but stays moist on the interior, potentially leading to mold growth, later in storage. As a result, it has been advised that food to be dried at the optimal temperature of 140°F to produce the maximum outcomes. Different drying methods, such as utilizing a dehydrator, oven, microwave, or air-drying, can affect the quality and features of food items. Oven drying, for example, is more difficult to manage than dehydrating and takes longer, resulting in increased energy use. Blanching vegetables and pre-treating fruits before drying can help preserve food quality. Furthermore, keeping dried goods in a dark, cold place and insect-proof containers is required to retain their quality over time. By choosing the optimal drying process and executing suitable storage practices are critical for keeping food product quality and qualities [4, 6, 7].

3. Role of Drying Techniques for Food Safety and Quality

Drying techniques are utilized for various purposes and products (Figure 1) in food sector, few of them discussed below:

3.1. Preservation of Food Products

Drying is a common, oldest and most basic food preservation method, with a recorded history in many civilizations and communities [10, 11, 13]. The primary purpose of drying methods is to eliminate moisture from food products, which limits the growth of bacteria, mold, and yeast that cause spoilage. The shelf life of foods may be greatly extended by using the right drying techniques and storage setups while drying also decreases the water content of foods, making them lighter and easier to store and transport, as dried foods are lightweight, take up little room, and do not require refrigeration along their suitability for outdoor activities like trekking and camping. Drying may be accomplished in a number of ways, including the sun, an oven, or a food dehydrator set to the ideal temperature, humidity, and airflow. Food enzymes are not entirely deactivated by drying, even if it slows down their activity. However, combining drying with additional preservation processes like freezing or canning might improve the overall preservation process. Drying is essential for food preservation as it removes moisture and creates an environment that prevents the growth of bacteria that cause degradation [9, 11, 12, 14].

Figure 1 Preservation of different food products [15, 16, 17]

3.2. Inhibition of Bacterial Growth

Drying inhibits the development of microorganisms in food by lowering water activity, which is a fundamental element in microbial survival and growth. The process of drying has an impact on the microorganisms and their methods for survival, which inhibits or delays their growth. Dry foods are hygroscopic, meaning they can draw and hold moisture. When the equilibrium between relative humidity and moisture content is disrupted, this feature produces an appropriate moisture environment for mold development. For this reason, it's critical to maintain the proper relative humidity in the storage environment to limit microbial development in dried foods. However, drying may not entirely eradicate germs and spore cells, which can survive for months and create health concerns. Due to the elimination of water, drying causes several changes in the structure of microorganisms, including denaturation of proteins and damage to cell walls. Additionally, microorganisms defend against cellular damage rather than repair it, in response to drying stress. The drying process also diminishes the efficacy of the resonance strength of water molecules, which helps prevent membrane protein denaturation even at high temperatures. As a result of drying, bacteria are exposed to stressful settings that might inhibit or inactivate them. These environments can include ones with high or low temperatures, increased osmolality, and acidic pH [18]. Various drying processes and technologies have been developed to efficiently suppress microbial growth and assure microbiological safety in dried items. A combination of approaches is sometimes required to efficiently inactivate or kill microorganisms during the drying process to make it an effective method for delaying the development of microbes in food and extending the shelf life of dried goods.

3.3. Production of Powdered Products

Drying processes are critical in the manufacturing of powdered commodities, serving different uses and providing numerous benefits. To ensure the goods' long-term stability and availability all year round, one of the main goals is to eliminate moisture from them. Drying processes enable simpler storage and transportation by converting liquid material into dry, powdery form. Furthermore, drying processes are regarded Best Available processes in the industry since they not only preserve the product but also improve its quality. For example, drying improves the re-hydrating characteristics of powdered commodities, resulting in higher quality powders with improved sensory attributes. Drying procedures restrict bacterial development and microbial activity by eliminating moisture from the fresh food, extending its shelf life. Additionally, drying techniques and factors affect not only the bulk density of dried goods but also how big and how angular they appear to be to the client [19, 20]. Drying techniques enable the production of powdered commodities that may be used as coatings, flavorings, or full meals depending on the unique food product, increasing convenience and diversity in food consumption. Drying techniques are essential for generating stable, useful, and superior-quality powdered goods [21]. In order to maintain the quality and increase the shelf life of powdered commodities, drying processes are essential as the volume and weight of the items may be decreased using these methods, which lowers the expenses associated with packing, storage, and transportation. Drying procedures achieve a water activity level of less than 0.3, effectively inhibiting microbe development and undesirable chemical reactions and thereby extending the storage duration of powdered commodities. Depending on the unique properties of the raw material, different drying procedures may be used to protect the quality and shelf life of powdered commodities, including thermal drying, osmotic dehydration and mechanical dewatering [20].

For example, freeze-drying is advised for retaining the functional integrity of powdered items, but osmotic pre-treatment can be employed to minimize elasticity and viscosity loss during rehydration. Drying procedures have the ability to alter the flavor and texture of the items in addition to keeping their physical qualities, resulting in the creation of novel and healthier snack choices. Color, bulk density, porosity, phytochemicals, sugars, proteins, volatile substances, and sensory qualities are used to evaluate the quality of dried items. The best drying method may differ based on the particular material being dried, hence careful analysis of drying protocols is required in order to suggest particular drying parameters for each product. In order to preserve the quality and lengthen the shelf life of powdered items, moisture must be removed, and microbiological contamination must be kept to a minimum [20, 22, 23, 24]. Examples of powdered products are given in Table 1 along their visuals in Figure 2.

Figure 2a Spray-drying Machine for powdered goods [30]

Table 1 Different dried food products in market

Product name	Description	Reference
Egg powder	Egg powder is a dried version of eggs that may be reconstituted with water and used in place of fresh eggs in cooking and baking. It is manufactured by eliminating the moisture from eggs, generally by a spray-drying technique, and grinding them into a fine powder. When compared to fresh eggs, this powder has a longer shelf life and is easier to store and transport	[25]
Milk powder	Milk powder, often known as powdered milk or dry milk, is a dairy product prepared by evaporating milk to eliminate its moisture content. The powder that results can be reconstituted with water to make liquid milk or utilized as a component in a variety of culinary and beverage applications	[26]
Coffee powder	Coffee powder, often known as instant coffee, is a form of coffee that is produced by drying. It entails removing soluble chemicals from brewed coffee and then dehydrating the liquid to get a dry, powdered form	[27]
Orange powder	Orange powder is commonly used to describe a powdered version of oranges or orange zest. Oranges or their peels are dried and ground into a fine powder to make it	[28]
Strawberry powder	Strawberry powder is a powdered version of strawberries created by drying and crushing the fruit into a fine powder. It's a common natural flavoring and coloring component in a variety of food and beverage applications	[29]

3.4. Production of Ready-to-Eat Meals

Preserving ready-to-eat meals by air drying is a widespread practice; however, it might negatively affect the food's quality and shelf life. Exposure to air and moisture during the drying process might reduce the overall quality of the food, therefore specific care must be taken to keep it fresh and extend its duration of storage. It is critical to store dried foods in airtight containers to avoid moisture reabsorption and retain quality [31]. Additionally, it is advised to regularly inspect the dried food during storage to make sure it is still dry and shows no symptoms of mold or rotting and to avoid spoiling, removal of any moisture from the food and re-drying should be done. The shelf life of air-dried meals is also significantly influenced by the surrounding storage conditions. Storing dried food in a cold, dry, and dark environment with a temperature below 60°F will help to increase its shelf life. However, if the humidity is excessive, the food may begin to mold before it dries by shortening its shelf life. In order to avoid moisture reabsorption and preserve the quality of air-dried ready-to-eat meals, it is crucial to take into account the storage conditions and implement the necessary steps [22, 31].

Figure 2b Left Freeze-dried variety soup box [32]; Right: Instant Asian ready-to-eat meals [33]

Freeze-drying is a particularly beneficial preservation technology for the creation of ready-to-eat meals. Freeze-dried meals have a number of benefits, including a lengthy shelf life that makes them perfect for long-term distribution and storage. Freeze-drying helps to keep key minerals and phytochemicals in foods, ensuring that ready-to-eat meals retain nutritious value, also, freeze-dried meals are lightweight, simple to handle, and transportable, which makes them practical for both producers and customers [34, 35]. Fruits and tiny vegetables are particularly well-suited for ready-to-eat meals since they may be freeze dried without losing quality or taste. Additionally, customers may quickly and easily rehydrate freeze-dried meals by just adding water, making them handy [36]. This technology makes it feasible to efficiently preserve freeze-dried dairy and egg products, something that is not achievable with conventional preservation methods [37]. The quality of freeze-dried foods is substantially superior to that of conventional drying processes, retaining fragrance, rehydration characteristics, and general bioactivity. In terms of making ready-to-eat meals, freeze-drying has a lot of benefits, including better quality preservation, a longer shelf life, and ease of handling and reconstitution. However, no possible drawbacks of freeze drying in the preparation of ready-to-eat meals are mentioned in the literature [35]. Some novel drying techniques for the Food Industry are presented in Figure 3.

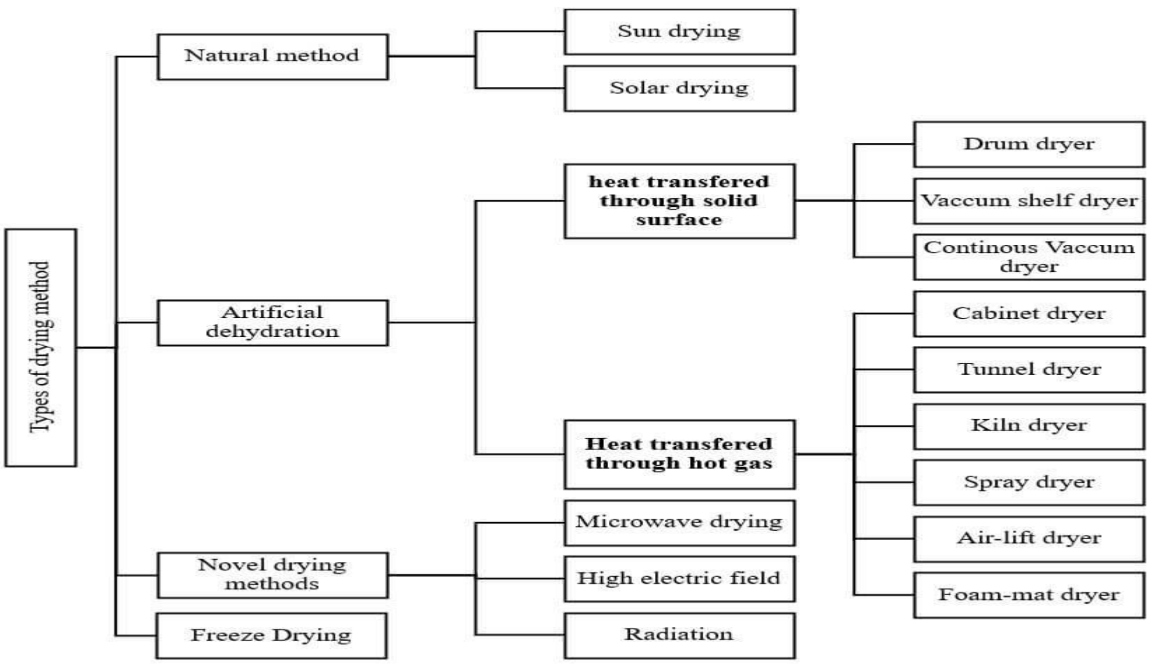

Figure 3 Novel Drying Techniques for the Food Industry [38]

4. Industrial Drying Processes and Challenges in the Food Industry

Effective industrial drying procedures are essential for preserving product quality, increasing shelf life, assuring food safety in the quick-paced and constantly changing food business. However, the obstacles that these drying processes encounter are diverse and frequently complicated. The food business is continuously looking for novel solutions to get around these challenges, from lowering energy use and costs to preserve product purity and fulfilling regulatory requirements [39]. This topic will cover the major issues encountered by industrial drying processes in the food industry, as well as the cutting-edge technology and methods that firms are using to optimize their drying operations.

4.1. Energy Usage

Food sector industrial drying operations face a number of difficulties that may reduce effectiveness and productivity. The problem of energy usage is one of the biggest obstacles. Food goods need to be dried with a lot of heat, which uses a lot of energy. Reducing energy use is essential as energy prices increase and sustainability gains much importance. Finding solutions to optimize drying operations and reduce energy use without sacrificing product quality is a perennial problem for food makers [40, 41].

4.2. Product Integrity

Another difficulty in industrial drying procedures is maintaining product integrity. The drying process must take into account the distinctive qualities and sensitivities of various food items. Delicate fruits and vegetables, for example, may be damaged or lose nutrients if exposed to high temperatures for a lengthy period. However, meat or fish items need specialized drying conditions to preserve food quality and avoid spoiling specialized food safety characteristics. It takes careful monitoring and management to strike the right balance between the demand for effective drying and the preservation of product quality and safety [42, 43].

4.3. Regulatory Compliance

Ensuring regulatory compliance to protect consumer safety, the food business is subject to follow stringent laws and standards. Specific standards for drying procedures, such as temperature limits, moisture levels, and sanitation procedures, are frequently stipulated by these rules. Compliance with these rules while preserving operational efficiency can be a difficult endeavor that necessitates constant monitoring, documentation, and adherence to best practices [44].

4.4. Environmental Concerns

Drying procedures in the food sector have major environmental implications, particularly in terms of energy usage and greenhouse gas emissions. Several solutions have been put out to reduce these effects. One strategy is to optimize drying process parameters such as temperature, humidity, and air velocity in order to reduce energy usage while preserving product quality. Utilizing renewable energy sources, such as solar energy, to power the drying process is another tactic. The utilization of developing technologies like as microwave drying, hoover drying, and freeze-drying can cut energy use while minimizing nutritional and flavor loss, therefore contributing to environmental sustainability [45, 46].

5. Best Practices for Overcoming Challenges in Industrial Drying Processes

To tackle the constraints of industrial drying processes, food producers are implementing a number of best practices that improve productivity, product quality, and regulatory compliance. One such practice is the use of quality management systems, such as Hazard Analysis and Critical Control Points (HACCP), to assure food safety throughout the drying process. These systems entail seeing possible risks, putting precautions in place, and then periodically checking to see if they are working. Food producers can reduce the chance of product contamination or safety concerns by proactively addressing possible hazards [47, 48]. By investing in personnel training and education is critical for tackling the obstacles of industrial drying operations. Employees who have received the appropriate training are aware of the nuances of drying, including the effects of various drying settings on product quality and safety and became able to efficiently monitor and manage these metrics, spot possible problems, and swiftly implement remedial measures. Employees are kept current with the most recent legal requirements and technical developments in drying processes to ongoing training and education programmers [49].

Collaboration and information exchange within the food industry is also critical for addressing obstacles in industrial drying processes. Food producers may exchange best practices, learn from one another's experiences, and work together to solve problems by taking part in trade groups, attending conferences, and working on cooperative research initiatives. Innovative solutions to improve drying processes and increase overall efficiency and sustainability may be created by utilizing the industry's pooled knowledge and skills [50].

5.1. Innovations and Advancements in Industrial Drying Technology

The limitations of industrial drying processes in the food sector are constantly dealt by investigating and implementing new technology. The application of microwave drying technology is one such development. Unlike traditional drying processes that rely on hot air, microwave drying directly heats the food product. This method has a number of benefits, including shorter drying periods, less energy use, and better product quality. Microwave drying is especially advantageous for heat-sensitive goods since it provides for exact temperature control while reducing the danger of over-drying or nutrient loss [51, 52].

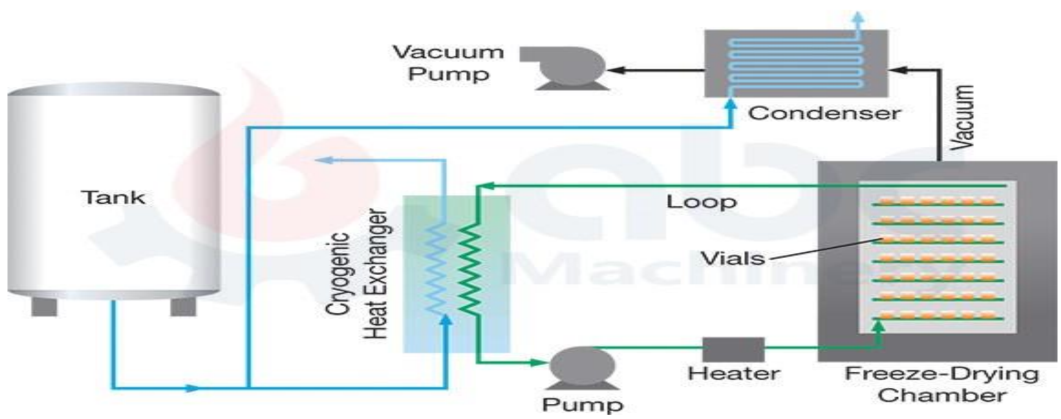

Figure 4 Vacuum Drying Process in Food Chemical Industry [53]

Advancement in industrial drying technology is the introduction of hoover drying devices. Vacuum drying (Figure 4) includes releasing the drying chamber's air pressure, which lowers water's boiling point and speeds up evaporation. This approach is very useful for drying heat-sensitive or fragile food goods since it reduces exposure to high temperatures. Additionally, hoover drying improves the preservation of the food product's natural color, flavor, and nutritional value, producing higher-quality finished goods [54].

Figure 5 Revolutionizing Manufacturing with AI and Machine Learning [55]

Additionally, the optimization of drying processes by food producers is revolutionized by the use of artificial intelligence (AI) and machine learning algorithms (Figure 5) into industrial drying processes. AI-powered systems can analyze massive volumes of data in real time and automatically modify drying settings to obtain the desired drying output. These systems are able to recognize patterns, anticipate possible problems, and efficiently use energy. Food producers may increase the accuracy, control, and productivity of their drying operations by utilizing AI and machine learning [55, 56].

6. Conclusion

In conclusion, the uses of drying processes in the food industry have shown to be very significant in a variety of ways. Throughout this study book chapter, the authors have looked at the various drying procedures used in the food sector and their uses. These techniques, which include air drying, freeze drying, spray drying, and others, are beneficial in preserving and improving the quality, shelf life, and safety of food items. The benefits of drying technologies are obvious in their capacity to decrease water content, hence reducing microbial development and enzymatic activity that led to deterioration. Drying processes lengthen shelf life, improve mobility, and promote customer convenience by eliminating moisture, reducing product weight and inhibition of bacterial growth. Furthermore, these approaches have aided in the preservation of nutritional content and sensory qualities of food, ensuring that critical nutrients are kept even after the drying process. Industrial drying procedures in the food sector encounter various issues, including energy usage, product purity, and regulatory compliance while food producers are overcoming these challenges by the use of cutting-edge technologies, best practices, and cooperative initiatives. From energy-efficient drying systems and sophisticated control technologies to the incorporation of renewable energy sources and breakthroughs in drying technology, the future of industrial drying in the food sector appears promising. The food sector can fulfill the expanding needs of customers while guaranteeing the safety and integrity of its goods by continually aiming for efficiency, sustainability, and product quality.

Author Contributions

Conceptualization, A.J.; validation, M.S.H. and U.J.; writing—original draft preparation, A.J. and R.A.; writing-review and editing, and visualization, U.J., R.A. and M.S.H.

Acknowledgments

The authors are highly obliged to their departments and institutes for access to journals, books and valuable database.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Javed, A., Imran, M., Ahmad, N., & Hussain, A. I. (2018). Fatty acids characterization and oxidative stability of spray dried designer egg powder. Lipids in health and disease, 17, 1-13.
2. Calín-Sánchez, Á., Lipan, L., Cano-Lamadrid, M., Kharaghani, A., Masztalerz, K., Carbonell-Barrachina, Á. A., & Figiel, A. (2020). Comparison of traditional and novel drying techniques and its effect on quality of fruits, vegetables and aromatic herbs. Foods, 9(9), 1261. https://doi.org/10.3390/foods9091261
3. Sairem. (2021b). What are the different industrial drying technologies? SAIREM. https://www.sairem.com/the-different-industrial-drying-technologies/
4. Schmutz, P. (2023, June 30). Drying Foods | Home & Garden Information Center. Home & Garden Information Center | Clemson University, South Carolina. http://1.https//hgic.clemson.edu/factsheet/drying-foods/
5. Dhakal, P. (2022). Drying Method of Food Preservation with Types, Examples. Microbe Notes. https://microbenotes.com/drying-method-food-preservation/
6. Drying food at home | UMN Extension. Retrieved July 18, 2023, from extension.umn.edu/preserving-and-preparing/drying-food
7. Home Drying Foods. Retrieved July 18, 2023, from extension.usu.edu
8. Drying Foods | New Mexico State University - BE BOLD. Shape the future. https://pubs.nmsu.edu/_e/E322/
9. Dhakal, P. (2022b). Drying Method of Food Preservation with Types, Examples. Microbe Notes. https://microbenotes.com/drying-method-food-preservation/
10. National Center for Home Food Preservation | NCHFP publications. https://nchfp.uga.edu/publications/nchfp/factsheets/food_pres_hist.html

11. How to Preserve Food by Drying. Retrieved July 3, 2023, from www.partselect.com/JustForFun/Preserving-Food-by-Drying.htm

12. Schmutz, P. (2023b, June 30). Drying Foods | Home & Garden Information Center. Home & Garden Information Center | Clemson University, South Carolina. https://hgic.clemson.edu/factsheet/drying-foods/

13. MN Editors. (2023, July 7). Drying Method of Food Preservation - Types, Methods, Examples. Microbiology Note – Online Biology Notes. https://microbiologynote.com/food-preservation-by-drying/

14. Poncin, A. (2023, April 14). What are the benefits of drying food? - Ruuvi. Ruuvi. https://ruuvi.com/what-are-the-benefits-of-drying-food/

15. Neil. (2019, January 23). How Does Drying Preserve Food? - Preserve & Pickle. Preserve & Pickle. https://preserveandpickle.com/how-does-drying-preserve-food/

16. Dehydrated food | How it works. https://www.foodunfolded.com/article/dehydrating-food-how-it-works

17. The process and method of the food product. Food Preservation. https://vlangosfoodpreservation.weebly.com/1-the-process-and-method-of-the-food-product.html

18. Alp, D., & Bulantekin, Ö. (2021). The microbiological quality of various foods dried by applying different drying methods: a review. European Food Research and Technology, 247(6), 1333–1343. https://doi.org/10.1007/s00217-021-03731-z

19. Drying in food industry. Retrieved July 3, 2023, from wiki.zero-emissions.at

20. Riaz, S., Kabir, A., Haroon, A., Ali, A., & Manzoor, M. F. (2022). Food dehydration Recent advances and approaches. In IntechOpen eBooks. https://doi.org/10.5772/intechopen.108649

21. Spray Nozzles & Spray Technology Solutions | Lechler US. &Copy; 2017 Lechler GmbH. https://www.lechlerusa.com/

22. Amit, S. K., Uddin, M. M., Rahman, R., Islam, S., & Khan, M. S. (2017). A review on mechanisms and commercial aspects of food preservation and processing. Agriculture & Food Security, 6(1). https://doi.org/10.1186/s40066-017-0130-8

23. Fellows, P. (2009). Dehydration. In Elsevier eBooks (pp. 481–524). https://doi.org/10.1533/9781845696344.3.481

24. Calín-Sánchez, Á., & Cano-Lamadrid, M. (2020). Traditional and novel drying techniques. encyclopedia.pub. https://encyclopedia.pub/entry/2195

25. USDA FoodData Central. (2021). Egg, whole, dried. Retrieved from https://fdc.nal.usda.gov/fdc-app.html#/food-details/173944/nutrients

26. Food and Agriculture Organization of the United Nations. (2020). Milk and Milk Products. Retrieved from http://www.fao.org/dairy-production-products/products/milk/en/

27. Clarke, R. J., & Macrae, R. (Eds.). (2001). Coffee: Volume 2: Technology. Springer Science & Business Media.

28. Gelinas, P., & McKenna, B. M. (2016). Fruit Powders: Production, Composition, Properties, and Potential Applications. In Fruit Juices: Extraction, Composition, Quality, and Analysis (pp. 357-377). Elsevier.

29. Machado, M. D., et al. (2019). Innovative food processing technologies applied to fruits and vegetables: A review. Food Research International, 115, 363-375.

30. Azeus Machinery. (2020, November 26). Spray Dryer Machine/Spray Drying Machine for Fruit Powder. Best Price Industrial Food Drying Oven Machine Manufacturer. https://fooddryingoven.com/food-drying-equipment/spray-drying-machine.html

31. Extend the Life of Your Produce: Dry Your Food. Retrieved July 5, 2023, from extension.sdstate.edu/extend-life-your-produce-dry-your-food

32. The Rotten Fruit Box. Freeze-Dried Variety Soup Box. https://therottenfruitbox.com/products/freeze-dried-soup-sampler-box-get-one-free-soup?selling_plan=1041989821

33. Buy Freshway Pack of 2 (Schezwan Rice & Veg Hyderabdi Biryani) ready to eat freeze dried meals online at best prices in India - JioMart. JioMart. https://www.jiomart.com/p/groceries/freshway-pack-of-2-schezwan-rice-veg-hyderabdi-biryani-ready-to-eat-freeze-dried-meals/594349771
34. Mba, A. L. B. (2022, July 20). How does Freeze-Drying work and are Freeze-Dried foods healthy? Healthline. https://www.healthline.com/nutrition/freeze-drying
35. Freeze drying food - cuddon freeze dry. (2015, May 14). Cuddon Freeze Dry. https://www.cuddonfreezedry.com/freeze-drying-food/
36. Utah State University. (2023, August 3). Utah State University Extension. USU. https://extension.usu.edu/
37. Wikipedia contributors. (2023). Freeze drying. Wikipedia. https://en.wikipedia.org/wiki/Freeze_drying
38. Dhakal, P. (2022). Drying Method of Food Preservation with Types, Examples. Microbe Notes. https://microbenotes.com/drying-method-food-preservation/
39. Chojnacka, K., Mikula, K., Izydorczyk, G., Skrzypczak, D., Witek-Krowiak, A., Moustakas, K., Ludwig, W., &Kułażyński, M. (2021). Improvements in drying technologies - Efficient solutions for cleaner production with higher energy efficiency and reduced emission. Journal of Cleaner Production, 320, 128706.
40. Adegbite, S. A., Asiru, W. B., Sartas, M., Tran, T., Andrade, L. a. T., Chapuis, A., Makuachukwu, O. G., &Abass, A. (2023). Development of a pilot scale energy efficient flash dryer for cassava flour. Development of a Pilot Scale Energy Efficient Flash Dryer for Cassava Flour, 13, 100117.
41. Colak, N., &Hepbasli, A. (2009). A review of heat pump drying: Part 1 – systems, models and studies. Energy Conversion and Management, 50(9), 2180-2186.
42. The Pennsylvania State University 2023 Code EE0065 3/23pod. Let's Preserve: Drying Fruits and Vegetables (Dehydration). https://extension.psu.edu/lets-preserve-drying-fruits-and-vegetables-dehydration.
43. Vågsholm, I., Arzoomand, N., & Boqvist, S. (2020). Food Security, Safety, and Sustainability—Getting the Trade-Offs right. Frontiers in Sustainable Food Systems, 4.
44. Regulatory Considerations for Small-Scale Produce Drying Operations: A Multi-State Perspective Obtained through Inspector Interview. (2022). Center for Low-Moisture Food Safety.
45. Bhattacharya, S., Kumar, P., & Mishra, H. N. (2016). Emerging technologies for the pretreatment of food processing industry effluents: A review. Journal of Environmental Chemical Engineering, 4(4), 4306-4317.
46. Dervisoglu, M., Goncuoglu, M. C., &Koseoglu, S. (2017). Drying of foods: A review. International Journal of Food Properties, 20(2), 425-455.
47. Food Safety. https://www.food-safety.com/articles/2095-beyond-haccp-constraints-to-haccp-implementation-in-developing-countries
48. Introduction to HACCP & Food Safety Plan — Food Law. https://www.ag.ndsu.edu/foodlaw/overview/introhaccp
49. Importance of Training and Development for Employees. (2022, December 15). Maryville Online. https://online.maryville.edu/blog/importance-of-training-and-development/
50. Akyazi, T., Goti, A., Oyarbide-Zubillaga, A., Alberdi, E., &Bayon, F. (2020). A Guide for the Food Industry to Meet the Future Skills Requirements Emerging with Industry 4.0. Foods, 9(4), 492.
51. Lv, W., Li, D., Hao, L., Jin, X., Han, Q., Su, D., & Wang, Y. (2019). Recent development of microwave fluidization technology for drying of fresh fruits and vegetables. Trends in Food Science and Technology, 86, 59–67.
52. Hu, Q., He, Y., Wang, F., Wu, J., Ci, Z., Chen, L. Q., Xu, R., Yang, M., Lin, J., Han, L., & Zhang, D. (2021). Microwave technology: a novel approach to the transformation of natural metabolites. Chinese Medicine, 16(1). https://doi.org/10.1186/s13020-021-00500-8

53. Vacuum Drying Process in Food Chemical Industry Application. http://www.bestdryermachine.com/related-post/vacuum-drying-process.html
54. Vacuum Drying - Advantages & Common Applications - amixon®. https://www.amixon.com/en/vacuum-drying
55. Dev, C. Revolutionizing Manufacturing with AI and Machine Learning. www.linkedin.com. https://www.linkedin.com/pulse/revolutionizing-manufacturing-ai-machine-learning-ctrlalt-dev
56. Talaviya, T., Shah, D., Patel, N., Yagnik, H., & Shah, M. (2020). Implementation of artificial intelligence in agriculture for optimisation of irrigation and application of pesticides and herbicides. Artificial Intelligence in Agriculture, 4, 58–73.

ISBN 978-1-960740-06-9

DRYING TECHNOLOGY – CURRENT RESEARCH AND INDUSTRIAL APPLICATIONS

Editors

Muhammad Imran & Amna Javed

Review Based Book Chapter

DRYING PROCESS IN FRUITS AND VEGETABLES INDUSTRIES

November 17, 2023

doi: 10.5281/zenodo.10252331

Scientific Knowledge Publisher (SciKnowPub), USA

info@sciknowpub.com

REVIEW BASED BOOK CHAPTER

DRYING PROCESS IN FRUITS AND VEGETABLES INDUSTRIES

Tahniat Rehman[1]

[1]*Department of Nutrition and Dietetics, The University of Faisalabad, Faisalabad, Pakistan*

Abstract

Fruit and vegetables are vital parts of a human diet due to their high nutritional value. These food groups are the main source of micronutrients, fiber and important phytochemicals. Due to high moisture content (80%), loss and waste in fruits and vegetables are the highest among all types of foods, and may reach up to 60%. In this regard, drying process is an important parameter in fruit and vegetable industries used for processing or preservation purposes. A number of drying techniques have been developed over the years to turn perishable commodities into stabilized goods by preserving quality attributes, increase shelf life, and reduce transport weight. Advanced drying techniques such as solar, microwave, vacuum, infrared, freeze and spray dryings have been developed around the globe as being successfully used for various fruits and vegetables. Moreover, dried products of fruit and vegetables are broadly used by the industries related to confectionery, bakery, in sweets and distilling industries in the development of versatile by-products including sauces, teas, puddings, and food supplements for infants as well as children. The effect and applications of these drying techniques in fruit and vegetable industries are discussed in this chapter.

Keywords

Fruits, Vegetables, Drying Techniques, Preservation, Industrial Applications

1. Introduction

Fruits and vegetables are essential components of the human diet and there is considerable evidence that their ingestion has health and nutritional advantages [1]. Fruits and vegetables are widely recognized for their high nutritional value, which includes micronutrients (vitamins and minerals), dietary fibers and contains a wide range of phytochemicals that individually or combination are beneficial to human health [2]. The nutritive importance of fruits and vegetables along with their potential health benefits shows in Table 1.1. The World Health Organization (WHO) recommends consuming five to eight servings (400-600 g) of fruits and vegetables each day. In order to lower the risk of cardiovascular disease, cancer, poor cognitive function, and other diet-related disorders as well as to prevent micronutrient deficiencies [3].

Table 1.1 Nutritive value and potential health benefits of fruits and vegetables

Nutrients	Sources	Human health benefits	References
1. Micronutrients			
Vitamin C (ascorbic acid)	Broccoli, cabbage, citrus fruits, guava, kiwifruit, leafy greens, pineapples, potato, strawberry, tomato, watermelon	Scurvy prevention, wound healing, cardiovascular disease, healthy immune system	[2]
Vitamin E (tocopherols)	Avocado, nuts (such as almonds, nuts, peanuts, pistachio, walnuts), green leafy vegetables	Cancer, diabetes, heart disease, immune system, LDL oxidation	
Vitamin K	Crucifers (such as broccoli, sprouts, cabbage), green onions, nuts, leafy greens	Osteoporosis, synthesis of procoagulant factors	
Vitamin B9 (folate)	Dark green vegetables (such as spinach, mustard greens, lettuce, broccoli, sprouts)	Birth defects, cancer, heart disease	
2. Dietary Fibers			
Dietary fibers	Most fruits and vegetables	Decrease the risk of chronic diseases such as cardiovascular disease, type 2 diabetes mellitus, cancer and weight lose	[4]
3. Phytochemicals			
Phenolic acids	Seeds, fruits and leafy green vegetables	Prevents cardiovascular diseases, anti-inflammatory and anticancer	[5]
Flavonols	Kale, onion, lettuce, and tomatoes	prevent cardiovascular diseases, heart related disorder, prevents blood clotting and human gingival diseases	[6]
Flavones	Tomatoes, onions, lettuce and kale	Cardiovascular properties and neuroprotective	[7]
Flavanones	Lemons, oranges and grape fruits	Reduced lipid level and prevents cardiovascular	[8]

		diseases	
Anthocyanidin	Radish, beetroot, berries, strawberries and cherries	Antimicrobial properties, anticancer and antidiabetic activities, prevents cardiovascular disease	[9]
Resveratrol	Grapes, berries and wine	Lowers blood pressure, helps in preventing cardiovascular diseases and skin cancer	[8]
Lignans	Seeds (flax, pumpkin, sunflower, poppy, sesame), barriers	Reduced risk of osteoporosis, breast cancer, menopausal symptoms, and heart problems	[10]
Tannins	Legume seeds, peas, some leafy and green vegetables	Anti-inflammatory, anti-oxidant, anti-cancerous, and anti-microbial properties	[11]

Food is essential for both human survival and the ecosystem. It can be eaten either raw or processed to provide value-added goods. However, a growing concern has led to an increase in global food waste due to exponential rise in population and instability in supply chains [12]. Globally, around 1.3 billion tonnes of food are lost or wasted each year, and this figure is growing [13]. According to FAO [14], stages where possible causes of food loss and waste occurred are shown in Figure 1.

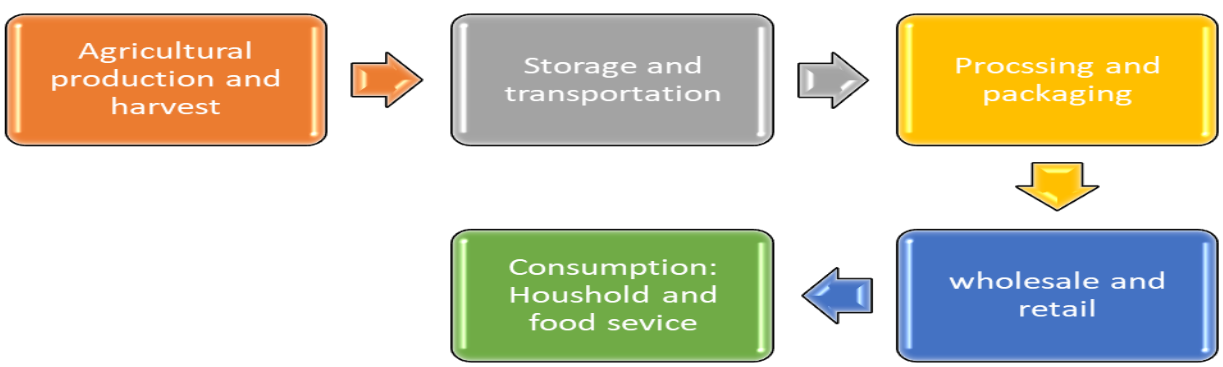

Figure 1 Possible causes of food loss and waste [14]

Fruit and vegetables are one of the most consumed commodities globally, accounting for more than 42% of total food wastage [13]. Food and Agriculture Organization (FAO) has estimated that losses and waste in fruits and vegetables are the highest among all types of foods, and may reach up to 60% [15]. Figure 2 depicts the amount of food waste caused by each food item, together with overall waste percentage in fruits and vegetables.

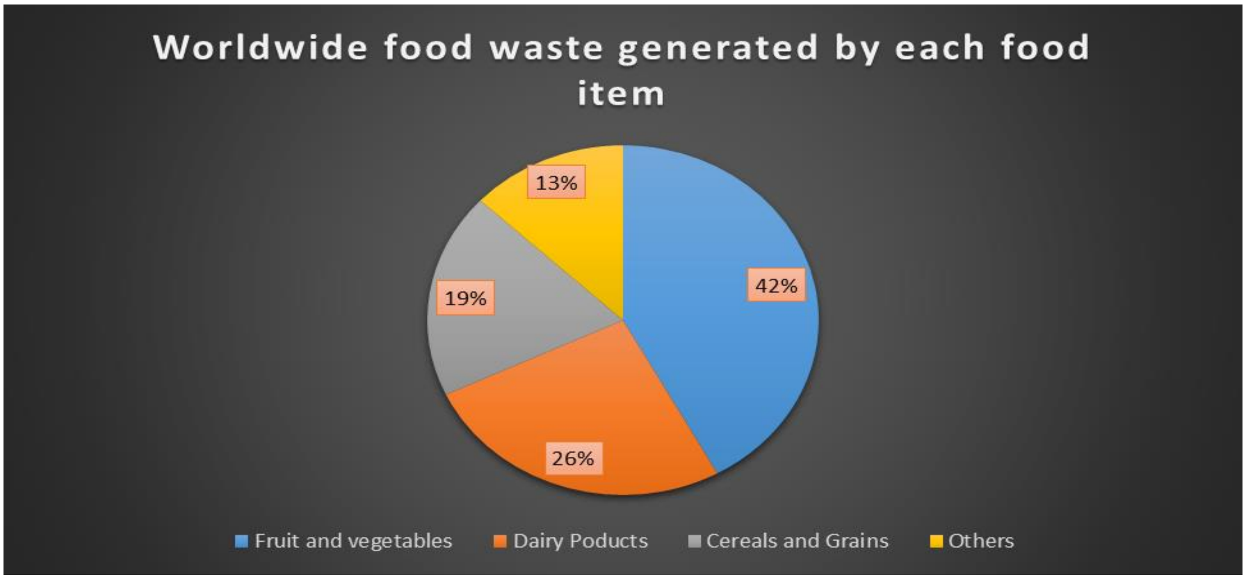

Figure 2 Worldwide food waste generated by each food item

Fruits and vegetables have grown more valuable commercially, and growing them on a large scale for market has become important sector of the agricultural industry [16]. Fresh fruits and vegetables contain more than 80% water and considered as extremely perishable items that degrade quickly [17]. Post-harvest losses and wastages plague the whole supply chain of perishable food commodities [18]. About 30% to 50% losses have been reported in fruits and vegetables from the farm gate to consumer's level. Losses result in unacceptable levels of food insecurity among the world's population. These commodities require suitable transportation, handling, and storage facilities in order to reach a consumer in a fresh form because of their short shelf life and perishable nature [17, 18]. After harvest, post storage procedures are necessary to keep the product fresh and preserve its nutritional content. Storage solutions available across the world demand a low temperature for product preservation; yet, their increased cost and lack of availability in many locations are significant limits [19]. One of the main objectives of food processing or preservation is to turn perishable commodities, including fruits and vegetables, into stabilized goods that can be kept for long periods of time to minimize postharvest losses [16]. Factors that Influence postharvest quality are represented in Table 1.2. Drying is an important process for preservation of food components and it is widely applicable in food sectors [20]. Different types of drying techniques are suitable to reduce losses and to preserve fruits and vegetables with maintained quality [17].

Table 1.2 Postharvest factors that influence quality of fruits and vegetables

Factors	Description	References
Intrinsic factors	Related to inherent characteristics, such as • Genetic factors, • Maturity stage in harvest • Susceptibility to physiological disorders	[21]
Extrinsic factors	Related to development's ambient and technologies, such as • Handling (harvest, package, transportation, storage, and commercialization) • Technological (control of temperature, relative humidity, irradiation, chemical treatments)	[21]

2. Drying Techniques in Fruit and Vegetables Industries

Drying is one of the oldest and widely used method of food preservation. It involves the removal of moisture from a product due to couple heat and mass transfer. The elimination of moisture reduces several moisture-mediated deteriorative processes and stops the development and reproduction of microorganisms that cause decay [16]. The preservation of fruits and vegetables through drying dates back many centuries due to preserve quality attributes, increase shelf life, and reduce transport weight of fruit and vegetable. The poor quality and product contamination lead to the development of alternate drying technologies [19, 22]. A number of drying techniques have been developed over the years. These different types of drying techniques and the impact of drying on selected fruits and vegetables preservation and quality discussed below.

2.1. Solar Drying

Solar drying is one of the oldest applications of solar energy; hence goods are exposed to direct sunlight by being put on the ground. Agricultural products were traditionally dried mechanically, which was time-consuming and expensive. Additionally, the dried goods from those dryers weren't fully hygienic. Therefore, with no energy cost, the solar dryer technology offered a new, safer, and healthier way to dry fruits and vegetables [23]. A solar dryer was used to dry fruit and vegetables because foods have a high primary moisture content; if it remains at the same level, the product will deteriorate and decrease its quality [24]. Numerous types of solar dryers have been developed with various designs such as chamber based, rack/tray type, bin, and tunnel type for agricultural products [25].

Solar drying is used to improve the color, taste and appearance of the products. Solar drying is lowering the possibility of microbial development, as well as preventing insect infection, contamination with foreign objects, and toxin buildup. The solar drier developed was able to produce 48 °C to 54 °C average drying temperature [26]. Solar dryers are classified according to the mode of air circulation, such as natural circulation known as passive dryers and forced circulation dryers also called active dryers [27]. According to the study passive type solar dryers have property of natural heated air movement that is easily constructed, and inexpensive. These are used to dry various fruits (bananas, pineapples, and mangoes) and vegetables (potatoes, carrots, and French beans) in small batches [17].

2.2. Microwave Drying

A different drying technique that has gained favor in recent years for a number of commercial food items is microwave drying (MWD). It can be regarded as a rapid dehydration process significantly reducing the drying time, up to 89% according to certain authors. A MW drying process consists in three drying phases (1) a heating-up period during which the product's temperature rises over time as MW energy is transformed into thermal energy inside the wet materials (2) thermal energy is employed for moisture vaporization and transmission during a quick drying phase (3) reduced drying rate period during which the local moisture is reduced to a point that the energy needed for moisture vaporization is lower than the thermal energy induced by MW [28].

Microwave technology is used to quickly dry fruits and vegetables, and electromagnetic radiation plays a significant role in both the internal and external heating of the product [17]. Numerous studies have demonstrated the benefits of microwave-assisted fruit and vegetable drying. Excellent quality was identified in dried carrots in terms of color, shrinkage, and rehydration ability [29]. Microwave-dried raisins were found to be of higher quality than hot air-dried samples in terms of color, damage, blackness, sugar crystallization, stickiness, and uniformity [30]. Compared to convection drying, microwave drying has a number of benefits, but there are some drawbacks as well that are presented in Table 2.1.

Table 2.1 Advantages and limitations of microwave drying [29]

Advantages	Limitations
Higher drying rate	Product texture may be affected
Lower operating costs	High initial costs for industrial scale dryer
Short drying time	Partial loss of aroma and negative sensory changes
Reduced energy consumption	Specific sample size and shape may be required for effective drying

2.3. Freeze Drying

Freeze drying (FD) has become an important technology used to extend shelf-life and to preserve food nutritional quality [31]. Drying different fruits and vegetables using the freeze-drying technique is a useful method. Freeze drying is the sublimation of an ice fraction, which is the process by which water transforms from a solid into a gas. Due to very low temperature all the deterioration activity and microbiological activity are stopped and provide better quality to the final product [17, 19]. Recently, the market for organic products is increasing. Therefore, the use of freeze drying of fruits and vegetables is not only increasing in volume but also diversifying [19]. Sanchez et al. [32] showed that, encapsulated freeze-dried cherry juice in powdered form produced a higher stability of total monomeric anthocyanin during storage at 38 °C.

When compared to guava powder made by vacuum and heat pump dryers, FD-produced guava had the best porosity, colour, rehydration, and vitamin C retention. The heat pump dryer only managed to preserve 25% of the vitamin C, compared to 63% for the FD [33]. FD reduced the drying time for the development of banana chips with the assistance of infrared radiation treatment and additionally dipping of acid improves color retention and produced crispiness [34]. Additionally, FD increased the number of flavonoids and anthocyanins in red onions during extraction and preserved those substances (flavonoids and anthocyanins) in their powder form for up to six months of storage [35]. It has been reported that berries (blueberries, tart cherries, strawberries, and cranberries) dried using FD retained more phytochemicals, such as antioxidants, ascorbic acid, and phenolic contents, compared to berries dried using air drying (AD), which produced worse quality [36]. FD showed improved preservation of chemical profiles, antioxidant activity, and cellular structure due to its less extreme heating. However, had relatively higher energy consumption and drying time [37].

2.4. Vacuum Drying

Vacuum drying is a novel technology that allows obtaining a high-quality final product while preserving its original nutritional value. Vacuum drying is performed under low pressure conditions. The heat transfer effect is produced by the convection or radiation method. The use of vacuum guarantees a sparing effect on the product being dried due to the low values of drying temperatures [38]. Vacuum drying technology is an important process for drying highly heat-sensitive and perishable commodities, which are widely used in the pharmaceutical as well as in food products and biotechnology The methods of vacuum drying can be analyzed based on the physical parameters utilized for applying heat and eliminating water vapor [17, 39]. It can dry products more quickly, at a lower temperature, with better rehydration capacity and less energy use. It also helps preserve product color, flavor, and other contents including vitamins and volatile aromas as shown in Table 2.2 [17]. Fernando and Thangavel [40] compared the quality of coconut which is dried through VDT and found it superior as compared to the product that was conventionally dried.

Table 2.2 Effects of vacuum drying on the quality of different fruits and vegetables

Fruit/vegetable	Effect	Reference
Beetroots	High quality product with no color degradation	[41]
Carrots	Positive impact on drying time and quality improvement	[42]
Apples	Had no effect on the	[43]

	compositions of slices that were enhanced with quercetin	
Dates	Maintains overall quality with no color degradation of their pulp	[44]
Mangoes	enhances color parameter, drying consistency, and reduced drying time	[45]
Potato	High drying rate and reduced moisture percentage with assistance of infrared	[46]

2.5. Spray Drying

Making fruit and vegetable juice powders is a viable way to cut costs associated with shipping, storage, and packaging. Juices from fruit and vegetable can be preserved from weeks to months while powdered products produced from fruit and vegetable juices can be preserved from months to years depending on packaging. Spray drying is the most cost-effective method for quickly dehydrating food while preserving quality and turned liquid goods directly into powder [47]. SD is widely utilized in industry, particularly in the production of fruit and dairy products [47, 48]. The spray-dried product is highly stable, because of its low moisture content and water activity. The typical ranges for spray-dried fruit and vegetable powders' moisture content and water activity are 2–5% and 0.2–0.6, respectively [47].

It was discovered that spray drying method was 4-5 times less expensive than freeze-drying. Furthermore, compared to FD, it was demonstrated that using the SD technique to dehydrate chokeberry juice into powders improved the retention of total phenolic components, total flavonoids, and total monomeric anthocyanin [49, 50]. Izidoro et al. [51] concluded that because of the high temperature and atomization nature of the spray drying approach, green banana starch solubility, swelling power, and water absorption capacity are increased. In another study banana was dried into powder using modified spray dryer and result showed that banana powder retained its color and flavor [52]. Quek et al. [53] produced spray-dried watermelon powder with best colorimetric results, low moisture content, low water activity and good lycopene and ß-carotene contents in powder. Phoungchandang and Sertwasana [54] spray dried the ginger juice. Goula and Adamopoulos [55] studied the performance of a modified spray dryer for tomato powder preparation under various operating conditions.

2.6. Infrared (IR) Drying

Infrared drying is based on a property of water to absorb infrared radiation [56]. The fundamental idea of an infrared dryer is to heat and dry materials that contain moisture by using radiations. These radiations enter exposed materials and increase their internal temperature [17]. Infrared drying has great advantages over traditional air drying. Studies have shown that infrared has an effective moisture diffusivity and a higher thermal sensitivity than air drying [57].

Zhu and Pan [58] study showed that the high radiation intensity and apple thin slices had faster increase of product temperature, and quicker moisture removal. According to another study irradiated surface evaporates significantly more water than that which is not heated by IR energy [59]. Nimmol et al. [60] examined the behavior of heat transport and drying in bananas using infrared radiation and low-pressure superheated steam. IR drying could be a favorable way to drying carrots. One of the ways to shorten the carrot slice drying time is to supply heat by IR radiation [61].

3. Drying Applications in Selected Fruit and Vegetable Crops

3.1. Potatoes

Potato (Solanum tuberosum L.) belongs to *Soulanacea* family. After corn, wheat, and rice, potatoes are the fourth-largest food crop, and they are widely grown and eaten all over the world [62]. The Food and Agriculture Organization (FAO) reported that global potato output was around 3.68 108 t in 2018 and the top five potato producers worldwide were China, India, the United States, Ukraine, and the Russian Federation [63]. The important amino acids histidine and lysine, which are limited in grains, are abundant in potato tubers along with vitamins, dietary fiber, minerals, and other nutrients [64].

Due to their short dormancy period and high moisture content, fresh potatoes have a limited shelf life and are sensitive to deterioration. Drying is one of the most widely used methods for potato preservation and processing [64, 65]. Potato drying is believed as a better method of storage as well as the best choice for value-added product development which ultimately enhances profitability [17]. In order to increase the nutritional content of flour-based foods, the dried potato powder can be used as a thickening to enhance flavour and colour as well as to partially replace wheat flour [62]. Different drying methods, such as microwave drying, high voltage electric field drying, vacuum heat pump drying, and freeze drying were available for fruit and vegetable products [63].

One of the most popular drying techniques for agricultural products has been hot-air drying. However, its two main drawbacks are the low quality of its dried goods and the lengthy drying process [66]. Supmoon and Noomhorm [67] studied hot-air-assisted with infrared drying to produce potato chips that is health-friendly instead of traditional deep-fat drying method. In previous studies, infrared drying offered a faster rate of drying, a lower proportion of shrinkage, and also a lessened colour degradation [17]. Potato slices were successfully dried using far infrared radiations and vacuum technology; the process was very energy-efficient, uniformly heated, and produced a high-quality end product [46]. The most important aspect of thermal mode drying is temperature optimization; drying potatoes at 70°C in a microwave-vacuum dryer results in a reduced moisture percentage but degrades the quality in terms of visual colour. However, after 150 minutes of drying at 50 and 60 degrees Celsius, the visual colour quality was adequate, although drying at 50 degrees required more time [68].

3.2. Carrots

Carrot (*Daucus carrota* L.) is one of the important vegetables grown throughout the word [69]. The carrot is widely utilized in human nutrition because to its high level of fiber, b-carotene, and vitamins A, B1, B2, B6, and B12. Its water content ranges from 86% to 93%, and it is highly vulnerable to moisture loss, which shortens its shelf life [17]. Carrots can also be stored for a long time by drying them. Dried carrots are used as an ingredient in various food products, such as soups, sauces, ready-meals as well as healthy snacks [70]. Therefore, numerous researchers have looked at the effects of various drying techniques and dryers such as vacuum dryer, microwave and hot-air drying on the drying of carrots [17].

A novel drying technique using a combination of ultrasound and vacuum dehydration was developed to shorten the drying time and improve the quality of carrot slices. The high content of carotene is a unique property that makes dried carrot slices an excellent candidate for developing oil free, healthy snack foods. However, the nutritional value must be well preserved and a puffed texture should be generated in the drying process [42].

Kocabiyik et al. [70] dried carrot slices from initial moisture content of 8.52 kg water kg−1 dry matter to 0.11 kg water kg−1 dry matter by infrared dryer however, Shrinkage, rehydration ratio and colour parameters were found to be affected by process variables. A two-step microwave drying procedure and its impact on carrot quality were described by Wang and Xi [71]. It was shown that utilizing a lower power level during the second drying cycle can successfully minimize the loss of β-carotene.

3.3. Tomatoes

Tomato is the world's most commonly commercially produced vegetable. The world tomato production reached 124,111,781 metric tons [72]. Epidemiological studies have shown that consumption of tomatoes lowers the incidence of certain malignancies and cardiovascular diseases, demonstrating that tomatoes are unquestionably a functional diet [73]. Tomatoes are consumed fresh as well as in a processed form, around 80% of the crop is processed to create value-added products including tomato juices, ketchup, and sauces. Tomatoes can be preserved in a variety of ways, including canning, drying, and processing. To store tomatoes for an extended period of time, they can be dried and turned into flakes or powder. Different techniques, including hot air, sunlight, microwave, and freeze drying have been employed [17, 72].

Industrial processing of tomatoes to a final moisture content of <15% often involves high temperatures (60–110 °C) for a period of 2–10 h in the presence of oxygen, and therefore, the products show some oxidative damage and during the production of dried tomato halves and tomato pulp at high temperatures, significant ascorbic acid losses have been shown [74]. Air-drying is reported to have little effect on the lycopene content of tomatoes [75].

3.4. Spinach

Spinach (Spinacia oleracea L.) is a cool season annual vegetable. This widely used vegetable can be eaten raw, cooked, or baked in a variety of recipes. Spinach is a good source of many important vitamins, minerals fiber and carotenoids but low in calories [76]. Table 3.1 shows nutritional composition of spinach. Spinach is a vegetable that rapidly perishes after harvest, which is consumed only in the product season. Like other leafy greens, spinach has high water content. Drying is one of the preservation methods that has the capability of extending the consumption period of spinach [77]. It has been shown that a variety of dehydration methods, including microwave, hot-air, freeze, infrared, convective, and high electric field drying, can be used to dry spinach into dried flakes or powder [17, 78]. The powdered or flakes of dried spinach are lighter in weight and can be used in a variety of recipes. Tray drying or cabinet drying, which allow for temperature control and produce results nearly identical to FD, are more cost-effective than freezing spinach to dry it [78]. The best quality of spinach in terms of colour and ascorbic acid values were obtained in the drying period with 750 W microwave power [76].

Table 3.1 Nutritional composition of spinach

Nutrients	Composition	Reference
Moisture	91% - 92%	[79] [80]
Lipid	0.4% - 0.6%	
Protein	2.9%	
Carbohydrate	2%-10%	
vitamin A	469 µg/100 g	
Vitamin C	30 to 155 mg/100 g	
Vitamin K	378-483 µg/100 g	
Vitamin E	12.3 µg/100g	
Vitamin B9	140 -194 µg/100 g	
Iron	4-35 mg/100 g	
Magnesium	58 mg/100 g	
Potassium	633 mg/100 g	
Zinc	0.5-4.25 mg/100 g	

3.5. Bananas

Bananas are the most widely grown fruit crop and play a significant role in the production of horticulture fruit crops in tropical and subtropical regions of the world. It is regarded as a superfood (high energy food) in terms of nutrition since it is rich in minerals, nutrients, carbs, and phenolics and carotenoids, two bioactive components that support human health [81]. The postharvest losses during the whole supply chain of bananas reach up to 40% due to inadequate techniques used by growers at harvesting as well as inappropriate postharvest management. Bananas stored at low temperatures can cause a number of problems when it comes to preservation; nonetheless, drying is seen to be the greatest method for producing by-products that can be stored for a long time, such as flour and flakes [17]. Dried banana powder has many advantages when compared with raw bananas. Dried bananas have higher quality and longer shelf life and can be used for instant cooking. Products with additional value can be made using the dried banana powder [82, 83].

According to a study, developing value-added products will be a useful strategy to prevent the exploitation of bananas. Dried banana powder can be used to make snacks, fast mixes, dietary meals, etc [84]. Kabeer et al. [82] results showed that freeze-drying was the best technique to preserve nutrients present in ripe banana. Flour from unripe bananas is produced by using various drying techniques because of its positive impact on the human health as it increases the intake of unavailable carbohydrates, which may reduce the risk of non-communicable diseases [85].

Banana peels which account for approximately 38% of the fruit weight, are considered as waste with no value. The peels have been found to have significant antioxidant, antibacterial, and antibiotic qualities. They also have a high phenolic content and high dietary fibre level. Since drying has an impact on both manufacturing costs and material quality, it is a crucial step in preparing beginning material for additional processing. The microwave drying method is recommended for drying banana peels at an industrial scale [86].

3.6. Apples

Apples (Malus domestica L.) are one of the most widely grown fruits in the world. Quercetin glycosides, a naturally occurring antioxidant molecule from the flavonoid family with anti-cancer and heart-protective qualities, are abundant in apples [17]. Apples are eaten raw or processed into a variety of foods such juice, marmalade, jam, dried apples, etc. Moreover, dried apples are also used in the preparation of baby food [87].

Freeze drying is considered as a best technique for the preservation of quality characteristics of apples [88]. Lately, apple powder made by hot-air drying at 70°C showed colour retention and increased total phenolics, antioxidant capacity, and free radical scavenging activity [89]. In an experiment utilizing the microwave vacuum drying (MVD) technology for drying apple slices, showed a notable enrichment with quercetin derivatives through vacuum impregnation. MVD and FD of apples significantly retained its total quercetin glycoside content but AD showed a negative impact on quality attributes during drying; caused loss (44%) of quercetin glycoside and undesirable changes [43]. Doymaz [87] studied drying behavior of green apples and showed best results in describing thin-layer drying of apple slices. Moreover, pretreated samples with citric acid solution had a higher effective moisture diffusivity than the other samples.

3.7. Mangoes

Mango (Mangifera indica L.) is the most commercially important fruit in the Anacardiaceae family. Rich in antioxidants including pro-vitamin A and vitamin C, it has a high nutritional value to go along with its sensory quality in terms of flavour and taste. Mango, like other fruits and vegetables, has a short shelf life due to its high moisture content [90]. A study showed that, in comparison to hot air and freeze drying, microwave drying at 350 W may produce mango slices of excellent quality with the added benefit of a shorter drying time [91]. Vacuum-assisted osmotic drying resulted in lower losses of sucrose and fructose than the conventional osmotic drying technique [17]. Combining hot-air drying with microwave vacuum drying can greatly improve mango slices by reducing drying time and improving colour quality. Since the size of samples also has an effect on the drying uniformity and efficiency, the application of different drying techniques to larger samples should be considered in the future study [45].

3.8. Dates

Date palm (Pheonix dactylifera L.) is valued for its socioeconomic and historic significance, making it the primary crop throughout the Middle East and North Africa [92]. Date fruit is remarkably popular for their delicious sweety taste, dietary and medicinal values. It is a good source for carbohydrates (70–80%), dietary fiber (6.4–11.5%), protein (2.3–5.6%), minerals (0.10–916 mg/100 g dry weight) and vitamins (C, B1, B2, B3 and A) [93]. Dates are vulnerable to microbial deterioration due to their high moisture content when harvested, it is best to dry them before storing them. Drying is among the most traditional methods of food preservation used to increase product shelf life. Open sun drying method is traditionally used to produce dried dates as it is cheap and cost effective. However, it gives low quality products as a result of contamination from foreign materials (litters, dust, soil and sand particles) and insect infestation. Some of the problems related to sun drying can be overcome using solar dryers [94]. According to a study when dates are vacuum-dried, the moisture level of the product is reduced from 15% to 5% and the product's colour quality is good [44]. Seerangurayar et al. [94] investigated the effect of solar drying methods on the color and textural attributes of Khalas dates at three ripening stages and concluded that, all ripening phases, dates dried in forced convective drying showed the best colour and texture characteristics when compared to dates dried in open sun drying. İZLİ and Technology [95] determined drying characteristics and to compare the dried fruit quality by using three drying methods convective (60, 70 and 80 °C), microwave (120 W) and freeze drying. This study showed that microwave drying can produce high quality date slices with the additional advantage of reduced drying times compared to convective and freeze drying.

4. Conclusion

The drying process for fruits and vegetables is a critical method used to extend their shelf life while retaining nutritional value and flavor. Through this process, water is removed from the produce, inhibiting the growth of microorganisms and enzymes that cause spoilage. This preservation technique is cost-effective and can be done using various methods such as sun drying, microwave drying, freeze-drying, vacuum drying, spray drying and infrared (IR) drying. Many of the new drying techniques developed internationally found to be more efficient in energy use and time as compared with traditional drying techniques. Each method has its advantages and limitations. Sun drying and air drying are traditional and accessible but may take longer and can be affected by environmental conditions. Freeze-drying involves freezing produce and then removing the ice through sublimation, maintaining flavor and nutrients exceptionally well but requires specialized equipment and is costlier. Microwave drying has higher drying rate and short drying time but product texture may be affected and partial loss of aroma and negative sensory changes are seen.

In conclusion, the drying process for fruits and vegetables is a valuable preservation technique. Choosing the appropriate drying method depends on factors like cost, equipment availability, desired quality, and intended use of the dried produce. Regardless of the method used, proper storage is crucial to maintain the quality and safety of dried fruits and vegetables.

Author Contributions

Conceptualization; validation; writing—original draft preparation, writing-review and editing, and..; visualization: T.R.

Acknowledgments

The author is highly obliged to department and institute for access to journals, books and valuable database.

Conflicts of Interest

The author declares no conflict of interest.

References

[1] Ramos, B., F. Miller, T. Brandão, P. Teixeira, C.J.I.F.S. Silva and E. Technologies. 2013. Fresh fruits and vegetables—An overview on applied methodologies to improve its quality and safety. 20:1-15.

[2] Yahia, E.M., P. García-Solís and M.E.M. Celis. 2019. Contribution of fruits and vegetables to human nutrition and health. Postharvest physiology and biochemistry of fruits and vegetables. Elsevier.

[3] Rodriguez-Casado, A.J.C.R.I.F.S. and Nutrition. 2016. The health potential of fruits and vegetables phytochemicals: notable examples. 56:1097-1107.

[4] Cui, J., Y. Lian, C. Zhao, H. Du, Y. Han, W. Gao, H. Xiao, J.J.C.R.I.F.S. Zheng and F. Safety. 2019. Dietary fibers from fruits and vegetables and their health benefits via modulation of gut microbiota. 18:1514-1532.

[5] Rana, A., M. Samtiya, T. Dhewa, V. Mishra and R.E.J.J.O.F.B. Aluko. 2022. Health benefits of polyphenols: A concise review. 46:e14264.

[6] Khalid, W., Z. Maqbool, M.S. Arshad, S. Kousar, R. Akram, A. Siddeeg, A. Ali, H. Qin, A. Aziz and A.J.I.J.O.F.P. Saeed. 2022. Plant-derived functional components: prevent from various disorders by regulating the endocrine glands. 25:976-995.
[7] Rasouli, H., M.H. Farzaei and R.J.I.J.O.F.P. Khodarahmi. 2017. Polyphenols and their benefits: A review. 20:1700-1741.
[8] Prabhu, S., A. Molath, H. Choksi, S. Kumar and R.J.I.J.P.N.P.E. Mehra. 2021. Classifications of polyphenols and their potential application in human health and diseases. 6:293-301.
[9] Wrolstad, R.J.J.O.F.S. 2004. Anthocyanin pigments—Bioactivity and coloring properties. 69:C419-C425.
[10] Rodríguez-García, C., C. Sánchez-Quesada, E. Toledo, M. Delgado-Rodríguez and J.J.J.M. Gaforio. 2019. Naturally lignan-rich foods: A dietary tool for health promotion? 24:917.
[11] Sharma, K., V. Kumar, J. Kaur, B. Tanwar, A. Goyal, R. Sharma, Y. Gat and A.J.T.R. Kumar. 2021. Health effects, sources, utilization and safety of tannins: A critical review. 40:432-444.
[12] Du, C., J.J. Abdullah, D. Greetham, D. Fu, M. Yu, L. Ren, S. Li and D.J.J.O.C.P. Lu. 2018. Valorization of food waste into biofertiliser and its field application. 187:273-284.
[13] Ganesh, K.S., A. Sridhar and S.J.C. Vishali. 2022. Utilization of fruit and vegetable waste to produce value-added products: Conventional utilization and emerging opportunities-A review. 287:132221.
[14] FAO. 2019. The State of Food and Agriculture 2019: Moving forward on food loss and waste reduction URL: https://www.fao.org/3/ca6030en/ca6030en.pdf
[15] Sagar, N.A., S. Pareek, S. Sharma, E.M. Yahia, M.G.J.C.R.I.F.S. Lobo and F. Safety. 2018. Fruit and vegetable waste: Bioactive compounds, their extraction, and possible utilization. 17:512-531.
[16] Jayaraman, K. and D.D. Gupta 2020. Drying of fruits and vegetables. Handbook of industrial drying. CRC Press.
[17] Hasan, M.U., A.U. Malik, S. Ali, A. Imtiaz, A. Munir, W. Amjad, R.J.J.O.F.P. Anwar and Preservation. 2019. Modern drying techniques in fruits and vegetables to overcome postharvest losses: A review. 43:e14280.
[18] Negi, S., N.J.E.I. Anand, T. "Challenges, W. Forward" and T. Dhingra, Ed. 2016. Factors leading to losses and wastage in the supply chain of fruits and vegetables sector in India.89-105.
[19] Sagar, V., P.J.J.O.F.S. Suresh Kumar and Technology. 2010. Recent advances in drying and dehydration of fruits and vegetables: a review. 47:15-26.
[20] Ray, S., U. Raychaudhuri and R.J.F.B. Chakraborty. 2016. An overview of encapsulation of active compounds used in food products by drying technology. 13:76-83.
[21] Brasil, I.M., M.W.J.P.M.O.P.F. Siddiqui and V. Quality. 2018. Postharvest quality of fruits and vegetables: An overview.1-40.
[22] Onwude, D.I., N. Hashim, R. Janius, K. Abdan, G. Chen, A.O.J.I.F.S. Oladejo and E. Technologies. 2017. Non-thermal hybrid drying of fruits and vegetables: A review of current technologies. 43:223-238.
[23] Ayyappan, S., K. Mayilsamy, V.J.H. Sreenarayanan and M. Transfer. 2016. Performance improvement studies in a solar greenhouse drier using sensible heat storage materials. 52:459-467.
[24] Zarezade, M., A.J.R. Mostafaeipour and S.E. Reviews. 2016. Identifying the effective factors on implementing the solar dryers for Yazd province, Iran. 57:765-775.
[25] Fudholi, A., K. Sopian, B. Bakhtyar, M. Gabbasa, M.Y. Othman, M.H.J.R. Ruslan and S.E. Reviews. 2015. Review of solar drying systems with air based solar collectors in Malaysia. 51:1191-1204.
[26] Rajarajeswari, K., K. Sunooj and A.J.C.S.R.E.R. Sreekumar. 2016. Thermal investigation and food quality analysis on a solar tunnel drier. 3:108-112.
[27] Devan, P., C. Bibin, I.A. Shabrin, R. Gokulnath and D.J.M.T.P. Karthick. 2020. Solar drying of fruits–A comprehensive review. 33:253-260.

[28] Karam, M.C., J. Petit, D. Zimmer, E.B. Djantou and J.J.J.O.F.E. Scher. 2016. Effects of drying and grinding in production of fruit and vegetable powders: A review. 188:32-49.
[29] Changrue, V., V. Raghavan, V. Orsat and G.J.S.P.R. Vijaya Raghavan. 2006. Microwave drying of fruits and vegetables. 2:1-7.
[30] Tulasidas, T., G. Raghavan and A.J.D.T. Mujumdar. 1995. Microwave drying of grapes in a single mode cavity at 2450 Mhz-11: quality and energy aspects. 13:1973-1992.
[31] Ma, Y., J. Yi, X. Jin, X. Li, S. Feng and J.J.F.R.I. Bi. 2022. Freeze-Drying of Fruits and Vegetables in Food Industry: Effects on Phytochemicals and Bioactive Properties Attributes-A Comprehensive Review.1-19.
[32] Sanchez, V., R. Baeza and J.J.J.O.B.R. Chirife. 2015. Comparison of monomeric anthocyanins and colour stability of fresh, concentrate and freeze-dried encapsulated cherry juice stored at 38 C. 5:243-251.
[33] Bhatta, S., T. Stevanovic Janezic and C.J.F. Ratti. 2020. Freeze-drying of plant-based foods. 9:87.
[34] Pan, Z., C. Shih, T.H. Mchugh, E.J.L.-F.S. Hirschberg and Technology. 2008. Study of banana dehydration using sequential infrared radiation heating and freeze-drying. 41:1944-1951.
[35] Pérez-Gregorio, M., J. Regueiro, C. González-Barreiro, R. Rial-Otero and J.J.F.C. Simal-Gándara. 2011. Changes in antioxidant flavonoids during freeze-drying of red onions and subsequent storage. 22:1108-1113.
[36] Añón, A., J.F. López, D. Hernando, I. Orriols, E. Revilla and M.M.J.F.C. Losada. 2014. Effect of five enological practices and of the general phenolic composition on fermentation-related aroma compounds in Mencia young red wines. 148:268-275.
[37] An, K., D. Zhao, Z. Wang, J. Wu, Y. Xu and G.J.F.C. Xiao. 2016. Comparison of different drying methods on Chinese ginger (Zingiber officinale Roscoe): Changes in volatiles, chemical profile, antioxidant properties, and microstructure. 197:1292-1300.
[38] Burova, N., N. Kislitsina, F. Gryazina, G. Pashkova and A.J.R.E. Kuzminykh. 2017. A review of techniques for drying food products in vacuum drying plants and methods for quality control of dried samples. 38.
[39] Bazyma, L. and V.J.S.P.R. Kutovoy. 2005. Vacuum drying and hybrid technologies. 4:6-13.
[40] Fernando, W. and T.J.D.T. Thangavel. 1987. Vaccum drying characteristics of coconut. 5:363-372.
[41] Musielak, G. and A.J.D.T. Kieca. 2014. Influence of varying microwave power during microwave–vacuum drying on the drying time and quality of beetroot and carrot slices. 32:1326-1333.
[42] Chen, Z.-G., X.-Y. Guo and T.J.U.S. Wu. 2016. A novel dehydration technique for carrot slices implementing ultrasound and vacuum drying methods. 30:28-34.
[43] Schulze, B., E.M. Hubbermann, K.J.L.-F.S. Schwarz and Technology. 2014. Stability of quercetin derivatives in vacuum impregnated apple slices after drying (microwave vacuum drying, air drying, freeze drying) and storage. 57:426-433.
[44] Amellal, H. and S.J.D.T. Benamara. 2008. Vacuum drying of common date pulp cubes. 26:378-382.
[45] Pu, Y.-Y., D.-W.J.I.F.S. Sun and E. Technologies. 2016. Prediction of moisture content uniformity of microwave-vacuum dried mangoes as affected by different shapes using NIR hyperspectral imaging. 33:348-356.
[46] Liu, Y., W. Zhu, L. Luo, X. Li and H.J.D.T. Yu. 2014. A mathematical model for vacuum far-infrared drying of potato slices. 32:180-189.
[47] Shishir, M.R.I., W.J.T.I.F.S. Chen and Technology. 2017. Trends of spray drying: A critical review on drying of fruit and vegetable juices. 65:49-67.
[48] Chiou, D. and T.J.J.O.F.E. Langrish. 2007. Development and characterisation of novel nutraceuticals with spray drying technology. 82:84-91.

[49] Hammami, C. and F.J.J.O.F.E. René. 1997. Determination of freeze-drying process variables for strawberries. 32:133-154.
[50] Horszwald, A., H. Julien and W.J.F.C. Andlauer. 2013. Characterisation of Aronia powders obtained by different drying processes. 141:2858-2863.
[51] Izidoro, D.R., M.-R. Sierakowski, C.W.I. Haminiuk, C.F. De Souza and A.J.J.O.F.E. De Paula Scheer. 2011. Physical and chemical properties of ultrasonically, spray-dried green banana (Musa cavendish) starch. 104:639-648.
[52] Mani, S., S. Jaya and H. Das. Sticky issues on spray drying of fruit juices. ASAE/CSAE North-Central Intersectional Meeting, 2002. 2035-2045.
[53] Quek, S.Y., N.K. Chok, P.J.C.E. Swedlund and P.P. Intensification. 2007. The physicochemical properties of spray-dried watermelon powders. 46:386-392.
[54] Phoungchandang, S. and A.J.S.A. Sertwasana. 2010. Spray-drying of ginger juice and physicochemical properties of ginger powders. 36:40-45.
[55] Goula, A.M. and K.G.J.J.O.F.E. Adamopoulos. 2005. Spray drying of tomato pulp in dehumidified air: I. The effect on product recovery. 66:25-34.
[56] Li, K., M. Zhang, A.S. Mujumdar and B.J.D.T. Chitrakar. 2019. Recent developments in physical field-based drying techniques for fruits and vegetables. 37:1954-1973.
[57] Wu, X.-F., M. Zhang and Z.J.L. Li. 2019. Influence of infrared drying on the drying kinetics, bioactive compounds and flavor of Cordyceps militaris. 111:790-798.
[58] Zhu, Y. and Z.J.J.O.F.E. Pan. 2009. Processing and quality characteristics of apple slices under simultaneous infrared dry-blanching and dehydration with continuous heating. 90:441-452.
[59] Nowak, D., P.P.J.I.F.S. Lewicki and E. Technologies. 2004. Infrared drying of apple slices. 5:353-360.
[60] Nimmol, C., S. Devahastin, T. Swasdisevi and S.J.a.T.E. Soponronnarit. 2007. Drying and heat transfer behavior of banana undergoing combined low-pressure superheated steam and far-infrared radiation drying. 27:2483-2494.
[61] Salehi, F., M. Kashaninejad, E. Akbari, S.M. Sobhani and F.J.J.O.T.S. Asadi. 2016. Potential of sponge cake making using infrared–hot air dried carrot. 47:34-39.
[62] Gan, Q., Y.-L. Jiang and D.J.J.O.I.A. Yun. 2019. Drying characteristics, functional properties and in vitro digestion of purple potato slices dried by different methods. 18:2162-2172.
[63] Wang, H., Z.-L. Liu, S.K. Vidyarthi, Q.-H. Wang, L. Gao, B.-R. Li, Q. Wei, Y.-H. Liu and H.-W.J.D.T. Xiao. 2020. Effects of different drying methods on drying kinetics, physicochemical properties, microstructure, and energy consumption of potato (Solanum tuberosum L.) cubes. 39:418-431.
[64] Wu, B., Y. Guo, J. Wang, Z. Pan and H.J.J.O.F.E. Ma. 2018. Effect of thickness on non-fried potato chips subjected to infrared radiation blanching and drying. 237:249-255.
[65] Amjad, W., S.O. Crichton, A. Munir, O. Hensel and B.J.B.E. Sturm. 2018. Hyperspectral imaging for the determination of potato slice moisture content and chromaticity during the convective hot air drying process. 166:170-183.
[66] Bondaruk, J., M. Markowski and W.J.J.O.F.E. Błaszczak. 2007. Effect of drying conditions on the quality of vacuum-microwave dried potato cubes. 81:306-312.
[67] Supmoon, N. and A.J.D.T. Noomhorm. 2013. Influence of combined hot air impingement and infrared drying on drying kinetics and physical properties of potato chips. 31:24-31.
[68] Setiady, D., C. Clary, F. Younce and B.a.J.D.T. Rasco. 2007. Optimizing drying conditions for microwave-vacuum (MIVAC®) drying of russet potatoes (Solanum tuberosum). 25:1483-1489.
[69] Toğrul, H.J.J.O.F.E. 2006. Suitable drying model for infrared drying of carrot. 77:610-619.
[70] Kocabiyik, H., D.J.I.J.O.F.S. Tezer and Technology. 2009. Drying of carrot slices using infrared radiation. 44:953-959.
[71] Wang, J. and Y.J.J.O.F.E. Xi. 2005. Drying characteristics and drying quality of carrot using a two-stage microwave process. 68:505-511.
[72] Doymaz, I.J.J.O.F.E. 2007. Air-drying characteristics of tomatoes. 78:1291-1297.

[73] Gümüşay, Ö.A., A.A. Borazan, N. Ercal and O.J.F.C. Demirkol. 2015. Drying effects on the antioxidant properties of tomatoes and ginger. 173:156-162.
[74] Toor, R.K. and G.P.J.F.C. Savage. 2006. Effect of semi-drying on the antioxidant components of tomatoes. 94:90-97.
[75] Giovanelli, G., B. Zanoni, V. Lavelli and R.J.J.O.F.E. Nani. 2002. Water sorption, drying and antioxidant properties of dried tomato products. 52:135-141.
[76] Ozkan, I.A., B. Akbudak and N.J.J.O.F.E. Akbudak. 2007. Microwave drying characteristics of spinach. 78:577-583.
[77] Doymaz, I.J.J.O.F.P.E. 2009b. Thin-layer drying of spinach leaves in a convective dryer. 32:112-125.
[78] Bajgai, T. and F.J.D.T. Hashinaga. 2001. Drying of spinach with a high electric field. 19:2331-2341.
[79] Roberts, J.L., R.J.F. Moreau and Function. 2016. Functional properties of spinach (Spinacia oleracea L.) phytochemicals and bioactives. 7:3337-3353.
[80] Murcia, M.A., A.M. Jiménez-Monreal, J. Gonzalez and M. Martínez-Tomé 2020. Spinach. Nutritional Composition and Antioxidant Properties of Fruits and Vegetables. Elsevier.
[81] Qamar, S., A.J.T.I.F.S. Shaikh and Technology. 2018. Therapeutic potentials and compositional changes of valuable compounds from banana-A review. 79:1-9.
[82] Kabeer, S., N. Govindarajan, R. Preetha, K. Ambrose, M.M. Essa, M.W.J.J.O.F.S. Qoronfleh and Technology. 2023. Effect of different drying techniques on the nutrient and physiochemical properties of Musa paradisiaca (ripe Nendran banana) powder. 60:1107-1116.
[83] Brouns, F., B. Kettlitz, E.J.T.I.F.S. Arrigoni and Technology. 2002. Resistant starch and "the butyrate revolution". 13:251-261.
[84] Kookal, S.K. and A.J.a.J.O.P.S. Thimmaiah. 2018. Nutritional composition of staple food bananas of three cultivars in India. 9:2480-2493.
[85] Menezes, E.W., C.C. Tadini, T.B. Tribess, A. Zuleta, J. Binaghi, N. Pak, G. Vera, M.C.T. Dan, A.C. Bertolini and B.R.J.P.F.F.H.N. Cordenunsi. 2011. Chemical composition and nutritional value of unripe banana flour (Musa acuminata, var. Nanicão). 66:231-237.
[86] Vu, H.T., C.J. Scarlett and Q.V.J.D.T. Vuong. 2017. Effects of drying conditions on physicochemical and antioxidant properties of banana (Musa cavendish) peels. 35:1141-1151.
[87] Doymaz, I.J.D.T. 2009a. An experimental study on drying of green apples. 27:478-485.
[88] Drouzas, A., E. Tsami and G.J.J.O.F.E. Saravacos. 1999. Microwave/vacuum drying of model fruit gels. 39:117-122.
[89] Bochnak, J., M.J.I.J.O.F.S. Świeca and Technology. 2020. Potentially bioaccessible phenolics, antioxidant capacities and the colour of carrot, pumpkin and apple powders–effect of drying temperature and sample structure. 55:136-145.
[90] Andrés, A., P. Fito, A. Heredia and E.J.D.T. Rosa. 2007. Combined drying technologies for development of high-quality shelf-stable mango products. 25:1857-1866.
[91] Izli, N., G. İzli, O.J.F.S. Taskin and Technology. 2017. Influence of different drying techniques on drying parameters of mango. 37:604-612.
[92] Vayalil, P.K.J.C.R.I.F.S. and Nutrition. 2012. Date fruits (Phoenix dactylifera Linn): an emerging medicinal food. 52:249-271.
[93] Guido, F., S.E. Behija, I. Manel, Z. Nesrine, F. Ali, H. Mohamed, H.A. Noureddine and A.J.F.C. Lotfi. 2011. Chemical and aroma volatile compositions of date palm (Phoenix dactylifera L.) fruits at three maturation stages. 127:1744-1754.
[94] Seerangurayar, T., A.M. Al-Ismaili, L.J. Jeewantha, N.a.J.F. Al-Habsi and B. Processing. 2019. Effect of solar drying methods on color kinetics and texture of dates. 116:227-239.
[95] İzlİ, G.J.F.S. and Technology. 2016. Total phenolics, antioxidant capacity, colour and drying characteristics of date fruit dried with different methods. 37:139-147.