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Impact of drying on techno-functional and nutritional properties of food proteins and carbohydrates - A comprehensive review

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ABSTRACT

Foods comprise of many macromolecules that have varying techno-functional and nutritional properties. The isolated proteins and carbohydrates from them are increasingly being used as potential ingredients in the food industries. Numerous processes like drying for food processing and preservation cause variations in functional and nutritional attributes of proteins and carbohydrates in different degrees in the food products that can ultimately affect their possible applications. This article explores different drying technologies being used in the food industries, including freeze-drying, microwave-assisted drying, infrared drying, vacuum drying, spray drying, and oven drying. Based on the evaluation of multiple studies, it can be inferred that these drying methods have the potential to contribute to low drying performance, high operational costs, and strong environmental impact. Moreover, they can affect the nutritional value of macronutrients such as proteins, starches, gums, and dietary fibers present in foods, the integrity of the food structures, and their functional properties. Understanding the correlation between the drying technique used and the functional and nutritional attributes of macromolecules will help to provide better insight into the importance of the different drying methods. Optimization of the operational parameters of the different drying methods could be vital and needs to be evaluated to avoid the degradation of the proteins and carbohydrates and the loss of their properties.

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1. Introduction

Fresh foods, such as fruits and vegetables, have a high water activity, are heat sensitive, and degrade quickly. They contain important nutrients, dietary fiber, vitamins, and a variety of micronutrients required for healthy living. However, seasonal availability and high perishability characterize fresh produce. Dehydration is thus one of the most popular techniques for extending the shelf life of food. Yet, the drying techniques used for food dehydration must also produce high-quality goods in terms of flavor, nutrition, color, rehydration, consistency, appearance, and texture in addition to being effective and economical [1, 2]. In the food industry, drying is a widely utilized concept that is frequently employed to transform surplus crops into shelf-stable products. It may be the earliest method of food preservation ever used by mankind for centuries [3].

Drying is a crucial method of food preservation that lowers the moisture content of food to stop it from rotting, create new products, and cut waste. Due to its adaptability, affordability, reasonable control, and ease of equipment, hot air drying accounts for more than 85% of food drying processes [4]. Water, the main component of food, is essential for the oxidation of fats and lipids as well as the growth of microorganisms in meals with a lot of moisture and high water activity. Additionally, the texture and

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flavor of dried foods are significantly influenced by the amount of water in the items. In order to improve shelf life and prevent food degradation, the primary goal of dehydration is to partially remove water from the food matrix [5]. However, because of the physical and biological changes that occur throughout the drying process, the quality of the finished product is significantly impacted. The changes in the food matrix are significantly influenced by variables like drying time, temperature, and the product's water activity [6]. Furthermore, the drying technology used for food dehydration offers desirable product qualities including color, nutrition, taste, texture, and rehydration capability in addition to being efficient and energy-saving [7]. The quality of the product after drying must be considered since, during traditional drying, a number of unfavorable physical and chemical changes as well as uneven moisture distributions (induced by the dispersion of temperature) take place [8].

Drying technologies can be divided into traditional and unconventional drying techniques. Among them, traditional drying methods include solar drying, hot air drying, osmotic dehydration, vacuum drying, freeze drying, heat pump-assisted drying, and spray drying [9]. Many traditional drying techniques are less expensive to run; however, the main drawbacks of traditional drying techniques are their lengthy drying times, poor quality, and inefficient use of energy [10]. Therefore, a lot of unconventional drying techniques are considered today [11]. For example, microwave freeze-drying and atmospheric freeze-drying were studied to satisfy tomorrow's food and energy needs. In addition to improving drying efficiency, lowering environmental impact, and improving dried product quality [3]. As well, because of their higher efficiency and shorter operating durations, the impacts of electro-hydrodynamic, pulsed electric field, microwave, radio frequency, and ultrasonic waves have garnered the most attention among all drying techniques [12].

To boost drying efficacy and efficiency so that energy consumption can be decreased while retaining quality, new and old procedures have been devised. Additionally, new drying methods are being developed to help reduce post-harvest losses, delay deterioration, and lengthen shelf life. New drying techniques have emerged as a result of research, which may enhance product quality and energy efficiency for the food business [13]. Each drying method has its benefits. Hot air drying employs simple, secure, and cost-effective machinery. The freeze-drying method can preserve food's color, flavor, and nutritional content while being particularly well suited for heat-sensitive items. The component that rapidly oxidizes is modified for the vacuum drying procedure. Quick drying times and consistent product quality are advantages of microwave technology. However, because of the intricacy of the components and their varied characteristics, a single type of drying process typically struggles to meet the finished product's quality requirements [14]. There have been numerous technological advancements in recent years related to the industrial drying of foods, including hybrid drying techniques. Hybrid drying systems, which combine several drying methods, led to an improvement in the product's quality. The goal of developing a hybrid drying system was to improve product quality while lowering the likelihood of product deterioration. Similar to that, this system uses less energy, runs more quickly, is affordable, and is simple to use [1].

The various drying procedures are responsible for the production of diverse porous micro- and macrostructures that usually differ from the initial fresh product due to the loss of water from the interior structure to the surrounding environment [6]. As a result, depending on the drying process and the applied conditions, the raw material may have a completely different structure. Food products can shrink significantly depending on the method and conditions used, resulting in the destruction or modification of their microstructure. Dehydration affects a variety of structural qualities, including moisture content, shrinkage, porosity, density, and surface area. Protein denaturation during drying can alter their solubility, digestibility, and bioavailability, reducing their nutritional value [7].

To improve drying applications for post-harvest drying in agricultural products and food and to suggest potential and successful industrial applications for the development of this inherent method that has been around for a long time, this review aims to shed light on the literature on drying preservation technology as well as the newly used drying methods for drying agriculture items and food. Moreover, their impacts on the technological, functional, and nutritional characteristics of food macromolecules were discussed.

2. Drying technologies in the food industry

The process of drying is a very ancient physical method applied by the food industries for food processing and food preservation. It is a very important technology for the food industry because it offers a great perspective to bring out emerging novel ingredients and the latest and most beneficial products for consumers. The final products obtained after drying generally have the characteristics of powders, granules, particles, or flakes of different configurations which depend on the requirements and kind of drying technology applied [15]. The method of drying is generally regarded as a reliable process for enhancing the storage stability of different processed foods [16]. This is because it aims to reduce the moisture content of highly perishable food products that have a high moisture content (>80%) including spices, fruits and vegetables. This helps to not only enhance their storage stability by increasing their shelf-life but also results in reduced packaging, handling and transportation costs because the volume of dried foods would be lesser [16]. Also, many of the bioactive compounds used in the food industries for developing functional foods have very low bioavailability that can result in an off odor when they are incorporated into a food matrix. However, when different drying-based encapsulation methods are used, it can increase the uptake of the different bioactive compounds from the foods and reduce their undesirable sensory properties.

The process of drying involves the principle of simultaneous heat and mass transfer and is quite an energy-intensive method. The conventional drying methods that are used in the food industries including sun or open-air drying can result in inferior product quality. However, various advanced methods that include freeze dryers, microwave dryers, infrared dryers, vacuum dryers, and oven dryers have been developed [17]. All these drying methods have different mechanisms and also disadvantages and advantages for drying food products. The freeze dryer uses a sample which is frozen before drying which is then sublimated from solid to gas in a vacuum due to the heat and pressure reduction [18]. Microwave drying involves the production of instant dry powders where electromagnetic radiations produce heat inside and outside the food commodity [17]. The infrared dryers utilize radiations to heat and dry the food material containing moisture by penetrating inside them whereas the vacuum dryers use reduced pressure that reduces the relative humidity of a product and the boiling point of water inside the product leading to an increased drying rate [17]. Spray dryers produce dry and fine particles through the process of atomization in a hot air environment whereas oven dryers involve drying of a particular product at high temperatures that transfer heat from the surface to the inside of the material [19].

These conventionally used drying methods however have few limitations as they are generally based on the use of hot air for drying and conductive methods of transfer of mass and heat which can contribute in a way to the product quality and enhance the possibility of product contamination [19]. The product quality can get affected due to under-drying or over-drying which can result in non-uniform exposure to high temperatures on the product or the harder texture of food products because of more time for drying [20]. The conventional drying methods can also contribute to changes in the color of the final product due to redox reactions and browning reactions taking place which can lead to low drying performance and higher costs of operation [2]. This can also majorly affect the standard of foods based on their functional, nutritional, and sensorial properties. Also, it has been reported that in hot air drying about 35–40% of the quantity of energy that is put in gets misspent because of hot gases that are exhausted out which results in a lot of energy loss [15]. This can lead to higher energy consumption, high overall processing costs, and a strong and bad impact on the environment.

Various novel processes for drying are being developed for the same that aim to enhance the conventional and commercial drying methods used which include reflectance window dehydration, superheated steam drying, and high electric field drying [21]. Also, processes that involve hybrid drying are being used largely now for drying to save energy and maintain the texture, nutrition profile, taste, and appearance of the foods [22]. It involves an amalgamation of numerous drying techniques to provide a harmonious and synergistic effect to minimize the shortcomings of a single drying process. This has led to a cut down in the time of drying as well as the energy needed along with maintaining the quality attributes of the final product and minimizing product degradation. A few of the hybrid drying technologies include sun-combined drying, and electromagnetic-based methods like infrared-, ultrasound-, and microwave-aided drying [22]. These technologies are still in the developmental phase and are yet to be properly investigated on the different food products to see what effects they have on them. Many studies have evaluated the consequences of using the numerous conventional drying processes on the physicochemical, functional, and nutritional attributes of different food macromolecules. This gives an insight into which drying method would be more suitable for a particular food product which is of pragmatic significance.

Table 1. Different drying methods and their impacts on food products and remedies.

Drying methods	Positive effects	Negative effects	Possible solutions	References
Freeze drying	Minimal heat exposure and long shelf life.	Takes a long time and affects product quality due to certain low temperature processes such as enzymatic browning, oxidation reactions, and protein denaturation.	Combining it with another drying technique and selecting the drying conditions based on the target attributes of each product.	[6]
Spray drying	Rapid drying with easy scalability.	High temperatures can contribute to protein denaturation and can also result in uneven particle size and size distribution.	Combining it with another drying technique such as vacuum assisted, ultrasound assisted and pulse combination spray drying.	[24]
Vacuum drying	Gentle drying at low temperatures with a short drying time.	Expensive for large scale drying.	Can be combined with other drying techniques to improve their efficiency.	[25]
Microwave assisted drying	High quality dried products due to volumetric heating that evenly spreads through the whole sample resulting in reduced costs and high energy efficiency.	Can damage the products due to heat control not being proper and mass transfer during the drying process.	Combining it with another drying technique such as vacuum assisted drying with reduced pressure or air drying.	[26]
Heat pump drying	Temperature and time reduction due to decline in relative humidity that reduces energy losses.	Have higher costs with more complex equipment and controls involved.	Can be combined with other drying techniques to improve their efficiency.	[26]
Hot air drying	Cost effective	Significant energy losses with long drying times that can affect product quality.	Use other drying techniques that can retain product quality.	[26]

3. Impact of drying on proteins

3.1. Techno-functional properties

In recent times, extensive research has been done on different proteins for their techno-functional and nutritional properties that are known to be mainly related to their structures, surface properties and amino acid compositions. These properties can enhance their potential to be availed in many food products. The functionality attributes of the proteins include their ability to solubilize, emulsify, foam, water holding, viscosity, oil holding and gelation which are important parameters for designing various foods [23]. However, these protein attributes can be modified by processing methods such as drying (Table 1). This is done to enhance the long-term storage stability of protein isolate powders or different food products, but it can result in insoluble aggregates developing and denaturation of protein [27]. This can ultimately cause alterations in the protein's techno-functional attributes (Figure 1). It was observed in a study that there are structural differences between different dried samples which suggests that the alterations in the techno-functional attributes can also be due to the different drying methods used [28] which has been summarized in Table 2.

3.1.1. Protein solubility

The solubility of proteins helps to determine the amount of proteins that are present in a soluble state under different conditions [38]. For food applications, good solubility is desired which is known to be affected by the different a drying processes. In particular, drying rice protein isolates using a spray dryer had better solubility at pH values greater than 5 when compared to protein isolates after freeze-drying [35]. Similarly, lentil protein isolates that were spray-dried had relatively more solubility (81.19%) than vacuum-dried (50.34%) and freeze-dried (78.39%) lentil protein isolates, respectively [30]. This was ascribed to the lesser destruction of proteins in powders that were dried by spray-drying and their smaller and uniform particle size distribution. It has also been shown that freeze-dried gelatins from splendid squid (*Loligo formosana*) skins also had lower solubility than spray-dried gelatins which was suggested to be because of the larger inlet temperature when spray drying was done that led to lower molecular weight peptides that were more hydrophilic [26]. On the contrary, freeze-dried gelatin from the swim bladder of Rohu had more solubility than gelatin which was dried by spray drying whereas the vacuum-dried gelatins demonstrated the least amounts of solubility [31]. Here, the differences in solubility were ascribed to variations in the molecular weight of peptides and the number of different groups present in amino acids [31]. Similarly, freeze-drying was seen to be a pleasant method over vacuum freeze-drying and spray drying for potato proteins which led to better solubility [32]. Overall, spray drying resulted in better protein

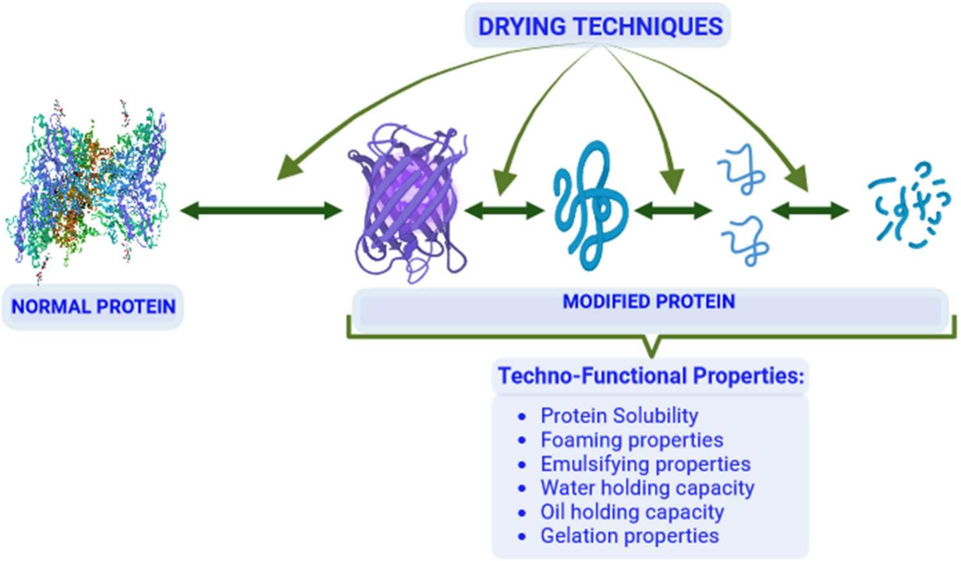

Figure 1. Impact of drying techniques on techno-functional properties of proteins.

solubility and led to a more uniform and smaller particle size distribution compared to freeze-drying [26]. Furthermore, freeze-drying led to better protein solubility than vacuum-drying due to greater protein denaturation contributed by vacuum-drying because of the formation of gas bubbles resulting in proteins binding to air-water interfaces and undergoing partial unfolding. Therefore, combining these different drying techniques could allow for enhanced protein solubility [31].

3.1.2. Foaming properties

The foaming properties of a protein determine its ability to form stable foams which are useful for different applications; and are affected by drying. The foaming capacity of spray-dried rice proteins was found more than the proteins that were dried by freeze drying which suggested that spray drying led to conformational changes at the connection of air and water and the smaller particle size of spray-dried rice protein isolate could adsorb rapidly during whipping at the interface [32]. However, no changes were seen in this study for foam stability that suggested that it was not much affected by the drying method. Similarly, spray-dried gelatins from goat and dogfish skin respectively showed greater foam expansion and foam stability than freeze-dried gelatins which is due to their better ability to form films at the interface of air and water [33, 34]. Besides, spray-dried gelatins from rohu bladder showed better foam-forming ability than gelatin after freeze drying and vacuum drying due to the presence of long and short peptides that can adsorb at the air-water interface and reduce surface tension [31]. Duck egg white proteins were dried by freeze-drying and an amalgamation of drying by both microwave vacuum and freeze-drying [39]. It was seen that freeze drying led to improved foaming capacity in the proteins which was attributed to significant changes to their structural and physiochemical properties by the amalgamation of drying by freeze and microwave vacuum drying.

3.1.3. Emulsifying properties

The ability to develop emulsions of a protein determines their potential to develop oil and water systems that are stable by interacting at the interface between water and oil and reducing surface tension. There are generally two factors that are measured to determine emulsifying abilities are emulsifying activity index (EAI) which quantifies interfacial area stabilized by a protein unit and the emulsion stability index (ESI) which determines the stability of the emulsions with time [29]. For rice protein isolate, spray-dried rice proteins had higher EAI and ESI values than proteins dried by freeze-drying principally at a pH of 9 and 10 because of the lesser size of particles of spray-dried protein powders [29]. Similarly, when gelatin was dried by spray drying from untreated dogfish skin had higher EAI than freeze-dried gelatin [33]. In another study, the spray-dried gelatins from rohu bladder showed higher EAI than freeze-dried and gelatins dried by vacuum drying respectively [31]. This was due to both long and short peptides being there where the former could move to the interface between oil and water to form emulsions and long-chain peptides could surround the oil droplets and form thicker and stronger films. Protein from duck egg white had higher EAI values after an amalgamation of freeze and microwave drying than only the freeze-dried samples

Table 2. Impact of different drying processes on the techno-functional attributes of different proteins.

Protein	Drying method used	Functional properties determined	Research outcomes	Ref.
Rice protein isolate	Spray-drying and freeze drying	Spray drying had higher protein solubility and emulsifying activity at the pH values between 5 and 11, with higher foaming capacities (127.08 ± 2.25% compared to 118.83 ± 2.71%) than freeze drying. However, freeze-drying had a larger mean diameter (2,114.2 ± 79.6 nm compared to 490.4 ± 44.8 nm of spray drying), higher water/oil holding capacity ($p < 0.05$), and thermal stability.	Freeze drying has higher water/oil holding capacity and thermal stability than spray drying.	[29]
Lentil protein isolate	Spray drying, vacuum drying, and freeze drying	Higher solubility (81 and 78%, freeze drying, spray drying respectively) compared to vacuum-dried powders (50%). Low water absorption capacity of spray-dried (0.43 ± 0.02 g/g), frozen (0.48 ± 0.02 g/g) and vacuum-dried (0.47 ± 0.01 g/g). Spray and freeze-dried powders demonstrated improved gelation ability and higher gel strength.	Higher solubility, reduced ability to hold water of spray-dried proteins and lower gel strength of vacuum-dried proteins.	[30]
Squid skin gelatin	Freeze-drying and spray drying	Gel strength (g): freeze drying (156), spray drying (137). Solubility (%): freeze drying (90), spray drying (94).	Lower solubility and higher gel strength of freeze-dried gelatin over spray-dried gelatin.	[26]
Rohu swim bladder gelatin	Spray drying, freeze drying, and vacuum drying	Freeze-drying presented the highest gelatin yield (g/100 g) (54.51), vacuum-drying (48.95) and spray-drying (41.76). Freeze-dried and spray-dried gelatin had the highest surface hydrophobicity, protein solubility, emulsifying, foaming and gelation property than vacuum-dried gelatin.	Higher solubility, and gel strength of proteins dried with freeze drying but better foaming ability and EAI of spray-dried gelatin.	[31]
Potato protein	Spray drying, freeze drying, and vacuum drying	The higher solubility was (at pH 5.0) 54.9% for the freeze-dried, 53.2% for vacuum drying, and 47.59% for Spray drying.	Better solubility of freeze-dried proteins over others.	[32]
Dogfish skin gelatin	Spray-drying, and freeze drying	Foaming: 163.48 % for freeze drying, 160.54% for Spray drying. Spray-dried gelatins generated emulsions with droplets larger in size than those of emulsions prepared with freeze-dried gelatins. WHC: Spray drying presented the highest value of WHC (5.7 ml/g), while it's (2.9 ml/g) for freeze drying.	The spray drying technique enhanced the foaming and emulsifying characteristics as well as the oil and water holding capacities. Gelatins' gel toughness was also boosted by spray drying.	[33]
Goat skin gelatin	Spray-drying, and freeze drying	Foam expansion and stability of all gelatins increased with increasing concentrations (10–30 g/L) ($p < 0.05$). Spray-dried had higher foam expansion and stability than freeze-dried.	Greater foam expansion, and foam stability of spray-dried gelatin	[34]
Duck egg white proteins	Freeze drying, and freeze + microwave drying	Spray drying had higher protein solubility and emulsifying activity at the pH values between 5 and 11, with higher foaming capacities (127.08 ± 2.25% compared to 118.83 ± 2.71%) than freeze drying. Freeze drying had a larger mean diameter (2,114.2 ± 79.6 nm compared to 490.4 ± 44.8 nm of spray drying), higher water/oil holding capacity ($p < 0.05$), and thermal stability.	Freeze-dried proteins had better foaming capacity and better gel strength but freeze + microwave-dried proteins had higher EAI.	[35]
Chicken skin gelatin hydrolysate	Vacuum-drying, and freeze drying	The emulsifying activity index for freeze-dried gelatin at pH 6 was 12.27 min, while it was 28.82 min for vacuum-dried gelatin. Which means the vacuum-dried gelatin is better.	Freeze-dried gelatin had EAI and water-holding capacity but vacuum-dried proteins had better ESI.	[36]
Potato protein isolate	Freeze-drying, and spray drying	Compared to freeze drying, spray drying generally did not affect the solubility or gel characteristics of complete protein isolates.	The larger storage modulus of spray-dried gelatin than freeze-dried gelatin.	[37]

which was because both the hydrophilic and hydrophobic groups of proteins were stretched out to the oil-water interface after microwave drying enhanced their emulsifying activity [39]. Chicken skin gelatin hydrolysates after freeze-drying showed better EAI in comparison to vacuum-dried gelatin due to smaller protein molecules but the gelatin dried by vacuum drying had improved and enhanced ESI in contrast to gelatin dried by freeze-drying [36].

3.1.4. Water and oil holding capacities

The power to hold water and oil respectively are also crucial attributes for various food applications but can be influenced by the numerous processes of drying. The water binding capacity of freeze-dried gelatins from chicken skin was higher than vacuum-dried gelatins due to greater amounts of hydrophilic amino acids but both these gelatins showed greater fat binding capacities than each other at different pH values [36]. The power to hold water and oil of freeze-dried rice protein isolates was enhanced over proteins dried at spray drying at a pH of 7 [32]. This was not found to be correlated with their solubility but with their different structures and types of the process used for drying. For lentil protein isolates the spray-dried proteins showed lower water-holding capacity than the protein dried with vacuum and freeze-drying which was ascribed to their ability to develop skins during the drying of the polymeric biomolecules [33]. Moreover, exposure to high temperatures during spray drying can result in protein denaturation and their ability to bind and hold water contributing to reduced water-holding capacity [30]. The fat binding capacity of freeze-dried gelatin from untreated dogfish skin was higher than spray-dried gelatins which had higher water binding capacity that is ascribed to the content of hydrophilic and hydrophobic amino acids in them [33]. Freeze-drying resulted in the exposure of more hydrophobic regions that could bind oil and increase their oil binding capacity [33]. This suggests that different drying processes affect water and oil-binding activities in different ways and based on the application they can be combined to retain the food quality and achieve the desired attributes.

3.1.5. Gelation properties

Gelation characteristics are important functional properties that can result in the hydration and adhesive characteristics of food products in which they are used as ingredients. In a study, the vacuum-dried lentil protein isolates demonstrated the highest amounts of gelation concentration and lower gel strength, which suggests their poor gelling ability when compared with spray and freeze-dry specimens, which is in line with their solubility characteristics [30]. Similarly, the gel strength of freeze-dried and spray-dried gelatins from rohu swim bladder was higher than vacuum-dried gelatins due to higher molecular weight peptides present in them that are capable of self-aggregation [31]. A comparative analysis of the method used for drying squid skin gelatin was conducted and the robustness of gels formed by freeze drying was found a lot more to gelatins obtained after spray drying because freeze-drying led to gel cross-linking that led to higher amounts of ß- and γ- components that contribute to gel strength [26]. The amount of robustness of gels developed with duck egg white proteins after freeze-drying was found to be more than those dried using a combination of microwave and freeze-drying due to their shorter times to dry in the latter samples led to lesser protein denaturation [39]. On the contrary, spray-dried potato protein isolates had a larger storage modulus (G') than freeze-dried proteins due to limited protein denaturation by spray drying, higher surface hydrophobicity, and partial protein unfolding that led to gel firmness [37]. The impact of drying on the gelling properties is mainly due to protein denaturation and by using rapid drying techniques with optimized formulations, it is possible to mitigate these effects and maintain or enhance the gelling properties of proteins for different food applications.

3.2. Nutritional properties

The nutritional properties of amino acids and proteins present in foods can be evaluated by establishing the composition of amino acids in them and their protein digestibility [40]. The traditional drying processes used in the food industries are known to contribute to different structural and physical changes in the food product or its components that may significantly reduce the nutritional and therapeutic properties of the proteins present in them which affect the product quality attributes. However, other drying techniques, such as vacuum drying or freeze drying, can raise the nutritional value and standards of many products, with freeze-drying being thought to have tremendous potential to produce high-standard items [41].

3.2.1. Amino acid composition

The amino acid profile or composition as well as the essential amino acid index provides a good reference for the quality of the proteins present in any given food product. However, amino acids can be destroyed by thermal treatment. In a study, the constitution of amino acids in dried seaweeds was determined following different processes for drying that included solar drying, freeze-drying, vacuum drying, and convective drying [41]. Dried seaweeds were found to contain amino acids like proline, glycine, phenylalanine, and tyrosine but reduced the content of isoleucine, aspartic acid, and glutamic acid despite the drying method used. The amino acid histidine was seen only in the vacuum-dried samples, but the least degradation of amino acids was seen following freeze-drying and the highest degradation was seen following convective drying due to their high heat exposure [41]. This suggested that the application of heat results in the compositional change in the nitrogenous compounds. Similarly, impacts of spray drying, freeze-drying, and vacuum-drying were studied to understand the amino acids profile of gelatin that was derived from rohu bladder and it was seen that all gelatins demonstrated glycine to be the amino acid found more [31]. The other amino acids observed in the gelatin in this study were proline, alanine, glutamic acid, hydroxyproline, arginine, cysteine, methionine, and tyrosine but their concentrations varied slightly in the gelatin samples depending on the drying method used. The constitution of amino acids present in gelatins that were extracted from the dogfish skin and subjected to different drying methods was determined and the major amino acid was found to be glycine [33] which was consistent with the data obtained for gelatin from rohu swim bladder [31]. However, there was a lower amount of tyrosine and methionine reported that could affect the nutritional attributes of the protein. In another study, squids were subjected to drying using freeze-drying, heat pump drying and air drying and the total essential amino acid content was found to improve significantly compared to the raw squids but the amounts of valine, isoleucine, and leucine were lower [42]. Considering the amounts of amino acids that were not essential, raw squids possessed greater amounts of glycine, arginine, and histidine as compared to the dried squids prepared using different drying methods. In another study, quinoa protein was dried by spray, vacuum, and freeze drying and the freeze-dried proteins showed larger quantities of certain amino acids such as glycine and alanine which was due to lesser thermal degradation during freeze-drying [43]. This suggests that the amino acid composition in a protein is very much susceptible to the drying method used.

The different drying methods can also contribute to differences in the predominant amino acids in the food proteins which can affect their nutritional properties. When insect proteins from black soldier fly were subjected to conventional and microwave drying respectively, the main amino acid present in conventionally dried protein was aspartic acid and the predominant amino acid found in microwave-dried protein was glutamic acid [40]. Also, when coffee beans were dried using different drying methods, it was seen that hot air drying resulted in greater amounts of total amino acids that were essential with the chief ones being lysine, phenylalanine, and leucine [44]. This was attributed to proteolysis occurring in the proteins because of heat in hot air drying. The amino acid profile of the proteins can also be attributed to different temperatures used in the drying process. For example, proteins from blood fruit seeds were dried using a spray dryer at 160 and 180 °C and it was observed that protein isolates after drying at 180 °C were low in all the amino acids as compared to those dried at 160 °C which suggested that amino acids degrade at elevated temperatures [42]. Variations in the profiles of amino acids of the food proteins following drying are very important to understand as that helps to provide an idea about changes in their nutritional value that can affect their efficiency for future applications. The amount of protein denaturation that occurs, which affects the amino acid content of proteins, varies depending on the method of drying utilized.

3.2.2. Protein digestibility

The digestibility of proteins is a crucial specification to determine the nutritional value of proteins as it helps to determine how our bodies can utilize and absorb a dietary protein. Food processing, including drying, can either increase or decrease the digestibility of a particular protein by modifying protein structure and that is why it is important to understand more about it in detail (Table 3). Proteins with higher digestibility result in higher amounts of nutritional standards than those with lower digestibility as they yield more amounts of amino acids that could be absorbed following proteolysis [46].

The impact of numerous processes of drying on the protein digestibility of different proteins is summarized in Table 4. Andean lupin (*Lupinus mutabilis*) was subjected to different processing methods of which one was spray-drying that resulted in the lowest protein content but the digestibility was found to increase after drying and be in the range of 72.8–74.0% [47].

Table 3. Impact of different drying processes on the composition of amino acids of proteins.

Protein	Drying method used	Key results	Overall findings	Ref.
Protein from seaweed	Freeze drying, convective drying, and vacuum drying	Convective drying produced the highest degradation ratio of amino acids in comparison to the freeze-drying sample (31.9%), followed by solar drying (24.6%) and vacuum drying (13.1%).	The least protein and amino acid degradation was after freeze drying and the highest after convective drying.	[41]
Gelatin from the rohu swim bladder	Freeze drying, spray drying, and vacuum drying	The maximum gelatin yield was produced by freeze-drying (54.51 g/100 g, dry weight basis), which was followed by vacuum-drying (48.95 g/100 g) and spray-drying (41.76 g/100 g).	The major amino acid observed was glycine and the amino acid composition varied depending on the drying method used.	[31]
Gelatin from dogfish skin	Freeze-drying, and spray drying	The freeze-dried yield had the highest yield (8.67%), whereas the freeze-dried gelatin from oven-pretreated skin had the lowest yield (3.06%).	The major amino acid observed was glycine with lower amounts of tyrosine and methionine that could affect nutritional attributes.	[33]
Squid proteins	Freeze drying, heat pump drying, and air drying	The highest percentages of *in vitro* digestibility was found in samples after freeze drying (76.81%), heat pump drying (70.51%), raw drying (67.99%), and hot air drying (61.47%).	Total essential amino acid content after drying with different methods increased significantly compared to the raw squids but the non-essential amino acid content was higher for the raw squids.	[45]
Quinoa protein	Spray drying, freeze drying, and vacuum drying	The freeze-dried protein exhibited the highest emulsification capacity and stability, while the spray-dried sample had the highest solubility and water absorption capacity.	Freeze-dried proteins had higher amounts of certain amino acids like glycine and alanine due to lesser thermal degradation.	[43]
Protein from black soldier fly	Conventional drying, and microwave drying	Both conventionally dried and microwave dried had a greater than 40% essential amino acid content of the total amino acids.	The chief amino acid found in conventionally dried protein was aspartic acid and in microwave-dried protein was glutamic acid.	[40]
Protein from coffee beans	Room drying, heat-pump drying, hot-air drying, solar drying and freeze-drying	Hot air drying was ideal for retaining amino acids.	Drying at elevated temperatures led to higher amounts of total essential amino acids with the chief ones being lysine, phenylalanine, and leucine.	[44]
Blood fruit seed proteins	Spray drying	Leucine, isoleucine, valine, histidine, tyrosine, methionine, and probiotic fermented spray dried samples were shown to have 20% greater levels of these amino acids.	After drying at 180 °C, all amino acids were low as compared to those dried at 160 °C due to protein at elevated temperatures.	[42]

Similarly, when blood fruit protein isolates were dried by spray drying at 160 °C, an increase in protein digestibility was observed that was due to increased protein unfolding and destruction of compounds that inhibited the protease activity [42]. But when the same proteins were spray dried at 180 °C, there was some reduction in the protein digestibility due to increased cross-linking of the proteins at those conditions. The conditions of drying with a freeze dryer for chicken meat protein hydrolysates were optimized with the help of response surface methodology for obtaining the best amounts of solubility and *in vitro* protein digestibility and a shelf and lyophilization temperature of 15 and −10 °C with a freezing rate of 2.0 °C/min led to a protein digestibility of 25.626 and 23.808%, respectively [48]. The drying of green peas using a channel air-flow dryer has been optimized for the drying temperature and the protein digestibility was found to increase at higher drying temperatures which were attributed to protein denaturation as seen by the reduction in the β-sheet secondary structures as confirmed by FTIR analysis [49]. The protein digestibility following drying at 50 °C was reported to be 76.26% whereas after drying at 70 °C, it was found to be 85.87%, suggesting that high temperatures can reduce the heat-labile compounds present in proteins, affecting their digestibility [49].

The impact of using different processes for drying such as freeze drying, heat-pump drying, and hot air drying) on the protein digestibility of proteins from squid, fillets were evaluated and it was observed that the proteins after freeze drying had the greatest amounts of protein digestibility with a percentage of 76.81% which was contributed by the porosity in the

Table 4. Impact of different drying processes on the protein digestibility of proteins.

Protein	Drying method used	Research outcomes	Ref.
Andean lupin protein	Spray drying	*In vitro* protein digestibility was found to increase following drying and be in the range of 72.8–74.0%. Spray-drying enhanced the chemical composition. Processing improved the food's nutritional value and digestion without causing any material heat damage.	[47]
Blood fruit protein isolates	Spray drying	At the most effective drying temperatures (160 and 180 °C), the distinctive functionality and bioactivity of the proteins discovered varied. An increase in protein digestibility was observed after drying at 160 °C which reduced after drying at 180 °C.	[42]
Chicken meat protein hydrolysates	Freeze drying	Freeze-drying conditions were optimized to get maximum protein digestibility of 23.808%. High-quality products can be produced by the utilization of this technology. Which results to improved functional and sensory characteristics.	[48]
Green peas proteins	Channel air-flow drying	Drying conditions were optimized and the protein digestibility was found to increase at higher drying temperatures. As drying temperature increased, so did the *in vitro* digestibility of protein and starch. Denaturation effects are responsible for the rise in protein digestibility.	[49]
Squid fillet proteins	Freeze drying, hot air drying, and heat-pump drying	Freeze-dried samples had the highest protein digestibility percentage of 76.81% which was contributed by the porous structure of the freeze-dried sample. The best quality was provided through freeze drying.	[45]
Protein from black soldier fly	Conventional drying, and microwave drying	Protein digestibility was higher for the conventional dried proteins because the proteins treated with microwave drying were harder to digest. Protein particles were polymerized and made more difficult to digest by microwave drying.	[40]
Protein from shrimps	Microwave drying	A significant reduction was observed in their concentration of protein and digestibility which was attributed to changes in the structures of the shrimp proteins. The modulation of the secondary structure of shrimp proteins was closely related to these modifications.	[50]
Soybeans	Freeze-drying and air drying	Freeze-dried samples were found to have higher protein digestibility which was found to increase between 82.6 and 85.0%.	[51]

structures after freeze drying [45]. After freeze drying, the highest digestibility percentage was seen in heat-pump dried samples when it was compared to samples that were air dried and this was ascribed to lower temperature processing in heat-pump drying and the denser and firm structure of air-dried samples that inhibited enzymatic digestion. Similarly, the effects of normal and microwave drying were compared for the protein digestibility of proteins from the black soldier flies and it was seen that protein digestibility was higher in the conventional dried proteins because the proteins treated with microwave drying were harder to digest [40]. In another study, when the shrimps (*Litopenaeus vannamei)* were dried by microwave drying, a significant reduction was observed in protein concentration and digestibility which was attributed to changes in shrimp protein secondary structure [50]. Also, soybeans have been treated with numerous processes for drying that air and freeze drying before making soy milk and the freeze-dried samples had greater protein digestibility which was found to increase between 82.6-85.0% respectively due to more soluble protein content [51].

4. Effect of drying on carbohydrates

4.1. Starch

There are few studies on the impacts of the dehydration process on the technological, functional, and nutritional attributes of starch (Figure 2). The internal structure and surface of starch granules are altered by drying circumstances, which subsequently affect their features like chemical reactivity, gelatinization, retrogradation, and pasting properties [52].

Resistant starch (RS) is a type of starch that can be fully or partially fermented by microbiota in the colon but cannot be broken down by human digestive enzymes, particularly amylases in the small intestine [53]. Bread and cookies are examples of foods high in carbohydrates. When RS is added, it has been found that the items' sensory qualities their appearance, texture, and mouth feel are improved over when traditional dietary fiber is used. This is due to RS's generally larger capacity to store water as well as its capacity to swell, gel, and bind water [54]. Different processes can be used to create RS. High-amylose starch has been proven to have a higher RS content after heating-cooling cycles [55].

Repeated heating of starch can cause amylose and amylopectin to become disorganized, and finally, they may partially shatter. Due to the limited accessibility of digestive enzymes, this action encourages the creation of denser but smaller crystals, increasing the RS concentration [56]. On the other hand, the development of the RS fraction is also a result of the retrogradation of starch chains [29]. The procedure includes crystal nucleation via intramolecular helical chain segment start, propagation via association of chain segment

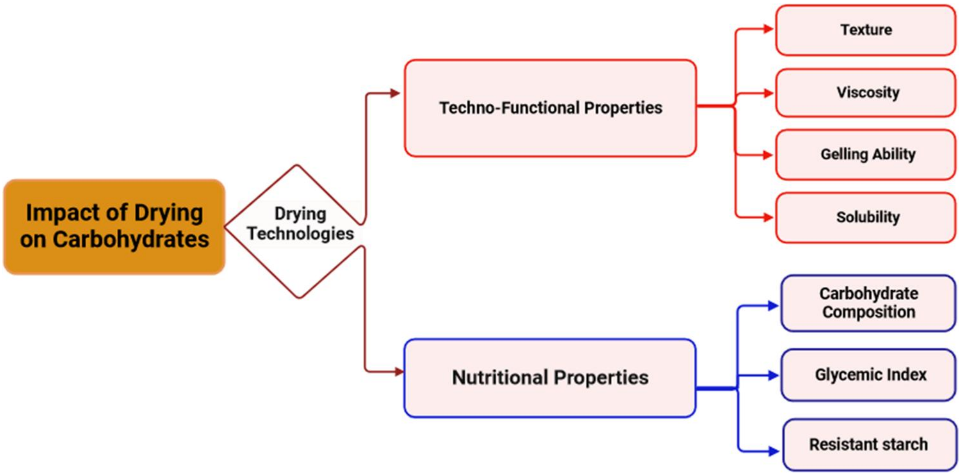

Figure 2. Impact of drying techniques on carbohydrates.

growth of crystals from the nucleus, and maturation via crystal perfection [57]. The optimum way to boost the RS content for a particular application will depend on how the resistant starch-rich powder is going to be used. The processes used to remove water from pre-gelatinized high amylose starch during the dehydration phase before the hydrothermal treatment affected how the starch components were reorganized. However, the freeze-dried material is significantly impacted by the hydrothermal treatment [58].

RS is often categorized into the following five groups. RS1 stands for physically entrapped, inaccessible starch in an indigestible matrix, RS2 for native, granular resistant starch (B- or C-polymorph), RS3 for retrograded starch, RS4 for chemically modified resistant starch, and RS5 for solitary, lipid-complexed amylose helix. At greater temperatures, RS4 and RS5 are more stable. However, when used in food, RS4 is not thought to be a clean material [53]. In contrast, RS5 has a significant potential for usage in food since it can withstand higher cooking temperatures and can regain its intricate structure after chilling. Additionally, exogenous or endogenous fatty acids can combine with single-helix amylose to create complexes.

Rewthong, Soponronnarit, Taechapairoj, Tungtrakul, and Prachayawarakorn [59] reported that the boiling, pretreatment, and drying processes affected the structure of the rice. After being rehydrated, samples cooked in the rice cooker had less hardness and stickiness than those made with freshly cooked rice, however, those cooked in the water bath displayed a noticeable improvement in both textural attributes. The freeze-dried products had the same texture as the products that were air-dried. The texture and glycemic index of fast rice were equal to those of freshly cooked rice after rehydrating because of the freezing pretreatment. In addition, the samples' tougher texture and higher glycemic index were caused by the cooling procedure. Therefore, it is suggested that boiling and freezing be done first, followed by drying while preparing instant rice. According to Zeng, Zhu, Chen, Gao, and Yu [56], short-chain amylose (SCA) crystals with various physical and chemical characteristics and *in vitro* digestibility were generated using various drying technique. These findings suggest that crystals with varying digestibility can have their molecular structures changed by various drying methods. Food processors will be able to alter the starch crystals' characteristics thanks to the findings of this study. By selecting the best drying techniques, short-chain amylose (SCA) crystal's digestibility can be controlled. Therefore, the drying procedure itself may have an impact on how SCA crystals' glycemic index changes. In pre-gelatinized high-amylose starch before hydrothermal treatment, the dehydration process affected the reorganization of the starch components due to the processes used to remove the water. The sample's elevated SDS and RS levels, however, show that the hydrothermal treatment had a significant impact on the freeze-dried material [58].

The glycemic index (GI) gauges how quickly blood sugar levels increase following the consumption of carbohydrates. Commonly regarded as one of the foods with a higher GI that is heavy in carbohydrates is white bread (higher than 75 in most cases). There is always interest in finding a solution to lower the GI of white bread. The *in vitro* GI of the bread was decreased by 16.5–23.5% from 100 after the addition of a commercial RS2 powder made from maize starch that provides 60% (dry basis) RS at 20–30% (12–18 g RS per 100 g of bread formulation) [60]. There are several methods for producing RS, including chemical, enzymatic, and physical processes. However, enzymatic and chemical processes take time. Chemical processes are linked to product safety issues and environmental contamination [61]. Resistant starch cannot be used in foods that need further high-temperature processing because it is typically manufactured using enzymatic processes (low melting temperature) [62]. The physical technique is intriguing because it does not employ potentially harmful chemicals [61]. Moreover, spray drying is advised for the production of RS that is powdery because it is speedier than traditional drying and eliminates the need for product grinding [63].

Starch granules appear to become stiffer at high drying temperatures, which reduces their water solubility indices and swelling potentials during the gelatinization process. Wet-milled starch granules have stiffness due to the high temperatures used during maize drying which was a key determinant in the creation of pastes or gels [64]. Depending on the thermal characteristics and starch content, freeze-drying is one of the finest dehydration techniques for heat-sensitive materials. Freeze-drying is thought to be the best method for dehydrating heat-sensitive materials to achieve the highest quality with the least amount of color, structure, nutrition, and flavor loss when compared to other drying procedures [65].

4.2. Gums

Gums are biopolymers with a variety of useful and cutting-edge qualities in the food sector. They are intricate biomolecules made of carbohydrates that can join with water to form gel and mucilage structures. Gums are among the few food additives with the necessary structural and functional characteristics, and they can be obtained from a range of sources [66]. A class of hydrophilic/hydrophobic polysaccharides with high molecular weight or derivatives of polysaccharides that can form a gel or viscous solutions in various solvents when present in tiny amounts are both referred to as gum [67]. These characteristics include stabilizing potential, viscosity enhancement, emulsifying and surface-active properties, extensive adaptability, and accessibility. Plant-based gums (PGBs) are often employed in beverages, other foods, emulsions, thickening/foaming agents, dietary fiber, confectionery, and flavor and color encapsulation as stabilizers [68]. As well as PBGs are organic polysaccharide polymers that are safe, non-toxic, and readily available in nature [69]. Due to their accessibility, affordability, and desirable properties, seed gums are favored among commercially available hydrocolloids [70]. Given their unique physicochemical characteristics, seed gums are also widely known for their uses as stabilizers, thickeners, and emulsifiers [71]. Polysaccharide gums are employed extensively for a wide range of uses because of their beneficial qualities. The ability of these substances to lower surface tension also permits the stability of a variety of phases through interactions with water, electricity, and space [72]. The source, extraction, and processing techniques of such polysaccharides frequently affect their molecular structure and chemical makeup. Plant-based gums are made of monomers of sugar [73]. Depending on many factors, natural polymers' functional properties and bioactivities might differ significantly [74]. Additionally, the procedure may result in a wide range of molecular weights based on the method and circumstances of dehydration.

Numerous studies have concentrated on the characterization of freshly seeded mucilages and gum exudates during the past ten years to foresee their prospective uses in the food, pharmaceutical, paper, textile, oil, and cosmetic industries [75]. Gum manufacture revolves around the drying process, which is crucial to the gum's qualities. The main drying methods most usually used in gum isolation are air drying, vacuum drying, spray drying, and freeze-drying. Studies in the past have shown that spray drying can be utilized to produce pure, white, homogeneous gum powder with better product qualities and eradicate hazardous germs [76]. Cao, Li, Qi, Sun, and Wang [77] evaluated the effect of spray drying on camelina gum yield and properties and they concluded that the temperature employed for drying had a substantial impact on the yield, purity, and rheological features of camelina gum, but not on the morphological properties of the gum itself. In contrast to freeze-dried gum, spray drying changes the viscosity of the gum.

Freeze-drying is a method of dehydration based on the sublimation of water in a product. The product is frozen to put it under vacuum pressure, which causes the water to sublimate and desorb. To maintain qualities like flavor, color, or appearance and to reduce the breakdown of the labile compounds, many of which are responsible for the fragrances and nutritional content of the fruits, freeze-drying is done at low temperatures. As a result, the finished freeze-dried product is of high quality when compared to other dehydration methods. The final product's chemical and physical properties may occasionally suffer despite its improved microbiological stability [78].

Dried seed gums' physicochemical characteristics and rheological behavior are influenced by the drying process and environment. Additionally, a crucial aspect of product quality that is impacted by the drying conditions is the color of the dried goods. For instance, Salehi and Kashaninejad [79] studied how various dehydration techniques affected the physicochemical characteristics of basil seed mucilage. The findings revealed that gums' rheological and viscosity characteristics are functional characteristics that are particularly vulnerable to drying. The coloring variations and brightness of the gum solution are adversely impacted by the increase in temperature. While the gum that had been frozen-dried was the hardest and most consistent. To assess the physicochemical characteristics, microstructure, and storage durability of xylooligosaccharides, four drying procedures were employed in the presence of drying agents (maltodextrin and gum Arabic). Vacuum drying was used to enhance their physical and chemical qualities. Despite this, spray drying emerged as the most effective drying method for maintaining the finished product with a high level of storage stability. With vacuum drying and a carefully calibrated drying agent dosage, transition temperature and a drop in water activity were attained.

To preserve a long-lasting food product, freeze-drying was suggested as a practical industrial method [80]. According to Zain, Ghani, Kasim, and Hashim [81], the drying procedure significantly decreased the powdered chia mucilage's ability to hold water. It might be because polysaccharide gums' chemical makeup varies significantly depending on the drying stage. Nearly all hydrocolloids have side units, which alter how they function. These side units are typically sugar units, but they can also be carboxyl groups, sulfate groups, or methyl ether groups. Some gums' sugar units contain hydroxyl and anionic groups that are arranged around water molecules.

Plant gums' rheological and textural characteristics are influenced by the technique and environment used for extraction, purification, and drying. Depending on the type and circumstances of drying, a drying process can produce a wide range of molecular weights, hence altering viscosity. According to Amid and Mirhosseini [82], the viscosity variations in all durian seed gums dried using various drying techniques (oven, freeze drying, spray drying, and vacuum oven drying) may be caused by variations in their molecular weights. All of the dried durian seed gums were discovered to exhibit pseudoplastic (shear-thinning) flow behavior. Nep and Conway [83] discovered that the grewia gum's viscosity varied from 0.20 to 0.32 Pa.s depending on the drying technique, where reached at 0.1 Hz (Pa.s) 0.32 in air drying, 0.29 in freeze-dried and 0.2 in spray-dried. They reported that compared to spray-dried and freeze-dried grewia gum, air-dried grewia gum had a higher viscosity. With an increase in shear rate, the viscosity of the gum dispersions reduces. As a decreasing number of chain entanglements at high shear rates accounts for the decrease in viscosity with increasing shear, this is suggestive of pseudoplastic flow behavior or shear-thinning [84]. Salehi and Kashaninejad [85] investigated how different drying techniques affected the rheological, textural, and color changes of wild sage seed gum. The findings showed that the gum that had been freeze-dried had the highest levels of hardness, stickiness, consistency, and adhesiveness. Freeze-dried gum has the highest viscosity when compared to oven and vacuum oven drying. The drying process often results in a decrease in the viscosity of wild sage seed gum. From 40 to 80 °C, increasing the temperature caused a decrease in perceived viscosity.

Flaxseed gum's viscosity after being dried using various methods was compared by Wang, Law, Nema, Zhao, Liu, Deng, Gao, and Xiao [86]. According to their assessment, flaxseed gum has a viscosity that ranges from 1.382 to 5.087 Pa.s. It's possible that the drying process had a considerable impact on the chemical makeup of balangu seed gum, causing noticeable changes in apparent viscosity. Depending on the drying circumstances, the drying procedures considerably alter the ratio of soluble to insoluble materials, which alters the powder's viscosity.

4.3. Dietary fibers

Increased interest in developing nutritious diets has resulted in a greater emphasis on dietary fiber in food products [87]. Due to its major contribution to improved health through illness prevention and management, dietary fiber is a subject of study that is intriguing to food scientists, nutritionists, and food makers. Dietary fibers are said to have several important physiological health advantages; they make up a significant portion of the market for functional foods because of these health advantages [88]. In the digestive system, dietary fiber serves several functions [89]. Dietary fiber is typically obtained from grains, legumes, oilseeds, fruits, vegetables, and a variety of plant parts [90]. Dietary fiber has been extracted from various sources using thermal, chemical, enzymatic, mechanical, and physical processes. However, in the majority of cases, the extraction circumstances call for extended periods and high temperatures, which could alter the structure of the resulting fiber and alter its usefulness [91].

A critical step in the production of dietary fiber powder is drying. The most common way for producing dietary fiber powder is hot air drying, but it is well recognized that this drying technique significantly lowers product quality, especially in terms of its functional characteristics. Vacuum drying may therefore be an alternate method for creating high-quality dietary fiber powder. Water boils at a lower temperature

Table 5. The impact of different drying methods on dietary fiber.

Drying method	Main effect	Ref.
Sun drying	This technique effectively increases the amount of dietary fiber in the fruit or vegetable. The average nutritional content of dietary fiber in sun-dried guava was 21.86%, in hot air ovens, 24.39%, and in freeze-dried guava, 18.01%. This process might be an effective way to increase the amount of nutritional fiber in fruit or vegetables.	[93]
Hot air drying	Soluble dietary fiber's molecular weight dropped as a result of hot air drying. The moisture contents of the dietary fiber samples varied from 6.38 to 8.51 g/100 g. Hot air drying resulted in a drop in molecular weight and a decrease in the viscosity of the soluble fiber solutions.	[8]
Vacuum drying	Nonuniformity's local warming problem led to significant chlorophyll and vitamin C losses. The vacuum freeze-drying samples showed minor shrinkage (11.37) compared to microwave vacuum drying, and pulse-spouted microwave vacuum drying. In terms of product quality, vacuum drying kept the original qualities to the fullest extent possible, including color, flavor, form, and nutritional value.	[94]
Freeze drying	The physical and chemical properties and hypoglycemic effects were enhanced *in vitro* for dietary fibers, and their use in processing dietary fibers may improve their nutritional and commercial value. Freeze-drying significantly decreased the bulk density of the soluble and insoluble dietary fiber and increased the viscosity of soluble dietary fiber solutions (36.33 mPa s). The microstructure and bulk density of the dietary fibers were altered by freeze-drying, which might have an impact on their functional properties.	[8]
Microwave drying	The heating of the material and the alteration in the microstructure were significantly impacted by the microwave energy that was applied. Higher microwave power may deteriorate the product's color quality.	[95]
Spray drying	The optimized powder retained its nutritive and functional value and had more stability due to its low hygroscopicity and lower water content. Which means food products with better nutritional, functional, and sensory attributes.	[96]

when the absolute pressure is reduced, which accelerates the evaporation of moisture from a sample [92]. In the literature review, numerous food items with high fiber content have been dried using a variety of techniques (Table 5). On the other hand, moderate drying conditions with lower temperatures may result in a higher-quality final product while delaying the dehydration process and extending the processing period [97]. Liu, Fan, Tian, Yang, Liu, and Pan [8] investigated how various drying techniques affected the physical and chemical properties and *in vitro* hypoglycemic effects of soluble and insoluble dietary fiber. The physical and chemical properties and *in vitro* hypoglycemic impacts of dietary fibers from orange peel were shown to be significantly influenced by these techniques, the results suggested. As well the dietary fibers' functional characteristics may change after freeze-drying. By using various spray drying conditions, the inulin extract was turned into a powder by spray drying. The extraction and spray drying operations resulted in solids losses, which resulted in a relatively low yield of inulin powder. The commercial inulin powders had substantially bigger particle sizes than the inulin powders created by spray drying [98]. Chantaro, Devahastin, and Chiewchan [99] evaluated the synthesis of an antioxidant-rich, high-dietary fiber powder from carrot peels, and evaluated the impact of blanching and hot air drying (60–80 °C) on the physicochemical properties and drying kinetics of the dietary fiber powder. The results showed that blanching had a noticeable effect on the fiber quantities and compositions, water retention, and swelling capacities of the fiber powder. The drying temperature within the selected range, however, had little effect on the hydration values. When it comes to antioxidant activity, heat degradation during both blanching and drying led to a decrease in the amount of carotene and phenolic compounds, which in turn caused a decrease in the antioxidant activity of the finished product. Higher temperatures during drying caused nutritional loss, but there have not been many studies to establish how dietary fiber has changed. Fruits and vegetables were dried by freeze drying, hot air oven drying, and natural sun drying. According to the findings, dried pumpkin, yardlong beans, red cabbage, and guava all tended to contain more dietary fiber than other foods due to natural drying methods such as sun drying, hot air oven drying, and freeze drying. Tomatoes, on the other hand, showed increased contents in a hot air oven, freeze drying, and natural sun drying, respectively. The findings led to the conclusion that natural sun drying could be an effective way to increase the amount of nutritional fiber in fruits and vegetables [93]. In their study on the impact of air-drying temperature on the physicochemical characteristics of dietary fiber and the antioxidant capacity of orange (*Citrus aurantium v. Canoneta*) by-products, Garau, Simal, Rossello, and Femenia [100] hypothesized that dehydration promoted significant modifications affecting both the physicochemical characteristics of dietary fiber. The air-drying temperature (from 30 to 90 °C) utilized had a significant impact on the importance of these alterations. The primary changes in dietary fiber components were found when either extended drying times at lower temperatures or elevated drying temperatures were used. Dehydration at 50–60 °C appears to have aided in the modest breakdown of cell wall polymers. However, as the air-drying temperature climbed, the water retention capacity (WRC), FAC, and solubility values for both by-products decreased significantly. These investigations demonstrated that the physical and chemical characteristics of dietary fibers are significantly influenced by the various drying techniques.

5. Future remarks

In addition to being the oldest method of food preservation and the most popular commercial process, drying is cutting-edge hot technology. It is distinguished by its significance in relation to human health and global food security, as well as by the extent to which it contributes to minimizing food waste and the efficiency with which it preserves and sustains food. By fuzing the benefits of several drying technologies, an increasing number of drying and hybrid drying technologies have been developed to enhance the product's quality and dehydration efficiency. More advanced dryers have also been developed to address problems caused by older technologies. Even though drying food products has seen considerable advancements in recent years, there are still a number of problems that need to be fixed before these technologies can be made more effective and efficient. In addition to being effective and energy-saving, the drying technique used to dry food should also provide desirable product quality features, such as color, nutrition, taste, texture, and capacity for rehydration. The use of novel pretreatments prior to drying as alternatives to traditional pretreatments has proven advantageous for enhancing drying. These new technologies can address the drawbacks and shortcomings of some existing technologies, which improve drying efficiency and preserve the product's Techno-Functional and nutritional properties. With an increased dedication to future research, pretreatments before drying could become an effective and efficient solution for the drying industry to increase product quality and process efficiency.

Developing new dryers, modifying existing systems, reducing energy use, and streamlining processes can all be aided by sophisticated computer modeling and simulation tools. Food quality is another crucial factor while drying food goods, and it may be improved by utilizing the right models [101]. Fruits and vegetables drying kinetics and qualitative traits are greatly impacted by the drying temperature, air velocity, and material thickness. Automatic relative humidity (RH) management and adjustment have been researched based on the material's temperature. The effectiveness and quality of fruit and vegetable materials can be improved by the use of this RH control drying technique. In recent years, it has evolved into one of the modern approaches for the progress of drying technology [102]. RH during the hot-air impingement roast drying process has a big influence on production and product quality [103]. To improve drying efficiency and the quality of dried products, drying techniques can also be combined. For instance, various technologies can be integrated with freeze-drying technology, such as microwave-assisted freeze-drying (MFD), infrared radiation-assisted freeze-drying (IRFD), and other techniques. A high drying efficiency and superior quality of dried products may be obtained by using infrared-assisted hot air drying [104]. Pulsed vacuum drying [105] and pulse pressure osmotic dehydration assisted by hot air drying resulted in products of high quality [106]. Food and agricultural products must be pretreated before drying, which may offer chances to control sample dielectric properties and prevent quality degradation of final products. Numerous pretreatment techniques have been investigated in efforts to accelerate the drying process and enhance product quality [107, 108]. Other pretreatments, besides the addition of salt or sucrose, benefit the color, rehydration, and nutritional value of final goods after drying. These include osmotic dehydration, blanching, dipping ultrasonography, and pulsed electric fields. There will be a need for a lot more research in the future to examine different pretreatments that can offer desired physical and chemical changes as well as improve heat and mass transmission [7]. To meet the market demand for high-quality dried products, dried foods must maintain the nutritional and sensory qualities of the primary fresh ingredients at extremely high levels. As a result, combining the existing techniques with the initial pre-drying treatments will represent the best chance for an effective drying technology, to deliver desiccant products that are of the highest standard, environmentally friendly, and highly energy-efficient.

6. Conclusion

Drying and dehydration techniques have been continually evolving since ancient times, from the sun and convective air dryings to innovative drying techniques and their combinations (hybrid). Dried foods must meet the demands of modern consumers for fresh, healthful prepared foods that have a long shelf life and closely resemble the nutritional and esthetic qualities of fresh foods. These factors serve as the foundation for research on food industry quality traits and processing methods. This article provides a comprehensive review of the impact of drying on the nutritional and techno-functional properties of food macromolecules. The fundamental elements of various drying procedures, their most recent technologies, and their consequences on the techno-functional and nutritional properties of food are all highlighted in this work. Nowadays, the use of hybrid dryers, which enhance energy efficiency, process economics, and product quality, is encouraged and supported by researchers and individuals with an interest in the food sector. Therefore, researchers and scientists from other sectors can pool their expertise and efforts to merge two or more diverse drying methods in order to minimize the drawbacks of these methods individually while also maintaining the quality of dried products.

Author contribution statement

S.A.S. – Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Resources, Writing - Original Draft, Writing - Review and Editing, Visualization, Data Curation, Software, Project administration, Supervision. I.U. – Data Curation, Writing - Original Draft, Formal Analysis. S.J. – Writing - Original Draft, Formal Analysis. W.E. – Data Curation, Writing - Original Draft, Formal Analysis. A.A.R. – Validation, Writing - Review and Editing. A.K. – Writing - Review and Editing. O.S.T. – Conceptualization, Validation, Review, Supervision.

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