



FRUIT LEATHERS AS FUNCTIONAL SNACKS: A COMPREHENSIVE REVIEW ON FORMULATION, DRYING TECHNOLOGIES, QUALITY ATTRIBUTES, AND MARKET POTENTIAL

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Abstract

Fruit leathers are nutritious, shelf-stable snack products obtained by dehydrating fruit purees into thin, pliable sheets. Traditionally prepared from single fruits using simple drying techniques, these products have evolved in response to increasing consumer interest in functional, plant-based, and minimally processed foods. This review highlights the scientific formulation strategies, processing technologies, physicochemical and sensory attributes, advancements and market outlook of functional fruit leathers, with a special focus on ABC (Apple, Beetroot, Carrot) leather. The blend of apple, beetroot, and carrot offers a balanced profile of natural sweetness, dietary fiber, antioxidants, and provitamin A, along with vibrant color and desirable flavor. Various drying technologies including hot air, tray, freeze, and dehydrator methods are discussed in relation to their effects on product quality and nutrient preservation. Additionally, the functional enhancement of fruit leathers through additives such as honey, lemon juice, and guar gum are also explored. The review also examines the growing demand for health-oriented snacks, current production challenges, and potential areas for future research and development. ABC fruit leather, as a functional snack, demonstrates significant promise for both nutritional advancement and commercial growth within the evolving health food market.

Keywords: *Fruit leather, Functional foods, Nutritional snacks, Natural additives,*

1. Introduction

Fruit leather is a fruit-based snack made by drying fruit purée into thin, flexible sheets. It is soft, chewy, sweet, and usually made from fresh fruits. This method is a simple and effective way to preserve fruits for longer periods without the use of chemical preservatives. The idea of drying mashed fruit into leathery sheets dates back to ancient times in countries like Iran, Turkey, and India. In the past, people sun-dried seasonal fruits to reduce spoilage and enjoy them throughout the year. Today, these traditional methods have been modernized using advanced drying machines that make the process faster, safer, and more consistent [71].

Fruit leather production is now a part of the larger dried fruit and healthy snack industry, which is growing worldwide. The global market for fruit snacks—including fruit leathers was valued at more than USD 6 billion in 2023 and is expected to reach over USD 10 billion by 2030, growing at a compound annual growth rate (CAGR) of over (7%) [72]. In India, fruit processing accounts for only about (2.2%) of the total fruit

production, but the sector is expected to expand rapidly due to improved infrastructure, food preservation efforts, and government incentives [73].

India is one of the world's top producers of apples, carrots, and beetroots—the main ingredients in ABC fruit leather. India produces around 100 million metric tons of fruits annually, with approximately 2.5 million tons of apples, 10 million tons of carrots, and 1.4 million tons of beetroot [74]. However, a large portion of these perishables is lost postharvest estimated at (18–30%) due to inadequate cold chains, poor handling, and inefficient transportation [75].

Fruit leather is not only a means of waste reduction but also a nutritious and portable snack. It retains many of the original nutrients, such as dietary fiber, natural sugars, vitamins, and antioxidants. Moreover, fruit leather does not require refrigeration, making it suitable for school children, busy workers, and travelers. Over time, fruit leathers have moved beyond simple fruit snacks and have become a type of functional food—a category that includes products offering health benefits beyond basic nutrition [76].

A recent innovation in this category is ABC (apple, beetroot, carrot) fruit leather. This blend brings together three highly nutritious ingredients. Apple contributes natural sugars and pectin for flavor and texture, beetroot adds antioxidants and nitrates that support cardiovascular health; and carrot supplies beta-carotene, which the body converts to vitamin A [77].

Unlike traditional fruit leathers, which are mostly made from sweet fruits like mango or banana, ABC fruit leather incorporates vegetables. This lowers the overall sugar content while increasing the levels of fiber, vitamins, and phytochemicals. Beetroot offers betalains, powerful antioxidants with anti-inflammatory properties, while carrots are rich in provitamin A compounds such as beta-carotene [78].

The growing consumer preference for plant-based, clean-label foods has further increased the demand for healthy snack alternatives like fruit leather. Modern consumers look for foods that are free from synthetic colors, preservatives, and artificial sweeteners. ABC fruit leather fits well into this trend, offering a natural, minimally processed product with strong visual and nutritional appeal [79].

Many different fruits can be used to make fruit leather, and the best choices are those with high sugar, acid, and pectin content. Commonly used fruits include mango, banana, guava, papaya, and apple all of which create a smooth purée and a stable structure when dried. Berries like strawberry and blueberry are used for their color and antioxidant value. In recent years, vegetables such as carrot, beetroot, and pumpkin have been added to boost the nutritional profile and introduce new flavors [80].

Various drying methods are used to prepare fruit leather. Hot air drying is the most commonly used technique due to its cost-effectiveness and ease of operation. Tray drying, cabinet drying, and dehydrators are also suitable for small- to medium-scale operations. Freeze drying offers superior quality and nutrient retention but is more expensive. Each method affects the final product's color, texture, and nutritional value differently [81].

Packaging is another important factor in fruit leather production. It prevents moisture reabsorption, protects the product from contaminants, and extends shelf life. Common packaging materials include polyethylene film and vacuum-sealed pouches. With the rising focus on environmental sustainability, some producers are turning to biodegradable or edible packaging materials to make their products more eco-friendly [82].

Despite these advancements, challenges remain in scaling up production and maintaining consistency in quality, flavor, and shelf stability. More research is needed to understand how various fruit and vegetable combinations affect the sensory attributes, nutrient stability, and consumer acceptance of the final product. In addition, studies on storage behavior and packaging solutions can help improve shelf life and reduce post-processing losses [83].

2. Nutritional and Functional Properties of Fruit Leathers

Fruit leathers are dehydrated fruit-based products that retain much of the nutritional integrity of the original raw materials. Made primarily from puréed or concentrated fruit pulp, these snacks are naturally rich in dietary fiber, natural sugars, and essential micronutrients, including vitamins A and C. Among apple, beetroot, and carrot, carrots are the dominant source of vitamin A, accounting for approximately 99% of the total vitamin A content in a combined ABC formulation, while apples and beetroots contribute only about (0.36% and 0.24%), respectively. In contrast, vitamin C is more evenly distributed, with carrots contributing around (39%), beetroots (33%) and apples (28%). Additionally, these products contain important minerals such as potassium, iron, and calcium [2].

The drying method plays a crucial role in nutrient retention. Traditional hot air drying can lead to losses of heat-sensitive vitamins such as vitamin C, whereas advanced technologies like freeze-drying and infrared drying better preserve these nutrients by minimizing thermal degradation [3]. Fruit leathers also deliver a range of bioactive compounds, including polyphenols, flavonoids, and carotenoids, which contribute to their antioxidant activity [4]. These compounds help combat oxidative stress and inflammation and are associated with reduced risks of chronic diseases, including heart disease and some types of cancer [5]. For instance, mango-based fruit leathers contain polyphenols in the range of (1.2% to 1.5%), while berry-based leathers have even higher contents, typically (2.5% to 4%), making them particularly rich in antioxidant potential [6].

Beyond their inherent nutritional value, fruit leathers can be fortified with functional ingredients to improve their health benefits. Additions like chia seeds, flaxseed, and psyllium husk contribute omega-3 fatty acids and additional dietary fiber, which support cardiovascular health and promote digestive function [7]. Other functional ingredients, such as probiotics, herbal extracts, and vitamin-mineral premixes, can be blended into the product without significantly affecting its taste or texture [8]. This makes it possible to transform a simple fruit leather into a functional food capable of delivering specific health effects such as enhanced immunity, improved gut microbiota, or reduced blood cholesterol levels [9].

Fruit leathers are also widely inclusive from a dietary perspective. They are naturally vegan, gluten-free, and typically free from major allergens, making them suitable for individuals with dietary restrictions [10]. Their sweet taste, colorful appearance, and soft, chewable texture make them particularly appealing to children, elderly individuals, and those with chewing or swallowing difficulties, offering a simple and palatable way to deliver nutrients [11].

From a caloric standpoint, fruit leathers are moderately energy-dense. A typical 20-gram serving provides approximately 60–80 kilocalories, depending on the fruit base and whether any added sugars or fats are used [13].

Given their nutrient density, flexibility in formulation, and wide consumer appeal, fruit leathers are becoming a prominent choice in the development of health-focused snack products. Their relevance is further supported by advancements in drying technology, ingredient innovation, and clean-label trends, positioning them as a progressive and adaptable option in the evolving functional food market [12].

2.1 Health benefit of fruit leather

Fruit leather is a shelf-stable product made by dehydrating fruit puree into a thin, flexible sheet, resulting in a chewy-textured snack. This processing method helps preserve much of the original fruit's nutritional profile over time. Fruit leathers are typically rich in essential nutrients such as dietary fiber, calcium, phosphorus, and iron [2]. Fruits and vegetables are valued in dietary recommendations for their high content of vitamins, particularly vitamins C and A [3].

2.2 Role of Fruit Leathers in Functional Food Development

Fruit leathers have become an important product within the functional food sector due to their capacity to maintain the nutritional value of fresh fruits while providing a longer shelf life [17]. Typically prepared by dehydrating fruit puree or a blend of fruit juice concentrate and supplementary ingredients into thin, flexible sheets, fruit leathers possess a chewy texture and retain much of the original fruit's taste and bioactive compounds [18]. The drying process significantly reduces moisture content, which inhibits microbial growth and enzymatic activity, thereby preserving key nutrients over time.[18]

These products are rich in dietary fiber, essential minerals such as calcium, phosphorus, and iron, as well as vital vitamins like vitamin C and carotenoids, making them a nutritionally dense snack option [14,15]. These nutrients play essential roles in supporting metabolic processes, bone development, immune function, and oxidative stress management. Since regular fruit and vegetable intake is linked to reduced risks of chronic diseases, fruit leathers serve as a convenient and shelf-stable alternative to fresh produce, especially in regions or seasons where fruit availability is limited [14].

In addition to their natural nutritional benefits, fruit leathers serve as a flexible medium for adding functional ingredients such as probiotics, prebiotics, omega-3 fatty acids, herbal extracts, and plant-based proteins [7]. These additions allow the product to be tailored for specific health benefits, such as digestive wellness, cardiovascular support, or enhanced cognitive function. This capacity for nutritional customization aligns well with contemporary consumer preferences for snacks that deliver functional benefits in addition to satisfying hunger [7].

The appealing taste, smooth texture, and easy-to-handle form of fruit leathers make them especially favored by children, the elders, and health-conscious adults, particularly those who find it challenging to use traditional supplements such as pills or powders. As vegan, gluten-free, and generally free from common allergens, fruit leathers also meet the growing demand for clean-label and inclusive dietary products [18].

Fruit leather production offers an efficient way to utilize excess or lower-grade fruits, thereby reducing post-harvest waste and enhancing value addition in the fruit processing industry [9]. Overall, these qualities make fruit leathers a versatile, nutrient-dense, and eco-friendly functional food with wide consumer appeal and strong potential in the growing health snack market [3].

2.3 Comparison with Functional Snacks

Conventional snacks such as potato chips, confectioneries, sweetened beverages, and processed bakery items are widely favored for their taste, affordability, and accessibility.[1]However, these products are typically high in added sugars, saturated fats, sodium, and artificial additives, contributing to a higher risk of lifestyle-related health issues including obesity, type 2 diabetes, hypertension, and cardiovascular diseases [2]. In contrast, fruit leathers offer a healthier alternative as they are made primarily from fruit purée or juice concentrates, preserving much of the fruit's natural nutrients such as dietary fiber, vitamins (A and C), potassium, iron, and bioactive phytochemicals like polyphenols and carotenoids [3, 4].

Unlike conventional snacks that often contain preservatives, synthetic colorants, and flavor enhancers, fruit leathers are perceived as clean-label and minimally processed products, aligning with consumer trends favoring natural and healthful ingredients [5]. When fortified with functional components like chia seeds, probiotics, omega-3 fatty acids, or herbal extracts, fruit leathers can be tailored to support specific health benefits such as digestive wellness, immune support, and antioxidant protection [6, 7].

Moreover, fruit leathers serve not only as a nutritious snack but also as a sustainable food product, utilizing surplus, overripe, or cosmetically imperfect fruits that might otherwise contribute to post-harvest losses [8]. This practice supports the global agenda for food waste reduction and sustainable processing. In summary, compared to many traditional snack foods, fruit leathers provide superior nutritional benefits, functional versatility, and a lower environmental footprint, making them an ideal candidate in the functional snack category [9].

3. Formulation strategies

Formulation strategies are central to the successful development of functional fruit leathers, particularly in terms of enhancing their nutritional value, sensory quality, and storage stability. The use of apple, beetroot, and carrot (ABC) as a composite blend offers a well-balanced combination of bioactive compounds, natural sweetness, and appealing color, making it an ideal formulation for health-oriented snack products.

3.1Role of Individual Components

Apple is commonly used as a base fruit in fruit leather formulations due to its high pectin content, inherent sweetness, and pleasant aroma, all of which contribute to a smooth, cohesive texture and improved palatability [30]. Beetroot enriches the product with betalains—bioactive pigments known for their antioxidant and anti-inflammatory properties—while also enhancing the color intensity of the leather [31].

However, its distinct earthy flavor requires balancing to prevent sensory rejection. Carrots, on the other hand, are rich in β -carotene and dietary fiber, and they contribute a mild sweetness and bright orange hue, complementing the sensory profile of the blend [34].

3.2 Optimization of Fruit Ratios

Determining the optimal ratio among apple, beetroot, and carrot is crucial to achieving a balanced flavor and desirable functional profile. Research suggests that a formulation such as (50%) apple,(30%) beetroot, and (20%)carrot yields favorable sensory and nutritional outcomes, ensuring the beetroot does not dominate the flavor while still delivering its functional benefits [33]. These proportions can be further adjusted to emphasize specific nutritional or sensory traits, such as increasing carrot content for enhanced provitamin A or beetroot for greater antioxidant potential [39].

3.3 Sweeteners and Acidity Control

Given that apples and carrots naturally provide sufficient sugars, the addition of external sweeteners can often be minimized or avoided. However, in cases where sweetness needs enhancement, natural sweeteners like honey, jaggery, or date paste may be used [30]. Moreover, the inclusion of citric acid or lemon juice not only balances flavor but also helps stabilize the vibrant pigments in beetroot and carrot by reducing pH and minimizing oxidative degradation [34].

3.4 Textural Agents and Binders

Although apples provide sufficient natural pectin for structure formation, small quantities of natural binders such as guar gum incorporated to enhance texture consistency, reduce stickiness, and ensure uniform drying especially in large-scale production settings [35]. These agents also contribute to the elasticity and bite of the final leather, improving its overall sensory quality.[34]

3.5 Nutritional Fortification

ABC-based fruit leathers offer significant opportunities for nutritional enhancement. For instance, micronutrients like vitamin C or iron can be added to complement the existing bioactive matrix, particularly as beetroot and apple contain compounds that aid in iron absorption [36]. In recent years, the incorporation of probiotics into fruit leathers has gained attention, where encapsulated probiotic strains can be applied post-drying to create a synbiotic product [37].

Table 1 different types of fruit leather and vegetable leather and their composition

Fruit/Vegetable Source	Key Constituents	Functional (if any)	Added Ingredients	Nutritional/Functional Benefits
Mango	β -carotene, vitamin C, dietary fiber		Sugar, citric acid, pectin	Antioxidant activity, immune support
Guava	Vitamin C, dietary fiber, lycopene		Citric acid, sugar	Antioxidant, digestive health
Apple	Polyphenols, dietary fiber		Cinnamon, sugar, ascorbic acid	Cardiovascular health, antioxidant
Strawberry	Anthocyanins, vitamin C		Sugar, pectin	Anti-inflammatory, skin health
Banana	Potassium, vitamin B6, dietary fiber		Honey, lemon juice	Energy boost, gut health
Papaya	Papain enzyme, vitamin A, fiber		Citric acid, pectin	Digestive aid, skin support
Carrot	β -carotene, dietary fiber		Lemon juice, sugar	Vision support, antioxidant
Beetroot	Betalains, nitrates		Sugar, lemon juice	Blood pressure regulation, antioxidant
Tomato	Lycopene, vitamin C		Salt, spices	Cardiovascular health, antioxidant

Pumpkin	Carotenoids, vitamin E, fiber	Cinnamon, nutmeg, honey	Eye health, immune support
Mixed Berry (blueberry, raspberry)	Anthocyanins, polyphenols	Pectin, lemon juice	Cognitive health, anti-aging
Spinach	Iron, folate, vitamin K	Lemon juice, spices	Hemoglobin synthesis, bone health

4. Drying Technologies in Fruit Leather Production

Drying is an essential step in making fruit leather. It removes most of the water from the fruit purée, which helps prevent spoilage, increases shelf life, and keeps the product safe to eat [45]. It also helps to preserve the flavor, nutrients, and texture of the final leather.

The practice of drying food has a very long history. Ancient civilizations such as those in Egypt, Mesopotamia, and China used the sun to dry fruits and vegetables thousands of years ago. In fact, there is evidence that sun drying was used as early as 12,000 B.C. in the Middle East to preserve food for long periods [46].

During the 18th and 19th centuries, with the start of the Industrial Revolution, machines were introduced to make drying faster, cleaner, and more controlled. These early machines used heated air in enclosed spaces to dry food and are considered the beginning of modern mechanical drying [47].

Today, drying technology has become much more advanced. Several modern methods are used to make fruit leather, including hot air drying, tray drying, freeze drying, and drying with food dehydrators [48]. Among these, hot air drying is the most common because it is affordable and easy to use. In this method, warm air flows over the fruit purée, slowly removing moisture. However, it can cause some loss of heat-sensitive nutrients, such as vitamin C.

Tray drying is a type of hot air drying where fruit purée is spread on trays, which allows better airflow and more even drying. It is often used in small and medium-sized businesses. Freeze drying is a more advanced method that removes moisture at very low temperatures under vacuum. It keeps most of the original nutrients and color of the fruit, but it is more expensive. Because of this, freeze drying is mainly used for high-value or premium products. Newer technologies like infrared drying and microwave-assisted drying are also being studied. These methods can dry food faster and use less energy. They may also help keep more nutrients in the final product, which is important for making healthy snacks like fortified fruit leather [49]

4.1 Hot air drying

Hot air drying is widely used due to its affordability and ease of use, involving the exposure of fruit purée to a steady stream of heated air typically at 50–70°C [47]. Although it is energy-efficient and scalable, this method often causes a reduction in sensitive nutrients like vitamin C and phenolics due to prolonged heat exposure [48]. Furthermore, hot air drying can lead to uneven moisture distribution and surface hardening (case hardening), which negatively affects the texture of the final product [49].

4.2 Tray drying

Tray drying is a type of convective drying, involves placing the fruit mixture on perforated trays and circulating hot air around them [50]. This technique ensures relatively uniform drying and is commonly used at pilot and laboratory scales [51]. However, like hot air drying, it may also cause degradation of bioactive compounds and changes in product color and texture if the drying time or temperature is not optimized [52].

4.3 Freeze drying

Freeze drying is considered a superior technique for preserving nutrients and sensory qualities because it uses low temperatures and vacuum conditions to remove moisture through the direct sublimation of ice into vapour [53]. It is highly effective in preserving heat-sensitive compounds such as polyphenols, flavonoids, and vitamin C, making it ideal for retaining the natural benefits of ABC fruits [54]. Despite these advantages, freeze drying is associated with high operational costs and limited accessibility, which restricts its use in large-scale production, especially in developing economies [55].

4.4 Food dehydrator

Food dehydrator, a form of low-temperature convective drying using portable devices with integrated fans and heaters is especially suitable for small-scale and domestic production [56]. This method enables better control over temperature and air circulation, leading to uniform drying and reduced nutrient loss compared

to conventional hot air systems [57]. In the case of ABC leather, dehydrator drying has been found effective in maintaining a pliable texture, vibrant color, and acceptable levels of moisture and bioactive content [58].

Among these methods, dehydrator drying offers a balance of quality, affordability, and efficiency, making it the most suitable for ABC fruit leather production at a small to medium scale [59].

Table 2 advantages and disadvantages of different drying method used in leather

Drying Method	Advantages	Disadvantages
Sun Drying	- Low-cost and energy-efficient- Simple technology requiring minimal equipment	- Dependent on weather conditions- Risk of contamination (dust, insects)- Inconsistent drying and prolonged drying time
Hot Air Drying (HAD)	- Widely used and economical for large-scale production- better control over temperature and time- Simple operation	- Can cause significant loss of heat-sensitive nutrients (e.g., Vitamin C)- Risk of shrinkage and color/taste degradation
Microwave Drying	- Fast drying time- Can help retain color and nutrients better than conventional drying- Uniform heat distribution	- High initial equipment cost- Risk of overheating or uneven texture if not properly controlled
Vacuum Drying	- Preserves nutritional and sensory qualities better than HAD- Suitable for heat-sensitive compounds	- Higher operational and equipment costs- Lower throughput compared to HAD
Freeze Drying (Lyophilization)	- Excellent retention of flavor, color, and nutrients- Produces high-quality, porous texture- Ideal for premium functional products	- Extremely high cost- Longer processing time- Not cost-effective for large-scale or low-cost snack production
Infrared Drying	- Efficient energy transfer- Faster drying than HAD- Reduced microbial load	- Limited industrial-scale adoption- Risk of surface overheating if not optimized
Hybrid Drying (e.g., Microwave-Vacuum)	- Combines benefits of multiple methods (e.g., speed, quality retention)- Can significantly improve drying efficiency	- High equipment and maintenance costs- Requires technical expertise to optimize process parameters

5. Physicochemical and Sensory Quality Attributes

5.1 Moisture content

Moisture plays a significant role in defining the shelf stability and textural quality of fruit leather, with the optimal range typically between 10% and 20% to ensure microbial safety and maintain a soft, chewy texture [60]. Too much moisture can result in spoilage, whereas too little may lead to a hard and brittle product.

5.2 Water activity (aw)

Water activity is directly linked to microbial and enzymatic activity, with values below 0.6 considered safe for long-term storage of fruit-based snacks [61]. Achieving and maintaining low water activity in ABC leather requires effective drying and moisture-proof packaging to ensure microbial safety during storage [62].

5.3 Shelf life

The shelf life of ABC fruit leather depends on both processing conditions and protective storage. Using ingredients like lemon juice (rich in citric acid) and honey (with mild antimicrobial effects) aids in maintaining product integrity by slowing down spoilage and oxidation [63]. When stored in sealed containers under ambient or controlled conditions, the product retains quality and nutritional value over several months [64].

5.4 Texture

Texture is a critical quality determinant influenced by fruit type, drying method, and use of stabilizers. Apple contributes pectin, promoting softness; beetroot and carrot enhance structure, while guar gum at 0.5% provides cohesiveness, reduces cracking, and improves chewiness [65]. The right ingredient balance results in a pliable, cohesive leather with good mouth feel [64].

5.5 Color

Color is an important sensory and quality attribute that depends on the retention of natural pigments anthocyanins from beetroot, β -carotene from carrot, and polyphenols from apple—which contribute to the vibrant reddish-orange color [66]. Moderate drying temperatures, particularly via dehydrator or freeze drying, help maintain pigment stability and prevent browning [67].

5.6 Appearance and aroma

Appearance and aroma are influenced by both composition and processing. Honey enhances sweetness and aroma, while lemon juice introduces freshness and acts as a natural antioxidant, balancing the earthy and sweet flavor profile of ABC leather [68]. A smooth, glossy surface and consistent color are indicators of good visual quality and processing control [69].

5.7 Sensory analysis

Sensory analysis of fruit leather generally involves evaluation of taste, texture, appearance, and aroma using structured panels and hedonic scales to assess consumer acceptability [70]. Panelists typically score well-formulated leathers with good textural integrity and balanced flavor above 7 on a 9-point scale, indicating high overall satisfaction [71].

6. Packaging and Storage Considerations

Proper packaging and storage are crucial for maintaining the quality, texture, color, and shelf life of fruit leather products, including those made from apple, beetroot, and carrot (ABC) [24]. Packaging protects the leather from environmental factors such as moisture, oxygen, and light, all of which can cause physical and chemical changes that degrade the product's appearance, flavor, and nutritional content over time [24].

Materials like low-density polyethylene (LDPE) and polyethylene terephthalate (PET) are commonly used due to their excellent moisture barrier properties, strength, and affordability [24]. In recent years, biodegradable films made from natural polymers such as starch, cellulose, and pectin have gained popularity because they are more environmentally friendly and still provide adequate protection for shelf-stable products like fruit leather [30].

Additionally, incorporating natural preservatives like honey and lemon juice into the formulation enhances both storage stability and flavor. Honey has antimicrobial properties, thanks to its low water activity and production of hydrogen peroxide through enzymatic activity. Lemon juice, on the other hand, lowers the pH of the product, creating an environment that inhibits the growth of spoilage-causing microbes [31]. These ingredients not only extend the shelf life but also enhance the nutritional profile and consumer appeal of the final product.[30]

One of the most important indicators of shelf stability is water activity (aw). A water activity level below 0.60 is generally required to prevent the growth of most bacteria, yeasts, and molds [31]. This level also slows down oxidation processes, helping to maintain the color and flavor of the leather. Among different drying techniques, dehydrator drying is particularly effective in achieving the low moisture content and water activity needed to ensure a flexible texture while enhancing shelf life [24].

Pigments such as betalains in beetroot are highly sensitive to environmental conditions, especially light and heat. Maintaining a stable water activity and using opaque or UV-resistant packaging helps retain the bright color and nutritional value of such pigments [25].

The ideal moisture content of fruit leather generally ranges between (12%) and (20%), depending on the fruit type and desired texture [50]. At this level, the product is flexible, non-sticky, and resistant to microbial spoilage. Moisture contents above (25%) may result in a sticky surface and shorter shelf life, while levels below 10% can make the product brittle and less palatable.[25]

When stored properly at ambient temperatures (20–25°C), in sealed, moisture-proof packaging, fruit leather can maintain its quality for up to 6–12 months [51]. The shelf life may vary depending on the specific formulation, drying method, and packaging material used. For maximum stability, it is recommended to store fruit leather in cool, dry, and dark conditions, preferably in airtight containers or vacuum-sealed pouches to avoid exposure to humidity and oxygen [30, 51]

7. Market Potential

Fruit leather is becoming more popular around the world as people look for healthier snack options. Today's consumers are more aware of what they eat and are choosing foods that are not only tasty but also good for their health. Fruit leathers, which are made by drying fruit purée, are a great choice because they are rich in natural sugars, fiber, vitamins, and antioxidants [24]. They are often seen as a better alternative to sugary snacks like candies or processed bars [25].

One reason for this growing interest is the shift in eating habits. Many people now prefer plant-based, natural, and less processed foods. Fruit leathers match this trend because they are made mostly from fruit and can be produced without artificial colors, flavors, or preservatives [30]. When ingredients like honey and lemon juice are added, they not only help keep the product fresh but also make it taste better and add health benefits [31].

Recent reports show that the global dried fruit snack market which includes fruit leathers is expected to grow quickly in the coming years [76]. This is due to factors like people living busier lives, needing snacks they can eat on the go, and having more interest in healthy eating. Fruit leather is easy to carry, doesn't spoil quickly, and can be eaten anywhere, making it a smart choice for both adults and children [76].

Many types of fruit are used to make fruit leather, including mango, banana, apple, guava, papaya, and berries. These fruits are chosen because they are naturally sweet, have strong flavors, and maintain a good texture after drying [24]. For example, mango leather is popular with kids, while berries offer extra health benefits because they contain more antioxidants [6]. These different fruit types allow producers to create a variety of flavors and styles that appeal to many people [25].

Even though the future looks good for fruit leather, there are some challenges. It can be hard to keep the product consistent in quality, make it in large quantities, and keep it fresh without preservatives [30]. Also, because fruit is seasonal and can spoil quickly, it's important to have good systems for storage and production. This can be difficult, especially for small-scale producers [5].

Dehydrators and tray dryers are now widely used to make drying more efficient, save energy, and help preserve the fruit's color, taste, and nutrition [24]. These tools make it easier to produce fruit leather in large amounts without losing quality [48]. Packaging also plays an important role. Using biodegradable or eco-friendly packaging is becoming more common, which is good for the environment and can attract customers who care about sustainability [30]. Packaging needs to protect the leather from moisture, light, and air to keep it fresh for longer [25].

Fruit leather is a good snack for a wide range of people. It is usually vegan, gluten-free, and free from major allergens, making it safe for people with special diets [10]. It's also easy to chew, so it's great for kids and older adults. Its sweet taste and colorful look make it more appealing, especially when it includes fruits known for their natural benefits [11].

If producers use good marketing and promote the health benefits of fruit leather, it could become a popular snack in both local and global markets [76]. There is also growing interest in fortified fruit leathers that include added nutrients like fiber, probiotics, or plant-based proteins [9].

Fruit leather has strong market potential because it fits well with current health and food trends. While ABC (apple, beetroot, carrot) leather is one example of an innovative blend, the overall category of fruit leathers—when made with care and marketed well—can become a favorite choice for modern, health-conscious consumers [12].

8 Future Prospects and Research Opportunities

The development of functional fruit leathers like ABC (Apple, Beetroot, Carrot) leather holds significant promise in the functional foods sector, especially as consumers increasingly seek nutritious, convenient alternatives to traditional snacks [30]. Enriching these products with health-promoting components such as natural antioxidants, plant extracts, and dietary fibers can enhance their physiological benefits, including antioxidant defense and gut health support [24].

An important area of future research lies in improving the stability and bioavailability of key nutrients through advanced techniques like microencapsulation. This approach protects sensitive compounds such as vitamin C and betalains from environmental degradation during processing and storage, thereby preserving the functional integrity of the product [25].

While hot air drying is widely used due to its simplicity, alternative methods such as freeze-drying, vacuum drying, and microwave-assisted drying offer advantages in nutrient preservation, improved texture, and reduced energy consumption [30]. Furthermore, hybrid drying systems or solar-assisted technologies may be

explored to increase energy efficiency and promote sustainable production, especially in rural or low-resource regions [67].

Packaging innovations also present a fertile area for research. The use of biodegradable and edible packaging materials such as starch, pectin, or protein-based films can significantly reduce environmental impact while enhancing product shelf life and consumer appeal [70].

To improve market competitiveness, sensory evaluation and consumer preference studies should be emphasized. Tailored formulations based on demographic-specific preferences (e.g., children, elderly, health-conscious consumers) can improve product acceptance and market reach [66]. These insights can also guide improvements in taste, texture, aroma, and visual appeal.[70]

9. Conclusion

Functional fruit leathers represent a promising innovation in the realm of healthy snack alternatives, offering a unique combination of nutritional value, sensory appeal, and shelf stability. Their formulation using a diverse range of fruits and functional ingredients such as dietary fibers, probiotics, and plant-based bioactives enhances not only their health benefits but also their market potential. As consumer demand for convenient, natural, and health-promoting foods continues to rise, functional fruit leathers provide an effective solution by integrating the advantages of functional foods with the appeal of traditional snacks. Future research should focus on optimizing processing techniques, improving sensory qualities, and validating health claims through clinical studies to fully harness their potential. Overall, functional fruit leathers hold significant promise in contributing to public health and advancing innovation in the functional food sector.

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