Discover Food

Review

Sustainable drying techniques for liquid foods and foam mat drying

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Abstract
Cutting-edge drying technologies represent a paradigm shift in the food industry, offering unique solutions to increase the efficiency, sustainability, and quality of the food drying process. The incorporation of vacuum freeze-drying, microwave drying, infrared drying, and other innovative processes has expanded the food processing sector's horizons. The development of hybrid drying systems that integrate several technologies produces synergistic benefits that improve overall performance. The advantages of novel drying methods include minimising heat exposure, increasing rehydration ratio, lowering bulk density and weight, and reducing the risk of microbial contaminations and oxidative damage to fruit juice powder to preserve its colour, texture, nutritional and bioactive component. The review discusses about the foam mat drying process, which can be utilised in microencapsulation and nano emulsion, while also addressing the problems related to agglomerations and nutritional property degradation in fruit juice powders.

Keywords Fruit juices · Foam-mat drying · Conventional drying · Foaming agents · Trending utilisation · Functional properties

1 Introduction

Fruits and vegetables are vital for human nutrition and are responsible for contributing to taste, variety, and vital nutrients to our diets [1]. Because of their numerous botanical origins, fruits and vegetables have a wide variety of forms, sizes, and flavours. They are also a great source of important vitamins, minerals, fibre, and antioxidants [2]. Due to their increased natural perishability, fruits and vegetables have a shorter shelf life depending on physiological, biological, and storage conditions that interfere with their nutritional value [3]. Most fruits, including mangos, papayas, apples, grapes, and so on, have higher water content, making them more susceptible to microbial attacks that cause deterioration [4].

Since ancient times, drying fruits and vegetables has been used to lower the percentage of accessible moisture and prevent microorganisms from growing and spoiling them. Recently, various novel drying processes have transformed food preservation by enhancing dried food product quality, shelf life, and energy efficiency [5]. Novel methods like freeze-drying and vacuum drying involve lower temperatures compared to traditional drying methods like sun drying or hot air drying which reduces heat-induced damage to the food's nutritional content and sensory attributes as well as helps to retain the essential nutrients in food, such as vitamins and antioxidants, by minimizing the exposure to high temperatures and oxygen, which can degrade these compounds [6, 7]. Novel drying methods like freeze drying,

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yield products that are easier to rehydrate, making them more convenient for consumers and retaining their taste and texture. These advanced drying technologies often use less energy due to reduced drying times and lower operating temperatures, contributing to sustainability and cost savings [8]. Overall, these innovative drying methods are essential in preserving food while maintaining its quality and nutritional value, making them highly valuable in the food industry and for consumers.

Foam-mat drying is a novel dehydration process used to produce powdered products from liquid solutions. Foam-mat drying assisted with various drying mode have been often used in industries nowadays for drying of fruit juice to make shelf stable powder for instant utilisation [9]. Drying factors including temperature and time, play a crucial role in determining the stability of fruit powder, affecting its quality, shelf life, and sensory attributes [10]. Balance between drying rate and temperature is essential to achieve a stable fruit powder. Slow drying at lower temperatures generally results in a more stable product in terms of flavor, color, nutrient content, and microbial stability [11]. However, the specific optimal conditions may vary depending on the type of fruit and the desired attributes of the fruit powder and careful control of these factors is crucial in the production of high-quality and stable fruit powders [12].

Previously, barberry (*Berberis vulgaris*) extract powder, date powder, kuini powder, pomegranate juice, saskatoon berry fruit juice powders were produced by foam-mat drying with various foaming agents [13–17]. The main carriers widely used includes maltodextrin, carboxymethyl cellulose, gelatin, whey proteins, glycerol compounds, gum arabic etc. Foam-mat drying involves creating a foam from the fruit juice by incorporating one or more of these foaming agents which is then spread onto a flat surface and subjected to controlled drying conditions to remove the moisture, leaving behind a dry product [18]. Although, each foaming agents act differently for different fruit juice and result in preventing the compounds from the effect of heat [16]. The choice of foaming agents can impact the quality and characteristics of the final dried product, so it is important to select the one that suit the specific requirement simultaneously temperature, drying time, foam thickness can affect the resultant powder [18]. Based on this the objective of this review is to discuss about the various cutting-edge drying technologies offering innovative solutions to enhance the efficiency, sustainability, and quality of the food drying process. The review analyses the selection of a particular technology and the impact of different drying technologies on the characteristics of the food product.

2 Conventional methods of drying and their limitations

Conventional methods of drying significantly reduce the water content from the fruit juices to obtain the dehydrated or powdered forms of fruits juices [19]. Each method has its advantages and limitations based on their applications.

2.1 Drum drying

In drum drying process, steam is applied to increase the internal surface temperature of drum. The substance adheres to the drums as it is sprayed on and dries within. The degree of separation between the drums, steam pressure, and drum rate of rotation can be modified to achieve the required output [20]. Drum drying particularly suited to produce the fruit juice concentrates, fruit leathers etc. It includes the advantages like efficient heat transfer and ability to process a wide range of fruit juices [21]. Besides, the process needs careful control of temperature and residence time to prevent overheating and maintain the quality of the final products [22]. Since there is no review of literature available on drying of fruit juices using drum drying. However, it has been used for producing powder from the fruit's peels, pulp, puree etc. [23]. Although, fruits concentrated and powder can be prepared by the drum drying method but due to various factors including heat sensitivity of fruits, mechanical degradation of fruits quality, substantial high cost of energy consumption, maintenance of equipment, limited product range, large space, initial capital cost and environmental concern the drum drying is not preferred to be used on an industrial level [24]. Tonin and co-workers utilised the drum drying process along with addition of various foaming agents like corn starch, maltodextrin and glyceryl monostearates at various concentration to produce mango pulp powder [25]. It was further reported that there was retention of vitamin C (61.0 ± 0.7%) with greater mass flow rate (8.0 ± 0.2 kg/h m^2) at a glass transition temperature of 29–38 °C. Similarly, Prangpru studied the effect of maltodextrin and modified starch on the quality characteristics of tamarind powder. They reported that increase of powder recovery by 80% along with reduction in moisture content and bulk density when 60% modified starch and 40% maltodextrin are taken together [26].

2.2 Cabinet drying

Cabinet drying or sometimes called as tray drying is drying method where a product is spread out on trays or shelves and subjected to controlled heat and air flow to remove moisture [27]. Tray drying is more gentle drying methods to produce the fruit juice powder due to its suitability with heat sensitive fruit juices [28]. Besides, it mostly takes longer drying time compared to some other methods like spray drying, drum drying, hot air oven drying etc. and the quality of the final product is highly dependent on control of the drying conditions [29]. Furthermore, Batch processing, uneven drying, quality loss, higher space requirement for equipment installation, limited application limited the use of tray drying [24]. However, tray drying remains a useful method for drying various products like fruits, vegetables, and higher viscous juices concentrates. It could be more effective if managed appropriately and often used to produced dried fruits and powder in food industries [28]. Khamjae and Rojanakorn utilised cabinet dryer for foam mat drying of passion fruit arils with addition of methylcellulose at 0.75, 1.5, 2.25 and 3% concentration at 60, 70 and 80 °C [30]. They observed increase in moisture infusibility with increase in temperature. Foam thickness of 1 mm shows the highest retention of ascorbic acid and Β-carotene along with highest antioxidant activity. Similarly, Sansomchai and co-workers studied the effect of glyceryl monostearates, sugar and soybean isolate in foam mat drying of mango. They reported 1% GM with 5% sugar as the optimised concentration during storage at 90% RH and 38 °C temperature. They found that powder produced using cabinet drying has less solubility and hygroscopicity and recommend being utilised in small enterprises due to low operational and maintenance cost [31].

2.3 Hot air oven drying

Hot air oven drying is the common method used for producing fruit juice powder, dried fruits to be used in food manufacturing, baking, or as ingredients in various products [32]. It is believed to be successful process in retaining the quality and flavour of the fruit juice while efficiently remove moisture. Hot air oven drying overcome various limitations of cabinet drying including gentle drying, controlled temperature, uniform heating, quality preservation, energy efficient and maintains versatility of wide range of fruits and vegetables juices. However, this drying process can be relatively slow, especially for the materials with high moisture content, it takes considerable amount of time [33]. Hot air oven drying process can be energy intensive for large scale drying processes and can lead to higher operational cost [34]. This method typically used for a batch processing that leads to the limited production capacity and might not be suitable for continuous and high-volume production. Cakmak and Ozyurt utilised carrot juices for preparation of foam mate dried powders. Addition of egg albumin and whey protein isolates at various concentration result in improvement of wettability, hygroscopicity, degree of caking along with antioxidant and phenolic contents due to encapsulation of carriers around the powder molecules [35]. Similarly, Tran and team utilised gum arabic and maltodextrin in 50:50 w/w to produced mango puree powder using hot air oven. The powder obtained at 55 °C has highest retention of TPC (21.24 ± 1.58 mg GAE/g) and TFC (0.34 ± 0.02 mg QE/g) with the highest solubility of 64.35% [35].

2.4 Air drying

Air drying is the traditional and simple method used primarily for producing dried fruits but also effective in drying of fruit juice in powdered form [37]. Air drying of fruit juice powder is a method of removing of moisture from the fruit juice to produce it in powdered form [38]. This process offers several benefits such as reduced volume and weight, easier handling, and transportation. Air drying is an important step in production of fruit juice powder allowing for easier storage, and consumption of fruit juice in powder from [39]. However, air drying cannot be acquired on an industrial level due slower drying compared to other drying methods due to prolong times to achieve the desired level of moisture content [40]. The effectiveness of air drying is highly dependent on weather conditions as rainy and high humid conditions hinder the drying process [41]. Moreover, slower drying time can lead to high risk of microbial growth, contamination, and spoilage if environment is not properly controlled [42]. Beşe and Polatoğlu studied the sun drying behaviour of cornelian cherry fruits. The results showed that the ascorbic acid content was degraded to about 51.1% [43]. Similarly, Osunde and Makama studied changes in the nutritional values of various vegetables, where β-carotene content of tomato, okra and sweet pepper were reduced by 80, 50 and 65% [44].

2.5 Vacuum drying

Vacuum drying is a valuable method for producing high-quality dried fruit concentrates and powder, while preserving the original flavour and nutritional content of the juice [45]. Vacuum drying generally at a low temperature compared to most of the drying methods and helps in preservation of natural flavour, color, and nutritional content [11]. Vacuum drying takes place at reduced pressure conditions that result in lowering of boiling point of the water and facilitates the evaporation of water from juice at a lower temperature, preventing heat damage to the produced powder [46]. Vacuum drying has several advantages upon air drying such as controlled environment condition that reduce the risk of contamination and spoilage from microbes and reduced oxygen content in the vacuum chamber which helps in minimising the oxidation of the fruit juice and retain the freshness and color in resultant powder [47]. Despite all these characteristics, there are several reasons that result in limited used of vacuum drying at an industrial scale including high equipment's cost, complexity in terms of temperature and pressure for different fruit juice, larger space requirement, higher energy consumption, maintenance, highly labour intensive for product handling etc. [48]. Islam and team used orange fruit juice to produced powder using carriers at 40-50ºC temperature with 5 kPa of pressure. Various parameters including moisture content, hygroscopicity, water activity, particle size, color, rehydration ratio and retention ascorbic acid content were affected by addition of maltodextrin [49]. Kim and Kerr studied the physical and quality properties of blueberry powder using vacuum drying. Addition of maltodextrin improved the flowability of the powder by 93%. Higher content of maltodextrin results in less monomeric anthocyanin content at 80 °C. Additionally, the stickiness of the powder reduced with increase in carriers [50].

2.6 Spray drying

Spray drying is a most common and versatile method used for drying fruit juice and other liquid products [51]. It is most popular method of producing juice powder in the food industries due to its high efficiency, produce quality, shelf stability with preserved flavour and color [52]. The main characteristics of spray drying includes its rapid drying capabilities that make it suitable for larger scale production, particle size control of dried powder based on specific requirements, short exposer to heat, longer shelf life and its versatility to various fruit-based products including instant beverages, flavouring and ingredients in the food industry [53]. Overall, spray drying is a popular and most used method in food industries for creating products like fruit juice powder due to its higher efficient product quality [19]. However, the equipment for spray drying is costly to acquire and maintain along with higher energy consumption to heat the drying air and to operate atomization equipment [54]. Recently, González and team used spray drying to produce grapefruit and studied the storage stability using various parameters. The total phenolics was found to be most stable while lycopene be unstable at 20 °C. The loss of 32 and 90% were observed for phenolics and lycopene respectively but maintained color and flowability [55]. Similarly, Qadri and team used spray drying to produce apple juice powder. They used apple juice concentrates to produce the spray dried apple powder and studied the changes in the physicochemical and nutritional properties [56]. The moisture content was reduced to 2.91%, water activity by 0.217 but the fiber content increased by 0.07%, carbohydrates content by 95.28% and total soluble solids by 95.78^{0}B. Overall, they concluded formation of concentrated before spray drying as the excellent raw material.

2.7 Freeze drying

Freeze drying or lyophilization is a drying process used to remove moisture from fruit juice for production of powder while preserving their structure, flavour and nutritional and bioactive content by the process of sublimation [57]. This method is convenience for industrial application. There are several benefits of using freeze drying upon other drying techniques includes quality preservation, higher shelf stability, better rehydration capacity, low bulk density and less chances of microbial contaminations [58]. However, equipment and processing cost, time, energy consumption, equipment complexity etc. are some of the barriers and limit the use of freeze drying at small industrial level [59]. Recently, Seerangurayar and co-workers utilised freeze drying to produce date powder using maltodextrin and gum arabicas a foaming agent [60]. The powder produced with gum arabic shows relatively more flowability and less cohesivity. The powder produced with gum arabic has less moisture, bulk density, particle density, Carr index and particle size. They further concluded that the powder produced with 50% carriers have improved the flowability of the powder. Similarly, the techno functional and physicochemical properties of freeze-dried pomegranate juice was studied. Maltodextrin and gum arabic are used as a foaming agent. They noticed the 6% more yield, 0.4% more solubility and 2.5% less hygroscopicity with maltodextrin as compared to gum arabic [61]. Further they concluded that freeze drying can be used for foam mat drying of pomegranate juice but it causes higher processing cost.

3 Novel methods of drying and advantages

Conventional drying methods lacks one or more qualitative and/or quantitative characteristics in term of improved quality preservations, reduced processing time, energy efficiency, control and customized process, product innovation, space and equipment requirements, safety, yields, environmental impact, scale up potential, overall product characteristics etc. making food industries to move toward the novel drying techniques which overcome all the deficient parameters (Fig. 1) of conventional drying techniques [34].

3.1 Spray freeze drying

Spray freeze drying is an innovative and advanced drying method used to preserve the characteristics and quality of various materials including fruit juice powder, pharmaceuticals, and biomaterials [62]. This process combines the elements of spray drying and freeze drying to achieve rapid drying while maintaining the integrity of the dried materials [63]. Spray-freeze drying posse's various advantages over conventional methods of drying such as rapid freezing of spay dried powder, minimising heat exposure, higher rehydration ratio, low bulk density and light weight making suitable for storage and transportation along with reducing risk of microbial contaminations and any oxidative damage to fruit juice powder to preserve its color, texture, nutritional and bioactive components [62]. Padma and Anandharamakrishnan studied the effect of spray-freeze-drying approach for soluble coffee processing and its effect on quality characteristics and observed the more solubility as well as good flowing properties as compared with individual methods. Spray-freeze

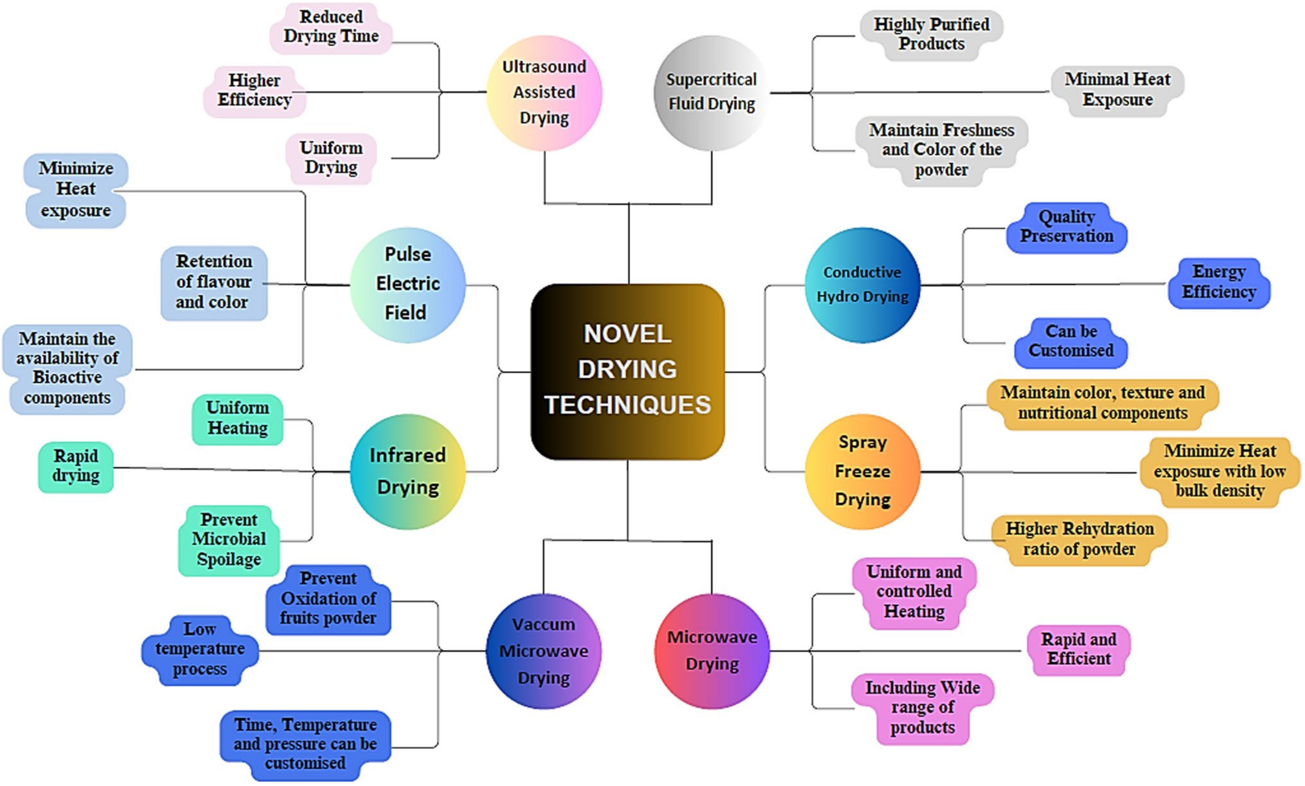

Fig. 1 Advantages of using novel drying methods in production of powder

drying results in volatile retention of 93% as compared to individual freeze drying (77%) and spray drying (57%). Moreover, the particle size, tapped and bulk density was improved by these techniques [64].

3.2 Pulse electric field (PEF) drying

Pulse electric field (PEF) drying of fruit juice is considered as innovative and novel drying techniques which includes the combination of PEF technology with drying process [65]. As the electric pulse are exposed to the fruit juice, the pules cause the cell membrane in the juice to become permeable and allow the intercellular water to move out freely which is than dried mainly using spray or freeze drying [57]. The application of PEF drying techniques helps in retention of flavour, color, nutritional and bioactive components of fruit juices by minimising the heat exposure during drying process. It accelerates the drying process by increasing the mobility of intercellular water, which can significantly reduce drying time [66]. Mechanical properties of fruit and vegetables were studied after PEF pretreatment and observed the distinguishable effects [67]. The viscosity coefficient decreased by 94% and retarded elastic modules by 92% after treatments and recommended PEF as the novel drying techniques. Similarly, Yu and team utilised PEF before vacuum drying of blueberry. The fruit treated with PEF significantly reduced the drying time from 35 to 40% and showed observable effects on retention of nutritive values [66].

3.3 Microwave drying

Microwave drying is novel techniques of drying that uses the microwave energy to remove moisture from the fruit juice while preserving its quality and characteristics [68]. When the fruit juice is exposed to a microwave, the electromagnetic waves penetrate the juice and produce heat within the juice result in vaporisation of water and leaving behind the dried fruit juice powder [69]. Microwave drying is known for its rapid and efficient drying, making it suitable for higher speed production of fruit juice powder [70]. Microwaves provide uniform and controlled heating result in even drying of entire product. In microwave drying the product is heated directly which reduce the need of any external heating source thus making drying process more energy efficient [34]. Besides, microwave drying allows for precise control of the drying process, including time and temperature that can be adjusted to meet specific product requirements [71]. Zielinska and team studied the effect of microwave drying on the drying kinetics of blueberry fruit. They noticed the comparable changes in phenolic and antioxidant activity at 90 °C with significant decrease in drying process from 70 to 95%. They further recommended microwave drying due to short time and improved product quality [72]. Similarly, Qadri and Srivastava (2017) studied the foam mat drying of guava pulp assisted by microwave heating. They reported reduction in the drying time with decrease in foam thickness [73]. They concluded 8% egg albumin as the optimised concentration which retain the color and ascorbic acid as 3.623 and 154.762 mg/100 g respectively and recommended to be used on the industrial level.

3.4 Infrared drying

Infrared drying is valuable method of producing higher quality fruit juice powder, that use infrared radiation to remove moisture from fruit juice [74]. The mechanism of infrared and microwave drying is similar. In infrared also the juice is exposed to electromagnetic radiation that result in generation of heat when encounters water which leads to evaporation of water and powder is obtained [75]. Infrared possess several advantages including uniform heating, energy efficiency, rapid drying, quality preservation, customisation, and prevention from microbial spoilage [76]. In another study, the effects of infrared on the drying kinetics of strawberry fruit was studied. As the infrared powder increased, the reduction in the drying time has been noticed [77]. They suggested 300 W, 60 °C 1.0 m/s as the best conditions to retain the total phenol and anthocyanin content but it leads to increase in N, P and K levels. The optimum condition suggest were 200 W, 100 °C and 1.5 m/s air velocity.

3.5 Vacuum microwave drying

Vacuum microwave drying is an advanced drying technique that combine microwave heating with reduced pressure to remove moisture from the fruit juice while preserving the overall quality of the powder [78]. This process is utilised in food processing industries along with pharmaceuticals and material sciences. Vacuum microwave drying is preferred over microwave drying when the quality of heat sensitivity and oxidation of fruit juice powder needs to preserve. Vacuum microwave drying also provides the customisation of time, temperature, and pressure adjustments [79]. In a research study, the effect of microwave vacuum drying on the quality of cranberries was observed [72]. They observed the retention of polyphenolic and antioxidant activity of vacuum microwave dried cranberries and recommended low microwave powder of 100 W to produce higher quality powder. Similarly, [80] studied the effect of microwave assisted vacuum drying on the quality attributes of dehydrated strawberries. The anthocyanin, flavonoid, phenolics and antioxidant activity gradually improved as compared to control. Moreover, the sensory attributes range between 3.5 and 4.3 on five-point hedonic scales. They concluded that fruit obtained with microwave vacuum drying can be stored for 68 days with least changes.

3.6 Conductive hydro-drying

A cutting-edge and innovative drying technique called Conductive Hydro-drying (CHD) transfers heat directly from a heated surface to the fruits. The fruits accumulate heat, which raises the inside temperature and stimulates the evaporation of moisture [81]. In CHD drying the fruit juice is uniformly spread on the heat resistance, transparent plastic conveyor belt and exposed to an infrared radiation of specific wavelength that result in efficient penetration and heating of the fruit without overheating and damaging the product [81]. Continuous heating result in vaporisation of the water and dried powder is obtained. Key characteristics of the powder obtained from CHD methods includes quality preservation, energy efficiency, reduced oxidation, customisation, and hygienic process [82]. Asiimwe and team optimised the CHD to study drying kinetics of passion fruit puree [83]. They studied retention of vitamin C, B-carotene, antioxidant activity and total phenol content by 90.2, 75.9, 89.7 and 88.3% respectively. Similarly, effect of CHD on strawberry puree was studied [84]. Total phenolic content was reduced by 20% as compared to fresh fruits. Similarly, the color become darker compared to fresh puree. They recommended the CHD to be used in order to reduce the production cost at commercial level.

3.7 Supercritical fluid drying

Supercritical fluid drying is also considered as novel drying technique of producing fruit juice powder. It is used in various applications, including the production of powdered fruit juice for instant beverages, food manufacturing, and dietary supplements [85]. In this process the CO_2 is mostly used as supercritical fluid which under specific pressure and temperature shows the properties of both liquid and gas. The fruit juice is homogeneously mixed with the supercritical CO_2 result in penetration into juice molecules and remove the moisture effectively [86]. Further the temperature and pressure are adjusted to initiate the expansion of supercritical fluid that leads to precipitation of the juice compounds and separation of CO_2 from the dried juice powder [87]. This process is conductive to producing high purity products as CO_2 is nontoxic in nature. Minimal heat exposure minimizes the oxidation, helping in maintenance of freshness and color of the powder [88]. Vetralla and co-workers utilised CO_2 for supercritical drying of apple pieces [89]. They concluded less shrinkage in the apple pieces and reduction in weight by 18% on first 120 min of treatments and confirmed the potential of supercritical drying of apple slices for short drying time. Similarly, this process was utilised to indicate the effects on strawberry drying [90]. The total retention was observed of total anthocyanin and total flavonoids by 95 and 76% respectively. Overall, this method is recommended to be used for producing healthy and safe dried fruits.

3.8 Infrared freeze drying

A specialised technique called infrared freeze drying (IFD) uses infrared (IR) radiation in addition to the principles of freeze drying to improve the drying process. Using infrared radiation, the material is gradually heated during the drying process in infrared freeze drying. Compared to traditional heating techniques, infrared radiation may be targeted with more precision, which might faster the sublimation process. The emitters or lamps that are placed within or around the drying chamber are usually the source of the infrared radiation. The goal of combining infrared heating with freeze drying is to shorten the total drying time and increase heat transfer efficiency while keeping the low temperatures required to prevent deterioration. Mid infrared freeze drying was compared with single stage freeze drying on the quality characteristics of pear [91]. They reported the reduction in drying time by 30%, better color preservations, 25% less hardness value resulting in better texture retention in IFR. Furthermore, vitamin C retention increase to 60–80 mg/100 g in IFD compared to 40–60 mg to 100 g in single freeze drying and concluded the use of IFD for more efficient and higher product quality. Similarly, the purpose of the study of Antal (2023) is to determine the way the physical qualities and drying characteristics of sweet potato slices are affected by two-stage techniques of hot air and freeze drying (HA-FD) and two-stage infrared and freeze drying (IR-FD). When compared to FD and HA-FD, they found that IR-FD had superior physical qualities, such as texture and colour, and being the most energy-efficient due to shorter drying durations and more efficient heat transmission. In comparison to FD (50–70 mg/100 g) and HA-FD (60–80 mg/100 g), IR-FD held the greatest amounts of vitamin C (70–90 mg/100 g), suggesting superior nutritional content retention. He concluded that the comparison highlights the benefits of employing two-stage drying techniques, especially those that include infrared assistance, for maximising the drying process and end product quality.

4 Roles of foaming agents in drying of fruit juices

Foaming agents plays a crucial and specific role in drying of fruit juices. The main objective of foaming agents is to convert liquid into froth or foam, which is efficient and easier to dry [92]. Commonly used foaming agents in the drying of fruit juices includes proteins like whey, albumin etc. and polysaccharides like maltodextrin, CMC etc. These agents are selected based on the specific requirements of drying methods and desired propertied of the dried fruit juice products [93]. When the foaming agents are added into the fruit juices, the stable foams are formed after whipping. The foaming agents reduce the surface tension and enhance the ability of the juice to trap and stabilise air or gas bubbles [94]. The resultant foam significantly increases surface area of the juice (Fig. 2). Due to increase in surface area the foam exposed in drying medium, the moisture within the foam can evaporates more rapidly thus reduce the drying time [95]. Foaming agents helps in maintaining the quality of the dried powder by reducing the exposure of heat and minimising thermal degradation of sensitive compounds such as flavour, color, ascorbic acid, bioactive compounds etc. [96]. Particle size can be enhance using foam mat drying of the fruit juices. Foaming agents prevents the caking or clumping of the dried fruit juice powder result in higher flowable properties and handling [97]. Different foaming agents have various properties and act differently with various drying process, that can be customised based on the required powder [98]. Overall, foaming agents are essential in process like spray drying, hot air oven drying etc. to convert liquid fruit juice to foam, to improve the drying efficiency while maintaining the powder quality [95].

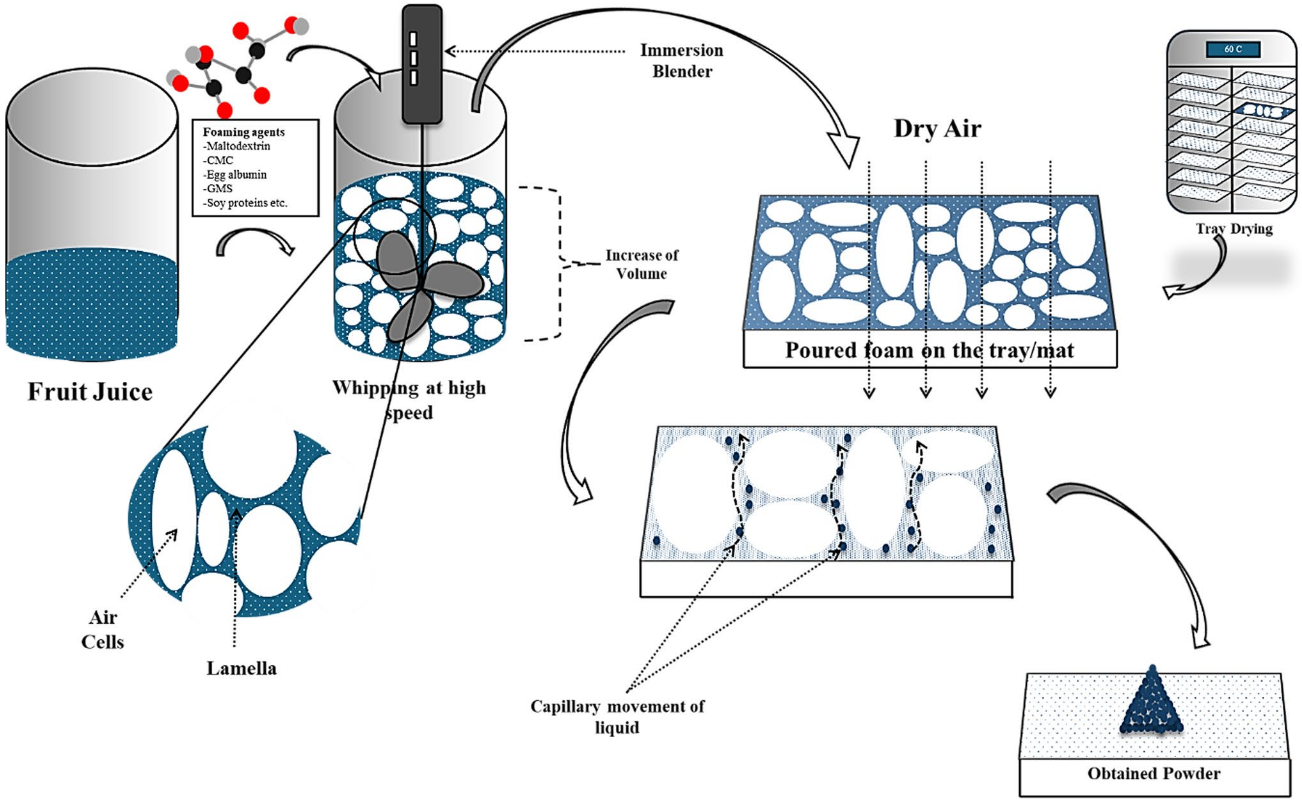

Fig. 2 Mechanism of foam mat drying of fruit juices with foaming agents

4.1 Maltodextrin

Fruit juices are dried using maltodextrin, a kind of polysaccharide composed of starch, which is extensively utilised in the food and beverage industry [99]. Maltodextrin acts as an emulsifier and carriers, making it easier to convert liquid substances into powdered forms [100]. Maltodextrin facilitates absorption and encasing the liquid components of fruit juices during the drying process, facilitating the creation of a powdered substance. Its role is vital in maintaining the fresh juice's flavour, colour, aroma and overall sensory qualities [101]. Maltodextrin further assists to maintain the juice in powder form from sticking and boosts its flow qualities [102]. Thus, ensuring easy handling and reconstitution. Furthermore, Maltodextrin enhances the solubility of the powdered product in water by forming an enduring matrix around the juice particles [99].

4.2 Carboxy methyl cellulose (CMC)

A widely used cellulose derivative in the food industry for its thickening, stabilizing, and emulsifying properties is carboxymethyl cellulose [103]. CMC is beneficial especially when it is used for drying fruit juices as it boosts the overall standard of the finished powder [104]. CMC thickens fruit liquids during the drying process, resulting in the development of a gel-like substance that makes handling and processing smoother [105]. By improving the juice's viscosity, it keeps the mixture homogeneous and prevents the separation of phases. This is especially crucial for spray drying, as the liquid splits into tiny droplets that dissolve rapidly [106]. Furthermore, by preventing solids from settling and preserving a consistent particle distribution, CMC serves to maintain the juice. Besides, CMC contributes to the formation of fruit juice powder with enhanced reconstitution and solubility properties. Especially beneficial in avoiding caking or clumping of the powdered juice during storage due to stabilizing effect of CMC [107].

4.3 Egg albumin

Fruit liquids can be dried using egg albumin, a protein present in egg whites, which is occasionally utilised in the food industry [108]. During spray drying, it plays an essential role, by engulfing the juice droplets in a protective coating. In order to stop the volatile ingredients in the fruit juice from degrading throughout the drying process, this layer aids in protecting and preserving them [109]. Egg albumin is used in the process of drying fruit juices as a component of encapsulation technology, which preserves biologically active substances that are susceptible to heat [110]. The protein surrounds the juice particles, serving as a shield against light, air, and other elements that can cause degradation in quality. The fruit juice's flavour, colour, and nutritional value are all preserved due to the technique of encapsulation [111]. Furthermore, throughout the drying process, the production of a homogeneous powder is facilitated by the capacity of egg albumin to form a stable emulsion. This is especially crucial if you want to make consistent, high-quality powdered fruit juice products [112].

4.4 Glycerol monostearates

Fruit juices can be dried using glycerol monostearate (GMS), an emulsifier and food ingredient that is frequently utilised in the food industry [113]. GMS acts as an emulsifier to enhance the final powdered fruit juice product's stability and smoothness. Glycerol monostearate contributes in the dispersion of fat-soluble components in the juice, which is one of its purposes throughout the drying process [114]. GMS assists in preventing the separation of the water- and oil-based phases during drying by producing stable emulsions. This improves the powdered product's overall homogeneity [115]. Glycerol monostearate additionally assists with the fruit juice powder's reconstitution. Its emulsifying qualities facilitate the powder's dissolution in water, promoting a steady and easy rehydration process [116]. This is essential to maintain the reconstituted juice's sensory attributes and commercial attractiveness. The objective of producing stable, superior powdered food products that satisfy both functional and sensory requirements is in line with the application of GMS in drying procedures [104].

4.5 Gum arabic

Acacia gum, or gum arabic, is a naturally occurring material obtained from the drip of Acacia plants. Because of its emulsifying and stabilising qualities, it is frequently used in the food industry and is beneficial for drying fruit juices [117]. Gum arabic functions as a hydrocolloid when it comes to drying fruit juice, producing a protective colloidal layer surrounding the juice particles. This coating ensures the development of a fine and consistent powder by inhibiting the accumulation of particles during the drying process [118]. Emulsifying qualities of Gum Arabic helps to keep the juice's constituent parts stable by retaining their flavour, colour, and nutritional value [119]. Moreover, gum arabic improves the fruit juice powder's solubility. When the powder is reconstituted, its water-soluble nature facilitates its rapid and thorough dispersion, producing a desired sensory outcome [116]. Beyond its technical uses, gum arabic is preferred as a natural, plant-based component in the food business. This is in line with the growing demand from consumers for natural and clean-label food items [118].

4.6 Soy proteins

Fruit juices can benefit from the use of soy protein, which is made from soybeans and is frequently used in the food sector for a variety of purposes, including drying [120]. Soy protein is a flexible component that works well as an encapsulating agent when drying. Soy protein contributes to the formation of a protective coating around the fruit juice particles during the drying process [121]. During the drying process, this encapsulation protects the fruit juice's delicate components from outside influences like light and air, maintaining the juice's flavour and nutritional value [122]. Furthermore, soy protein helps to create a stable emulsion that facilitates the juice's fat-soluble ingredients spreading. The ability to emulsify helps to create a more uniform and stable powdered product by avoiding the separation of water- and oil-based phases during the process of drying [123].

4.7 Whey protein isolates

As a byproduct of the production of cheese, whey protein isolates (WPI) are essential for many culinary applications, such as drying fruit juices. Whey protein isolates are frequently used as encapsulating agents in fruit juice drying [124]. Whey protein isolates play a crucial part in this process by surrounding each juice droplet in a protective layer that is applied via spray drying or other drying techniques. This coating protects the fruit juice's flavour, colour, and nutritional elements by acting as a barrier against outside elements including light, moisture, and oxygen [125]. The capacity of WPI to create a stable emulsion is very useful during the drying process. By avoiding particle agglomeration during drying, it contributes to the creation of a homogeneous, fine powder. This enhances the overall quality and solubility of powdered fruit juice [109]. Furthermore, the requirement for food items that are functional and enhanced with protein is fulfilled using whey protein isolates in fruit juice drying. Whey protein isolates are a good source of protein with well-defined amino acid profiles, therefore adding them to a product can improve its nutritional value. In conclusion, whey protein isolates have two functions in fruit juice drying: they offer a barrier to maintain the qualities of the juice and enhance the standard and nutritional value of the powdered product [126].

5 Effects of various foaming agents on the characteristics of dried fruit juices powder

There are various studies available on application and effects of different foaming agents (individually or in combinations) to retain the overall quality of the dried fruits powders. Maltodextrin, gum arabic, glycerol monostearates, CMC are the most abundant foaming agents utilised as the encapsulation of fruits juice molecules. Recently, Khatri and co-workers investigated the effect of MD, CMC and GMS as foaming agents on the quality and stability of black mulberry juice powder produced through foam mat drying [127]. They optimized the type and concentration of foaming agents to enhance foam stability, drying efficiency, and final product quality. The findings reveal that 5 g/100 ml of CMC significantly improved the retention of nutritional compounds, such as anthocyanins, and sensory attributes, including color and flavor. The optimized conditions resulted in a shelf-stable product with enhanced quality, demonstrating the critical role of foaming agents in the foam mat drying process. In another study, the effect of composition of foam on the quality of pomelo juice was studied [94]. They have taken MD, CMC and GMS as foaming agents and concluded the 6.027% MD can be used as an optimised concentration for the foam mat drying of pomelo fruits with good, reconstituted properties and rich in vitamin C content. They further suggest being utilised in bakery, ice cream and yogurt manufacturing. While Araujo and team (2023) used maltodextrin and gum arabic for production of sapota fruit juice powder [128]. Further, they found that gum arabic (30%) showing the best results with highest retention of antioxidant activity. Similarly, Zakiyah and Budiandari used maltodextrin (15, 20, 25%) to study the stability and vitamin C content of the cucumber powder drink obtained using foam mat drying [129]. They concluded nil effect on Vitamin C content but observative effects on its stability. Besides, they observed highest vitamin C and solubility as 1.287 and 147.16% respectively. Moreover, Leyva-Porras and co-workers (2021) utilised maltodextrin (5–10%) on the phenolic properties of spray dried strawberry juice [130]. They found that as the temperature and concentration of MD increases, the phenolic content of the dried powder decreased. Similarly, the antioxidant activity of the dried powder was decreased as the concentration increased. The optimum conditions were observed as 5% MD at 185 °C of inlet temperature in terms of microencapsulation of TPC and antioxidant activity. Moreover, Igual and team (2021) used resistant maltodextrin (RMD) on the physiochemical properties and powder functionality of spray dried orange juice powder [131]. They considered parameters including water content, hygroscopicity, bulk density, porosity, solubility, water absorption index, color and microstructures. Further they observed the more porous and less hygroscopic powder with low water content. They recommended the addition of 5% RMD to observed satisfactory results. While Lachowicz and team (2020) studied the effects of insulin and maltodextrin (MD) on the preservation of antioxidants in the berry fruit and powders obtained using vacuum and freeze drying [132]. They concluded that powder obtained by freeze drying with addition of 30% MD showed the highest retention and observed anthocyanin, phenolic acids and antioxidant activity and recommended to be used on commercial levels. Similarly, In another study, the concentration of maltodextrin and temperature was optimized to produce highly efficient combination to encapsulates noni fruit powder using foam mat drying method [133]. Further they concluded that the powder obtained using 20% (w/w) maltodextrin at 85 °C shows the highest retention rate of antioxidant activity, yield. Rohilla and Mahanta utilised egg albumin (ALB), whey protein concentrates (WPC), soy protein concentrates (SPC) and gelatin (GEL) on the drying kinetics and physicochemical properties of foam mat dried tamarillo powder with a concentration of 5 and 10% [134]. They further concluded that SPC and WPC at 10% concentration are most effective in retention of phytochemicals and foaming behaviours along with highest beta-carotene recovered. Similarly, the effects of addition of egg albumin in foam mat drying of banana juice using cabinet dryers at 60–80 °C was studied [135]. Further they concluded that the composition of different varieties of banana impact the solubility and moisture content of the banana powder. Furthermore, the foaming properties, drying kinetics and physicochemical characteristics of foam mate dried cantaloupe using gum arabic (5, 10 and 15%) as foaming agent, were studied [136]. Besides, they observed the best results for foam stability, foam density and foam density at 10% GA. The powder obtained at 15% GA shows good powder flowability and low cohesiveness. Furthermore, they utilized the obtained powder (15% GA) in the formation of higher antioxidant cake icing. Moreover, various other foaming agents with various parameters are showed in Table 1 and their effects on physicochemical and functional characteristics are shown in Table 2.

6 Application of dried fruits powder

Foam mat dried fruit juice powders are utilizing in the bakery industry on the larger scales as flavour enhancements and natural colouring materials in cake batters, muffin mix, cookies etc. [136]. Besides, incorporation of these powders boosts the nutritional content in baked foods in terms of vitamins, minerals and various secondary metabolites including bioactive compounds [137]. Moreover, fruit powders are utilized as a filling and frosting by blending with creams, icing and filling into pies and pastries [138]. Similarly, industries are utilising foam mat dried powder in beverage and dairy products as instant fruit flavoured beverages, flavoured yogurt and ice cream etc. [139]. Apart from food industries, fruit powder is utilised in cosmetic industries utilising fruit powders in the products like face masks or skin care formulations for its natural fragrance and potential skincare benefits [140]. Various fruit powders are utilised in formation of number of functional foods, that are mentioned in Table 3.

7 Future prospective of foam-mat drying

From a scientific standpoint, the future of foam mat drying for fruit juices appears promising due to anticipated advancements in technology and sustainability. Enhanced foam stability and more efficient drying equipment are expected to improve the drying process and product quality. Research suggests that advancements in foam formulation and drying technology can optimize the retention of bioactive compounds, such as vitamins and antioxidants, thereby preserving nutritional value more effectively [141]. The integration of automation and smart technologies is likely to enhance process control, reduce variability, and minimize waste [142]. Additionally, the development of energy-efficient drying methods aligns with sustainability goals, reducing the environmental impact of the process. The versatility of foam mat drying may also lead to novel applications and product formats, meeting evolving consumer demands and contributing to the creation of diverse, functional food products [143, 144]

Table 1 Application of foaming agents in Spray and freeze foam-mat drying of various fruit juices

Types of fruit	Foaming agents used	Concentration	Drying method	Temperature/time	Pressure	Flow rate	Reference
Bottle gourd	MD, WPI and SPI	5–15%	Spray drying	170 °C (inlet)	0.05 MPs (air)	5 mL/min	[145]
Apple	MD and GA	0–20%	Spray drying	160 °C (inlet)	–	350 rpm (feed flow rate)	[56]
Grapefruit	GA and CMC	8–14.7 g/100 g GA and 0–2.7 g/100 g	Spray drying	Below 50 °C (inlet)	–	Aspiration 35 m^3/h; air flow rate 473 L/h	[55]
Barberry	GM and MD	75:25 (MD:GM)	Spray drying	160–180 °C (inlet)	–	50 m^3/h	[146]
Orange	MD	40, 50, 60, 70%	Vacuum spray drying	40–50 °C in vacuum and 160 °C in spray	5 kPa	300 ml/h	[49]
Date	GM and MD	10–50%	Freeze drying	−40 °C for 72 h	42 Pa	–	[60]
Red Beetroot and Quince	MD	0%–10%–20%–30% MD	Hot sir oven (HAO) and freeze drying (FD) separately	60 °C (HAO) and −65 °C (FD) for 24 h	190 mtorr (FD)	1.5 m/s air velocity	[147]
Carrot	EA and WPI	15% EA + 10% WPI	Hot air oven	60 °C	–	–	[36]
Tropical red fruit (Acerola + guava + pitanga)	EA,GA, GG and gelatin	6% EA with 1% GA, GG and Gelatin	Hot air oven	50–80 °C	–	–	[148]
MANGO	GMS, SBI	1% GMS + 5% sugar +	Tray dryer	70 °C for 5 h	–	–	[31]
Mango	GA and MD	15% of (GA:MD 50:50 w/w)	Hot air oven	55 °C	–	–	[35]
BEET ROOT	OB, CMC and MD	3% OB + 1% CMC + 8% MD	Cabinet dryer	50–70 °C	–	–	[149]

* *SPI* soy protein isolates, *OB* Ovalbumin, *GA* Gum Arabic, *MD* Maltodextrin, *CMC* carboxy methyl cellulose, *SBI* Soybean isolates, *GMS* Glycerol monostearates, *EA* egg albumen, *GG* guar gum, *WPI* whey protein isolates

Table 2 Effects of carriers on the physical and functional properties of dried fruit juice powder

Type of fruit	Optimised concentration of carriers	Moisture content	Bulk density	Water activity	Solubility	Hygroscopicity	Anthocyanin	Ascorbic acid	Total phenolic	Total carotenoids	Reference
Orange	70% MD	2.29 ± 0.16	0.73 ± 0.02	0.15 ± 0.01	–	0.143 ± 0.01 gH_2O/g	4.94 ± 2.12 mg/100 g	–	–	–	[49]
Date	50% MD	7.1–9.7%	0.6–0.7 g/cm^3	0.14–0.39	–	–	–	–	–	–	[60]
Barberry	75:25 (MD:GM)	3.20%	0.520 g/cm^3	0.181	97.40%	–	390.46 mg/100 g	–	–	–	[146]
Tropical red fruit (Acerola + guava + pitanga)	6% EA with 1% GA, GG and Gelatin	7.48–7.70	–	0.286–0.271	65.96–93.47%	–	7.85–9.54 mg/100 g	19,358.11–22,198.07 mg/100 g	4568.44–5279.86 mg GAE/g DM	24.81–43.93 mg/100 g	[148]
Bottle gourd	15% WPI	–	0.36 ± 0.01 g/mL	0.07 ± 0.01 g/mL	–	20.56 ± 0.20	–	9.66 ± 0.37	447.1 ± 3.1	–	[145]
Apple	20% MD	2.91%	314.1 kg/m3	–	–	25.29%	–	–	–	–	[56]
MANGO	1% GMS + 5% sugar +	2.58 ± 0.36	–	–	1.554 ± 0.001	0.045 ± 0.005	–	–	–	–	[31]
Grapefruit	8–14.7 g/100 g GA and 0–2.7 g/100 g	–	–	0.0106 and 0.0828 g water/g	–	–	–	–	–	–	[55]
Red Beetroot and Quince	20% MD	4.59 ± 0.74%	–	–	–	–	–	–	–	–	[147]
Carrot	15% EA + 10% WPI	3.09 ± 0.62	–	–	–	4.30%	–	–	–	–	[36]
Mango	15% of (GA:MD 50:50 w/w)	–	–	–	82.67	–	–	0.09 ± 0.02 mg/g	3.65 ± 0.11 mg GAE/g	–	[35]

* *SPI* soy protein isolates, *OB* Ovalbumin, *GA* Gum Arabic, *MD* Maltodextrin, *CMC* carboxy methyl cellulose, *SBI* Soybean isolates, *GMS* Glycerol monostearates, *EA* egg albumen, *GG* guar gum, *WPI* whey protein isolates

Table 3 Application of dried fruits powder in various food industries

Kind of industry	Type of fruit	Functional food	Key findings	Reference
Bakery industry	Amla fruit powder	Pan Bread	Bread incorporated with amla powder increase the nutritional and sensory characteristics of pan bread which are well-accepted by the consumers	[150]
	Mango Kernel flour (MKF) + Wheat flour (WF)	Composite cakes	RSM model was adopted to optimise the best concentration. During sensory evaluation 20% MKF powder found to be the best and showed stability up to 7–10 days with any preservatives	[151]
	Dragon fruit powder (DFP)	Fiber rich Biscuits	30, 40, 50 and 60% of DFP were used with wheat flour to optimise the best concentrations. As per sensory evaluation 50% concentration found to the best days concentration with higher fiber and phytochemicals. Further, 100 g daily intake can fulfil the 20% RDA of dietary fibres	[152]
Dairy and frozen food industry	Pomegranate peel powder (PPP) + Apple pomace powder (APP)	Yogurt	Freeze dried powders of pomegranate and apple pomace were utilised in various concentration to optimised bioactive compound rich functional yogurt	[153]
	Red Pitaya Peel powder	Strawberry Ice cream	Red Pitaya Peel powder was utilised as a fat replacer in ice cream which is source of higher soluble dietary fiber. The final products show improved overrun and reduced fat up to 73.5%	[154]
	Jamun Juice powder	Antioxidant rich Ice cream	Spray dried jamun juice powder of 2, 4, 6 and 8% were utilised and various physicochemical analysis like TSS, fat, ash, titratable acidity, antioxidant activity, anthocyanin and TPC were conducted. Based on sensory analysis 6% jamun juice powder's ice cream was found to be best treatments	[155]
Beverage industry	Dates + papaya + pineapple + carrots	Mixed fruit drinks powders	Mixed fruit powder was developed rich in crude fibres and nutritional facts. The prepared drink was nutritionally accepted comparing with commercially available fruit drinks powder	[156]
	Cocoa powder + peppermint extract	Instant powder	Foam mat dried cocoa powder enriched with polyphenolic content, antioxidant capacity and optimised with sensory characteristics were created using response surface methodology with egg white and peppermint as a foaming agents	[157]
	Mango powder	Ready to serve beverages	Various cultivars like Amrapali, Mallika and one seedling mango was utilised for drying. CMC at 2% concentration was used as foaming agents and produced powder was stored at ambient temperature up to 90 days. Further the mango powder obtained can be utilised for preparation of drinks	[158]

8 Conclusions

The demand for enhanced energy efficiency, reduced processing durations, and the maintenance of sensory and nutritional attributes in dehydrated food products is propelling the adoption of these cutting-edge techniques. The abundance of novel drying techniques encompasses strategies such as minimising heat exposure, increasing rehydration ratio, reducing bulk density, and achieving light weight, which are advantageous for storage and transportation. These methods also help in mitigating the risks of microbial contamination and oxidative damage to fruit juice powder, thereby preserving its colour, texture, nutritional content, and bioactive components. The process of drying liquid materials using foam mat drying is highly effective. In addition, considering the potential application of foam mat dried powder in microencapsulation and nano emulsion, it is important to solve the issues of agglomerations and the loss of nutritional properties in fruit juice powders. The efficacy of this method relies on selecting foaming agents with optimal concentrations, ensuring foam stability, and controlling drying conditions. These measures are essential for preserving the flavour, colour, and nutritional content of powders. Advanced drying methods such as pulse electric field, refractive window drying, ultrasound, microwave vacuum drying, etc., are highly efficient in preserving the nutritious and bioactive elements of fruit juice molecules due to their use of gentle heating processes. Furthermore, the powder can be used as a primary component in health foods or as an alternative in several food production industries.

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Declarations

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