

Review Article

Bromelain-Infused Pineapple-Based Candies as Functional Confections: Potential Formulation and Health Benefits

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Pineapple (*Ananas comosus*) contains bromelain, a proteolytic enzyme with documented anti-inflammatory, digestive, and potential anticancer properties. This review examines the development of bromelain-infused pineapple candies as functional confections, addressing formulation challenges and health benefits. Current research demonstrates that bromelain exhibits therapeutic effects with oral bioavailability up to 12 g/day without significant adverse effects. However, critical challenges include bromelain stability during high-temperature processing (> 60°C causes rapid denaturation), pH-dependent activity loss in acidic candy matrices (pH < 4.0), sugar concentration effects on enzyme structure, and potential allergenic reactions in sensitive individuals. Innovative solutions include microencapsulation (> 80% efficiency), low-temperature processing, and controlled-release polymer systems. Despite promising health applications, gaps remain in comparative efficacy studies across different candy formulations and long-term stability data. This review critically analyzes current approaches and identifies research priorities for developing commercially viable bromelain-enriched confections.

Keywords: bromelain stability; candy processing; enzymatic activity; functional confections; microencapsulation

1. Introduction

Pineapple, a member of the Bromeliaceae family, is a highly valued fruit native to tropical and subtropical regions. It is well-known for its significant nutritional and economic benefits [1]. For consumption, fully ripened pineapples are preferred due to their optimal sweetness and nutrient content. Pineapple is enjoyed globally in various forms, such as juice, canned pieces, chunks, diced fruit, fruit salads, sugar syrup, alcoholic beverages, citric acid production, pineapple chips, and puree [2, 3].

The fruit primarily consists of carbohydrates and essential nutrients, including vitamin C and β -carotene.

Pineapple is also rich in antioxidants and enzymes that support digestion and overall health. It offers a delightful blend of sweetness and acidity, making it a significant source of organic acids and vitamin C [4]. Pineapple plants can produce fruit shortly after flowering, ensuring a continuous harvest throughout the year [5]. The fruit contains the enzyme bromelain, part of the cysteine-protease group of hydrolytic enzymes. This group also includes ribonuclease, protease inhibitors, carbohydrates, peroxidase, cellulase, glycoproteins, phosphatase, and bound organic calcium [6, 7].

Bromelain can reduce the surface tension of bacteria by hydrolyzing salivary proteins and glycoproteins. Bromelain

improves digestion [8]; this enzyme breaks down proteins by cleaving peptide bonds, contributing to its therapeutic effects through a complex mechanism of action. It exhibits various biological effects, including anti-angiogenic, anti-inflammatory, and antioxidant properties [9]. The combination of bromelain and vitamin C from pineapple has been reported to alleviate symptoms related to cardiovascular disease. Additionally, research by Joha et al. [10] has shown that bromelain can suppress proinflammatory cytokines and other inflammatory substances, both *in vitro* and *in vivo*.

To extend the freshness of pineapples, it is possible to increase their shelf-life through precise storage conditions and temperatures, and specific treatments can be implemented to prevent microbial contamination [11]. Consuming this fruit offers substantial benefits such as improving protein digestion, enhancing and relieving the common cold, and promoting immune system and bone health. Due to its nutritional, textural, and sensory attributes, it is suitable for individuals of all age groups [12]. In recent years, pineapples have gained considerable attention due to their nutritional value, leading to potential applications as a functional food and the development of diverse pineapple-derived products [13].

Consumers are growing interested in functional foods that promote overall health and well-being, a trend further accelerated by the COVID-19 pandemic [14]. According to the Functional Food Center (FFC), functional foods are processed or natural foods with safe levels of bioactive compounds. These compounds should offer proven health benefits backed by clinical evidence and specific biomarkers [15]. The primary purpose of functional foods is to manage, treat, or prevent chronic diseases or their associated symptoms [16]. While definitions may vary, scientists generally agree that functional foods consist of bioactive substances that provide health benefits beyond what typical dietary supplements offer [17]. According to the 2021 report on functional food and beverages, 31% of individuals are increasing their intake of supplements, and 29% are consuming more beverages and functional foods [18]. These dynamics impact the confectionery market, prompting manufacturers to enhance their products with innovative technologies and ingredients that align with consumer preferences [19].

Given the growing demand for functional foods, incorporating bioactive compounds into familiar products such as candy offers an accessible and appealing delivery format. However, it is recognized for its limited nutritional value. Therefore, a growing interest is in developing high-quality candy with added functional ingredients to meet market demand [19]. It is a confectionery made by coating fruits or vegetables with sugar syrup, draining, and drying to ensure stability and shelf life. [20]. Various fruits and vegetables, such as mangoes, apples, guava, carrots, ginger, and citrus peels, have been used to create candies. When a ripe fruit is soaked in thick sugar syrup until it becomes soft and translucent, it is called “preserves” [17].

On the other hand, when fruits and vegetables are infused with sugar or glucose syrup, followed by the removal of excess syrup and drying, the result is called “candy.”

Pineapple, cherry, papaya, and amla are the most suitable fruits and vegetables for making preserves and candy [21]. The candy market is experiencing annual growth at 12%–14%. It is expected to reach 86.65 billion USD by 2030, expanding at a rate 1.5 times faster than India’s fast-moving consumer goods (FMCG) industry. Hard candies, including lollipops, toffees, and gumdrops, come in a wide variety: sucrose, fructose, glucose, or maltose. They are known for their various colors and flavors, appealing to individuals of all ages. There are three primary categories of confectionery products. These include sugar confectionery, chocolate confectionery, and gum products. The use of large quantities of sugar and sugar substitutes characterizes each category. Although confectionery products are generally low in micronutrients, they are high in calories and carbohydrates [22].

The production process of bromelain-infused candy starts with the processing of raw pineapples (Figure 1), where the fruit pulp, stems, or peels are collected as sources of the enzyme. Bromelain is then extracted and purified. Following this, stabilization steps are employed, which may include encapsulation, immobilization, or blending with protective carriers. The stabilized bromelain is incorporated into the candy base, which can consist of boiled sugar, gelatin, or pectin systems. Throughout this process, it is crucial to carefully monitor critical control points such as temperature, pH, and sugar concentration to prevent the denaturation of the enzyme [23–27].

The review aims to investigate the potential of pineapple-based candies as functional foods by examining their nutritional composition, bioactive components such as bromelain, and associated health benefits. Also, thoroughly examine pineapple candy’s nutritional composition, including its vitamin, mineral, and fiber content, and explore the presence and significance of bioactive compounds such as bromelain and their therapeutic properties. So far, only one report has been published on this topic by [12]. This addresses the development of functional gummy candy with low sucrose and artificial additives, such as flavors and colorants, and is high in antioxidants, protein, and fiber. Therefore, this review seeks to scrutinize existing scientific research to determine the potential health advantages of consuming pineapple candy and its textural and colorful properties, particularly its role as an antioxidant-rich food. By assessing the practical implications of integrating pineapple candy into dietary plans, this review aims to provide valuable insights for both consumers and the food industry, enabling them to make informed choices about the role of pineapple candy in promoting overall health and well-being.

2. Nutritional Value of Pineapple

Pineapple is a delightful tropical fruit known for its abundant juiciness, lively tropical taste, and extensive health advantages [28]. Pineapple boosts significant dietary fiber, carbohydrates, potassium, calcium, vitamin C, and minerals that promote digestive health and aid in weight management and balanced nutrition. Fresh pineapples are a great source of bromelain, which is utilized as an anti-inflammatory

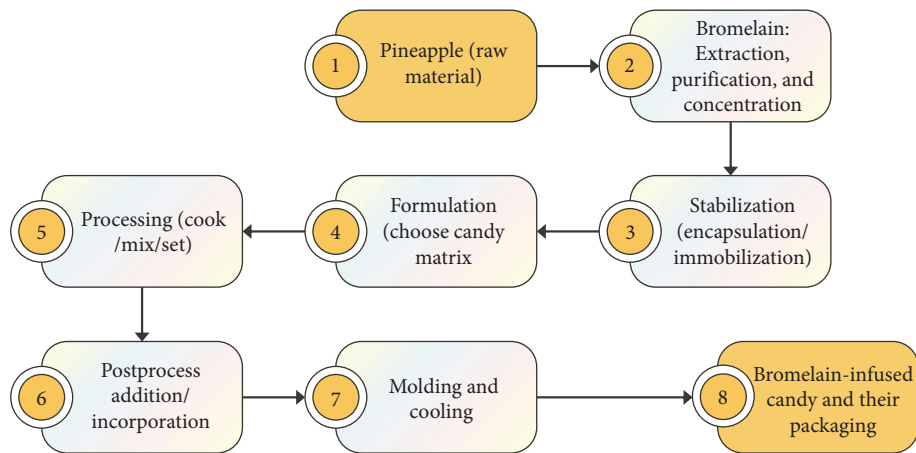


FIGURE 1: Flow diagram of bromelain-infused candy production.

agent to reduce swelling in conditions like sore arthritis, acute sinusitis, gout, and sore throat. Additionally, pineapple produces various food products such as condiments and preserves like pickles and jams [29].

Consumption of pineapples can boost immunity and reduce the onset of infections such as colds and coughs, strengthen the skeletal system, prevent degenerative diseases such as cancer, hypertension, and arthritis, and reduce the threat of hemorrhages [30]. The nutritional value of pineapple can be enhanced by combining it with medicinal herbs known for their health benefits. Holy basil (tulsi) helps with colds, digestive issues, cardiovascular health, migraines, kidney stones, and malaria. Mint is a medicinal condiment, while ginger aids digestion and relieves motion sickness and nausea [31, 32]. Rose supports hydration and skin health, while cardamom helps combat inflammation and oxidative stress. These herbs contribute to overall health benefits when combined with pineapple [33]. Figure 2 depicts the novel formulation of various pineapple-based candies. The most prevalent organic acid present in pineapple is citric acid. Additionally, fresh pineapple is an abundant source of multiple minerals, including sodium, potassium, calcium, phosphorus, and chlorine [4].

Pineapples are rich in essential minerals such as manganese, which is crucial for activating enzymes and bone formation. The fruit also contains copper, a trace mineral that aids in the absorption of iron while simultaneously playing a role in regulating heart rate and blood pressure [34]. Pineapple juice nutrients are crucial in combating bacterial and viral infections, serving as a potent antioxidant, and aiding in iron absorption [35].

Pineapple is a good choice for people trying to lose weight due to its low-calorie count. A 100 g serving has about 50 calories, similar to an apple. However, most of these calories come from natural sugars [2]. While natural sugars are part of a balanced diet, excessive intake may lead to health issues, so it is wise to follow the American Heart Association's advice of limiting daily sugar intake to 25 g for women and 37.5 g for men. It is also important to know the difference between the natural sugars in fruits and vegetables and the added sugars in packaged drinks and snacks [36].

Table 1 presents an overview of the nutritional and compositional attributes of pineapple.

Hossain [29], Ali et al. [13], and USDA [37] reported that pineapple juice is a nutritionally rich beverage with a diverse range of constituents. Proximate composition per 100 g contains approximately 0.4–0.54 g of protein, 12.1–13.7 g of carbohydrates, and 0.1–0.12 g of fat. The total sugar content ranges from 9.85 to 12.1 g, while the fiber content is around 0.2 g. The pineapple juice boasts a high moisture content, varying between 81.2% and 86.2%, and contains 0.4 g of ash. In the mineral category, it provides essential elements such as calcium (8.1–13 mg), magnesium (12–13.6 mg), potassium (109–150 mg), iron (0.2–0.28 mg), manganese (1.2 mg), sodium (5.2 mg), copper (0.04 mg), phosphorus (8–11 mg), and zinc (0.08–0.10 mg). Moreover, the vitamin content includes ascorbic acid (14–24 mg), thiamin (0.079–0.1 mg), folate (23 mg), riboflavin (0.02–0.031 mg), and niacin (0.3–0.489 mg). This comprehensive profile highlights pineapple juice as a flavorful and nutritious beverage, offering a spectrum of essential nutrients that contribute to a balanced diet and potential health benefits.

3. Therapeutic Properties of Bromelain Enzyme

Bromelain is an enzyme found in pineapples that has various applications in the food processing industry. It is commonly used to tenderize meat, assist in brewing, prevent browning in fruits, and enhance the baking process [38]. Bromelain consists of a group of protein-digesting enzymes derived from the fruit or stem of the pineapple. The human body can safely consume a substantial amount of bromelain—up to 12 g daily—without experiencing any significant adverse effects.

The composition of the complex enzyme bromelain can vary depending on its source, though it is most commonly derived from the stem. It contains several enzymes, including protease inhibitors, thiol endopeptidases, peroxidase, β -glucosidase, β -escarase, and cellulase, as shown in Figure 3 [39]. Studies have shown that bromelain has a range of effects, such as anti-inflammatory, antithrombotic, antiedema, and fibrinolytic effects, and it is easily absorbed

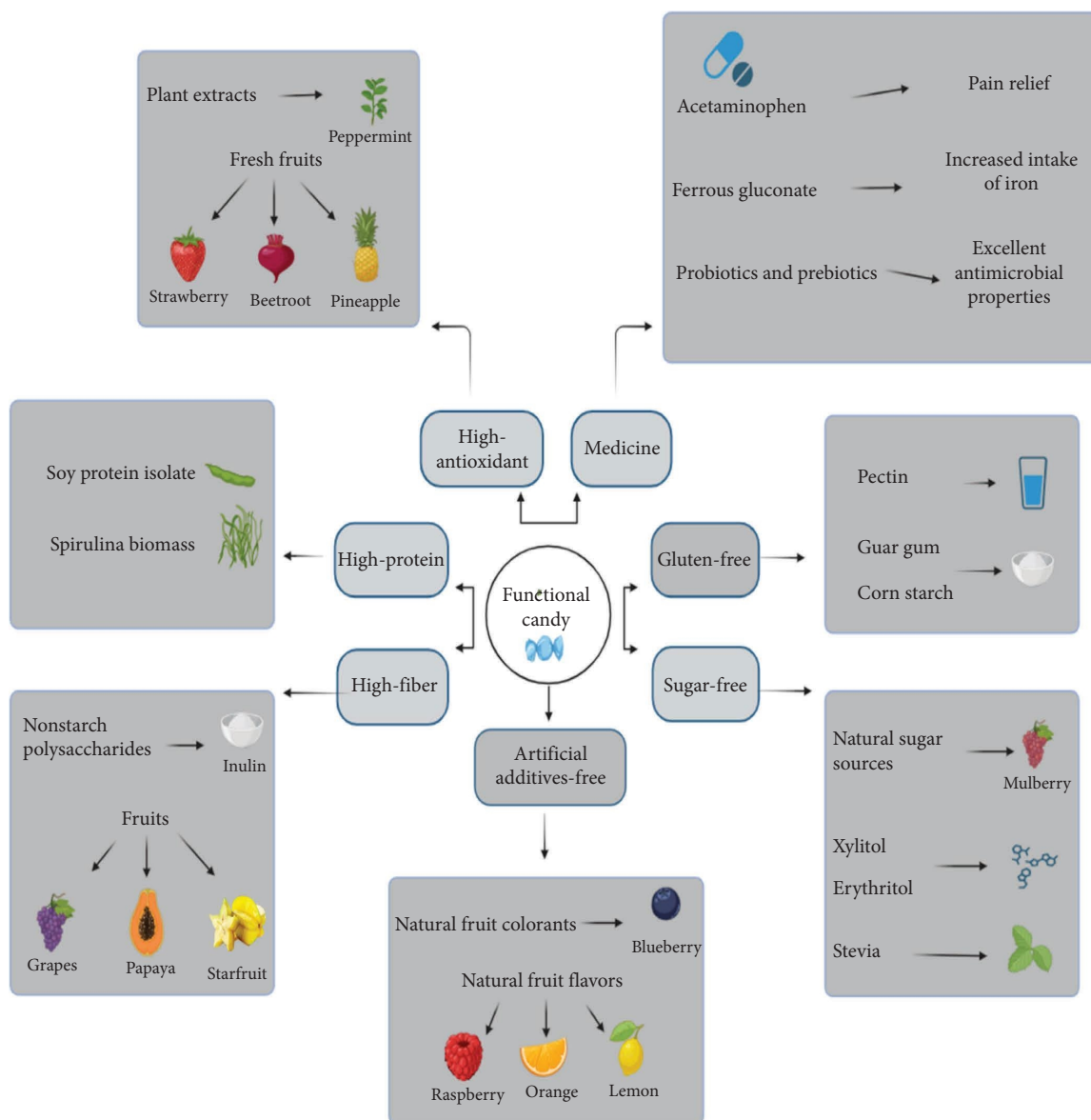


FIGURE 2: A schematic of novel formulations of functional candies.

by the body without causing significant side effects [40]. It has been found to have therapeutic benefits for various conditions, including sinusitis, bronchitis, osteoarthritis, thrombophlebitis, and wound debridement, and can improve drug absorption, particularly antibiotics. In addition, it can help relieve symptoms of certain cardiovascular disorders, diarrhea, and angina pectoris. Bromelain has also been found to have anticancer properties by inducing apoptotic cell death [30, 31, 39].

Bromelain is a naturally occurring proteolytic enzyme that plays several important roles in the production of pineapple-based candy [23]. Despite the wide variety of pineapple products already available in the market, the food industry continues to innovate and develop new products that leverage bromelain, particularly for its ability to tenderize meat [41]. Additionally, bromelain aids in breaking down food, making it easier to digest in the stomach, and it

has been shown to inhibit the growth of cancer cells [42]. From tenderizing and enhancing flavor to activating gelatin and clarifying juice, this proteolytic enzyme contributes to pineapple-based candies' overall quality and appeal. Its ability to improve texture, intensify taste, and potentially promote health makes bromelain an essential ingredient in crafting delightful and nutritious treats [43].

Building on its diverse applications, the comparative analysis of bromelain retention across different processing methods highlights that enzyme stability is highly dependent on the technique used. Conventional thermal treatments often result in substantial enzyme denaturation, while nonthermal methods such as freeze-drying, spray-freeze-drying with encapsulants, and pulsed electric field (PEF) processing show higher retention, thereby preserving bromelain's therapeutic and functional properties. This emphasizes the need to optimize processing methods to

TABLE 1: Chemical constituents of pineapple juice (Farid Hossain [29], Mohd Ali et al. [13], and USDA [37]).

Parameters	Value
<i>Proximate composition (g/100 g)</i>	
Protein	0.4–0.54
Carbohydrate	12.1–13.7
Fat	0.1–0.12
Total sugars	9.85–12.1
Fiber	0.2
Moisture	81.2–86.2
Ash	0.4
<i>Minerals (mg/100 g)</i>	
Calcium	8.1–13
Magnesium	12–13.6
Potassium	109–150
Iron	0.2–0.28
Manganese	1.2
Sodium	5.2
Copper	0.04
Phosphorus	8–11
Zinc	0.08–0.10
<i>Vitamins (mg/100 g)</i>	
Ascorbic acid	14–24
Folate	23
Niacin	0.3–0.489
Thiamin	0.079–0.1
Riboflavin	0.02–0.031

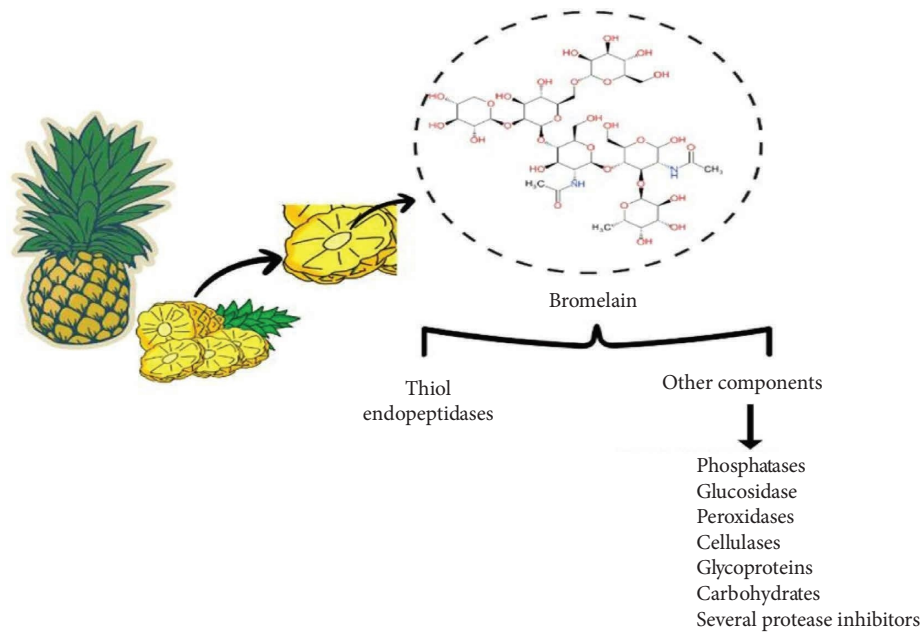


FIGURE 3: Enzymatic and nonenzymatic components of bromelain.

maintain bromelain bioactivity in pineapple-based functional foods [44–47].

Moreover, processing factors like heat, sugar concentration, and pH impact bromelain's stability in candy formulations. Heat can denature the enzyme, high sugar levels may destabilize it by altering water content, and extreme pH conditions can compromise its structure. Therefore,

controlling temperature, sugar, and pH is crucial for preserving bromelain's effectiveness. Reducing sugar affects food texture, shelf life, and consumer acceptance [38, 39]. It can lead to drier, more complex products and shorten shelf life due to reduced preservative effects. While some consumers prefer lower sugar products for health reasons, others may dislike the changes in taste and texture.

Additionally, bromelain can cause allergic reactions in sensitive individuals, especially those with pineapple allergies, highlighting the importance of proper labeling [6].

Moreover, a critical analysis of available studies reveals inconsistent reporting on bromelain's efficacy when delivered through confectionery matrices. While oral bioavailability is supported in capsule or supplement form, its stability and activity in a high-sugar food system remain underexplored. Challenges such as enzymatic degradation during storage, reduced activity due to acidic pH, and potential allergenicity in sensitive individuals demand more rigorous investigation. Notably, bromelain's proteolytic activity also risks interacting with other ingredients in candies, affecting texture and sensory properties [48].

A critical gap in current literature on bromelain-infused confections is the lack of comparative evaluation of diverse formulation strategies to stabilize the enzyme during processing. Different candy formulations—ranging from high-temperature boiled sugar matrices to gelatin- or pectin-based low-heat systems—have varying effects on bromelain stability and bioavailability. Studies indicate that high-temperature processing (above 60°C) can rapidly denature bromelain, rendering it therapeutically inactive [49]. Therefore, innovative formulation techniques such as encapsulation using biopolymers like pectin, alginate, or chitosan have been employed to protect bromelain against thermal and pH degradation while ensuring targeted release in the gastrointestinal tract [50, 51].

To address these challenges, researchers have turned to systematic formulation approaches such as microencapsulation, coacervation, or inclusion in semi-interpenetrating polymer networks, which have demonstrated promising encapsulation efficiencies (> 80%) and controlled release profiles [52]. Adopting low-temperature processing, delayed enzyme addition, and incorporation of enzyme stabilizers can enhance bromelain retention during manufacturing. These advancements highlight the importance of processing innovation and ingredient compatibility in developing effective bromelain-based functional confections. A structured, comparative synthesis of these methods is essential to establish reproducible standards for bromelain retention and delivery in real-world food products [53].

4. Characteristics and Properties of Candies

Candy is a sweet confectionery made from sugar [41]. The process begins by heating a sugar solution in water until it reaches the desired concentration through the evaporation of water, followed by cooling the mixture. When the sugar solution is heated to a high temperature without stirring, it can form glass. However, if stirred, it will undergo crystallization. Additionally, certain additives can initiate gelation, chemical reactions, or emulsification [54].

Textural properties of candy play a crucial role in determining the overall consumer experience. These properties include hardness, chewiness, stickiness, and brittleness. Ingredients, processing techniques, and formulation influence the texture of candy. In hard candy, the impact of sugar glass properties on texture provides valuable insights into

the factors influencing hardness and brittleness [25]. Crystallization processes are vital in chocolate confectionery, giving valuable insights into developing unique chocolate textures [55]. Chewing gum typically changes hardness and cohesiveness, affecting chewability [56]. Bubble gum, known for its stretchiness, is designed to form bubbles, requiring a balance of elasticity and pliability [57].

The production of jelly candies involves utilizing hydrocolloid components like gelatin, gum, starch, agar, carrageenan, pectin, and others to alter the texture, resulting in a malleable and chewy end product that undergoes processing aging before packaging. In the manufacturing process of jelly candies, it is common to include fruit juice or essence to introduce distinct color or flavor characteristics and improve the nutritional content of the candy. Furthermore, ingredients like milk can be employed instead of or in addition to fruit juice [58]. Jelly candies like jellybeans and gummy bears are composed of a gelling agent (starch, pectin, or gelatin) combined with a sugar syrup and elevated moisture content [59]. Including fruit juices and purées can contribute natural, functional, and sensory attributes to jelly candies [60]. The addition of 30 g of propolis to jelly candies improves the antioxidant capacity and acts as a functional ingredient in candy products [61]. Pomegranate jelly prepared with 20% gelatin with pure "*Mollar de Elche*" pomegranate juice enhances the texture, antioxidant capacity, and sensory attributes and promotes pomegranate products' consumption for consumer preference [62]. Watermelon jelly incorporated with red monk fruit powder has a shelf life of up to 30 days when stored at 6 [63]. Whereas, jelly with apple fiber, bamboo fiber, and psyllium fiber possesses favorable rheological, mechanical, and color properties after refrigeration for at least 30 days and also receives a higher rating in stability, appearance, flavor, and structure [26].

Hard candy can be described as a concentrated solution of carbohydrates from which most of the water has been extracted, resulting in a final moisture content of approximately 1%–3%. The candy is rapidly cooled below its glass transition temperature to prevent the occurrence of sugar crystallization [64]. Therefore, hard candy constitutes an amorphous glass with a molecular structure akin to window glass despite being composed of sugar rather than silica [65]. The diversity of hard candies extends to a wide range of shapes, sizes, and characteristics. Beyond the flavors offered, distinctions in hard candies arise from either the ingredients employed in their formulation or the processing methods utilized for shaping and creating the product. Typical presentations of hard candy include drops, lozenges, barrels, rods, and sticks [57].

The production of hard candy requires heating ingredients to very high temperatures to reduce the moisture content and subsequent cooling to obtain a solid matrix [66]. Also, it impacts the nutritional properties of candy. At the same time, heating fresh unripe mango impacts the nutritional composition, such as total solid sugar, total sugar, reducing sugar, ascorbic acid, and candy acidity [67]. Likewise, heating at 100°C–140°C for 10–180 min in preparing Chinese herb-based candy resulted in increased

phenolic content and antioxidant activity of candies, Yin et al. [66]. Heat processing of pineapple-based candy destroys heat-sensitive components such as vitamin C and bromelain, diminishing their functional advantages. Also, caramelization and Maillard reactions improve flavor and color; however, they can reduce sugar availability and lead to the production of advanced glycation end products [68]. Enzyme inactivation alters texture, but prolonged cooking can cause antioxidant loss, reducing overall nutritional value. Minerals, on the other hand, are stable, and controlled heating aids in the retention of nutrients while maintaining ideal taste, texture, and shelf life [69].

Feng et al. [70] developed probiotic gummies using *Bacillus subtilis*, *Bacillus clauseni*, and *Bacillus coagulans*, which increases the total phenolic content and antioxidant capacity. Combining xanthan gum with carrageenan and konjac gum enhances the compound system's cohesion, gel elasticity, and water-holding capacity [71]. The chewy consistency of gummy candy is primarily derived from components like gelatin, with options such as pectin or agar-agar for those adhering to a vegetarian diet [72]. The sugar level plays a dual role in determining sweetness and mouthfeel, and a coating of starch or sugar is applied to prevent adherence. The vivid hues of gummy candy are attained by incorporating food-grade colorings, which may be either natural or artificial, enhancing the visual allure of this widely enjoyed confectionery [73].

5. Candy as a Functional Food

Over the past few decades, what people want from the food they buy has shifted a lot. People are more aware of how good the food is and the health advantages it can offer. Candy constitutes a small portion of the total calorie intake, added sugars, and saturated fat in the overall American diet. Recent studies suggest that the current levels of candy consumption are not directly associated with an increased risk of obesity or cardiovascular diseases in either children or adults [74]. Nowadays, food functions not merely to satiate hunger but to supply the body with essential nutrients for optimal health and physiological functions. Therefore, it is crucial to create new foods with these benefits [33].

Recently, the food industry has been inclined toward creating products that contain less sucrose and artificial substances such as flavors and colorants [75]. Instead, food producers are now focusing on developing food items with high antioxidants, fiber, and protein [76]. The term "functional food" originated in Japan during the 1980s [77]. It refers to food items that have added beneficial substances, like prebiotics and probiotics, and compounds responsible for lowering cholesterol. These foods are meant to be eaten to make the body healthier, reduce the chances of certain illnesses, and even help treat some health issues [3, 76]. In 2021, the global confectionery market was valued at approximately USD 298.23 billion due to the wide variety of products available. Experts predict consistent growth in the market, estimating a yearly increase of 4.3% from 2022 to 2028. Soft candy has become extremely popular among

consumers of various ages, particularly children. This is due to its unique flavor, appearance, and texture [17].

In the last few years, the confectionery industry has seen significant changes with the addition of different sugar substitutes, antioxidants, gelling agents, natural flavors and colors, and other value-added ingredients in making sweets. This variation in the product offers a fresh and remarkable option for texture and taste according to the consumer's needs [74].

The preparation of novel functional candies with distinct ingredients such as gelatin, sugar, artificial additives, high amounts of fiber, protein, antioxidants, and medicines leads to potential disadvantages that affect the physicochemical and organoleptic properties of the candies. Substitutes for these ingredients are prominently used in several studies, as mentioned in Table 2. In a study, gelatin-free solutions use polysaccharides such as pectin and guar gum, suitable for vegan and vegetarian diets [79]. Sugar-free alternatives use natural sweeteners such as stevia and erythritol, which appeal to antidiabetic and low-calorie diets [80].

Stevia, erythritol, and xylitol are used in pineapple-based candies for their intense sweetness and negligible impact on blood glucose levels. [80]. Artificial additive-free candies contain natural fruit tastes and colorants, which provide antioxidant benefits [82]. High-antioxidant sweets contain plant extracts, while high-fiber choices have prebiotic properties [33]. High-protein candies using soy and lupine proteins improve storage stability [83]. Medicinal candies, including acetaminophen, ferrous gluconate (FeG), probiotics, prebiotics, and essential oils, are suitable for children and have antibacterial properties [85–88].

Pineapple-based sweets include herbal pineapple candy, pineapple and carrot gummy candies, pineapple and beetroot gummy candies, and flavored pineapple candy. Incorporating natural ingredients in novel functional candies yields advantages such as authentic flavors and profound health benefits [27, 84, 89–91]. Specifically, adding basil leaves, carrot juice, agar gums, beetroot juice, holy basil syrup, and mint extract imparts natural sweetening flavors, eliminating the need for artificial additives. Moreover, these ingredients confer numerous health benefits, as detailed in Table 3. The resultant candies exhibit the potential to mitigate heart disease risk, enhance digestive health, and boost antioxidant capabilities [93]. Notably, the bioactive compounds present in these natural ingredients have been linked to cancer prevention, improved bone health, and various other beneficial effects [27, 84, 89–91]. For instance, herbal pineapple candy, pineapple and carrot gummy candies, pineapple and beetroot gummy candies, and flavored pineapple candy have been shown to possess antioxidant, anti-inflammatory, and antimicrobial properties, underscoring their potential as functional foods [79, 83]. These novel chocolates offer a variety of health benefits, making them appealing choices for consumers looking for functional confectionery. However, there are possible issues in managing environmental conditions, sugar concentration, and color stability [79, 80, 82]. Acetaminophen is preferred over conventional oral tablets among children due to its ease of consumption and compatibility. It is a widely used

TABLE 2: Development of novel candy as a functional food.

Novel functional candies	Substitute ingredients	Benefits	Disadvantages	References
Vegan-friendly	Polysaccharides like guar gum, cassava starch, pectin alginat, carrageenan, corn starch, agar gum, and carboxymethyl cellulose (CMC)	Feasible for vegetarian and vegan diets.	Gelatin-based candies are more difficult to control their pH. Gel replacements require a higher sugar content than gelatin.	[22, 25, 26, 42, 78, 79]
Low sugar	Natural sugar sources (e.g., grape, mulberry, and carob molasses) honey, isomaltitol, corn syrup, xylitol, erythritol, isomaltulose, maltitol, apple concentrate, and stevia	Aids in anti-diabetic and low-calorie diets.	Sweeteners and sugar have different mouthfeels and aftertaste. Glucose intolerance may result from using certain replacement sweeteners.	[72, 80]
Fruit vinegars	Apple vinegar, apricot vinegar	Improves the nutritional profile of candies.	Usage of a high amount of fruit vinegar leads to high acidity and alters the textural properties of the candies.	[2, 70]
Nonsynthetic additives	Natural fruit colorants (e.g., grape, red beetroot, blueberry, etc.)—anthocyanin, betanin, and so on. Natural fruit flavors (e.g., lemon, pineapple, strawberry, orange, etc.)	Fruit flavors/colorants might provide possible health benefits due to their antioxidant characteristics. Enhanced overall and visual appearance.	Natural colorants such as betanin deteriorate with heat and pH changes.	[62, 73, 81]
Antioxidant-rich	Fresh fruits (e.g., red beetroots and strawberries), natural plant extracts (e.g., chokeberry, peppermint, rosemary, etc.), ginger powder, pineapple, and beetroot juice	Antioxidants improve product performance and increase consumer interest. Lowers the risk of heart disease and cancer.	Fruits like grapes give a bitter taste when used in high amounts. Shortens shelf life.	[33, 35, 62, 71]
Enriched fiber	Nonstarch polysaccharides (e.g., konjac glucomannan (KGM) and inulin), fibers derived from fruits (e.g., papaya, carambola starfruit, and grape)	Dietary fiber has potential prebiotic effects, antioxidant capabilities, and textural qualities that stay stable.	Dietary fibers can affect candy properties.	[82]
Protein fortified	Spirulina biomass, soy protein isolate (SPI), and lupine protein concentrate (LPC)	The storage stability, acceptability, amino acid composition, and genistein content have been improved.	Few ingredients alter the flavor.	[58, 83]
Medicinal	β -Carotene, ferrous gluconate, acetaminophen, metoclopramide hydrochloride, essential oils (e.g., <i>Citrus paradise</i> L., <i>Citrus reticulata</i> L., and <i>Thymus vulgaris</i> L.), prebiotics (e.g., psyllium husk fibers), and probiotics (e.g., <i>Lactobacillus plantarum</i> and <i>Lactobacillus paracasei</i>)	Enhanced antibacterial, antipyretic, and analgesic activities. Providing a nice flavor as a medication carrier	Difficulty in incorporating a few components.	[19, 33, 62, 73, 84]

TABLE 3: Health benefits of different pineapple-based candies.

Different pineapple-based candies	Composition of candy	Health benefits	Evidence strength	References
Herbal pineapple candy (pineapple and basil leaves)	Vitamin C, manganese, carbohydrates (sucrose, glucose, and fructose), fiber, flavonoids, polyphenols, citric acid, and minerals (calcium, chlorine, phosphorus, and sodium)	Reduced risk of heart disease and prevents cancer, kidney stones, blood clots, arthritis, and nausea. Treatment of skin acne, natural energizer, and stress buster.	Moderate: Supported by several studies on individual components (vitamin C, polyphenols, basil), but limited clinical evidence on the candy format	[21, 31]
Pineapple and carrot gummy candies (pineapple juice, carrot juice, agar-agar, and sugar)	Manganese, vitamin C, bromelain, β -carotene, vitamin A, rhodopsin, α -carotene, lutein, and soluble fiber	Prevent cell damage, heart diseases, microbial infections, arthritis, various cancers, and so on. Strengthening bones, teeth, and connective tissues, Improved vision and skin health, reduced cholesterol level	Strong: Carotenoids, vitamin C, and bromelain have well-documented effects supported by epidemiological and experimental studies	[73, 92]
Pineapple and beetroot gummy candies (pineapple and beetroot juice)	Protein, carbohydrates, total lipids, fiber, β -carotene, betanin, essential minerals (calcium, iron, magnesium, phosphorus, potassium, and sodium), and vitamins, including vitamins C, B1, B2, B3, B5, B6, and A, as well as folate and betaine	Improves digestive health; natural anti-inflammatory properties; rich in nutrients and high in β -carotene content.	Moderate to strong: Beetroot bioactives and pineapple antioxidants supported by human/animal trials; specific candy formulation less studied	[32, 84]
Flavored pineapple candy (pineapple, sugar syrup, and different syrup—tulsi extract, ginger extract, mint extract, and cardamom extract)	Essential nutrients such as vitamins A, B, and C, as well as organic acids, manganese, calcium, and the bromelain enzyme	Cold and cough treatment; bone and teeth health; prevent cancer, arthritis, blood clots, and hypertension	Limited to moderate: Traditional uses and bioactive properties documented, but limited controlled studies on candy matrices	[54, 85]

medication for pain relief and fever reduction [79]. FeG microparticles are based on chitosan to enhance iron consumption daily [80]. The development of gummy candies enriched with prebiotics and probiotics showed exceptional antimicrobial qualities against a range of pathogenic bacteria [82]. Regulatory bodies, such as the FDA or EFSA, assess the safety and efficacy of pineapple-derived ingredients like bromelain, ensure compliance with food safety standards, and monitor potential allergens. Additionally, pineapple-based products must adhere to labeling requirements, particularly when marketed as functional foods with added health benefits, to ensure consumer protection and truthful communication [37, 81].

6. Preparation of Pineapple-Based Candy

Preparing candied pineapple involves soaking pineapple slices in a salt solution, blanching, steeping in syrup, drying in a dehydrator, and storing for up to 3 months [12, 13]. A study conducted by Vaiphei & Joseph [33] included the development of pineapple candy using various syrup solutions, such as sugar, mint, rose, tulsi, ginger, and cardamom, in six different ratios. The most effective treatment contained 60% sugar syrup and 10% rose extract. The study revealed that this treatment yielded the best overall properties, including pH, ascorbic acid content, titratable acidity, total soluble solids (TSS), taste, color and appearance, aroma, and overall acceptability. The findings suggest that pineapple candy can be made using various syrup solutions, and the resulting properties can be enhanced by selecting the appropriate ratio and extract [31, 32].

A study by Jothi et al. [21] includes that the pineapples were sorted, peeled, washed, and salt-treated and then treated with potassium metabisulfite. Further, the slices were blanched and steeped in sugar syrup for 7 days. The boiling process with flavored syrups was done until reaching a 70 °Brix level. Pineapple slices were drained, dried, and packaged. Arya et al. [89] created herbal pineapple candy with six flavored syrups. The pineapple candy made with 70% sugar syrup and 10% basil leaves was found to have the best organoleptic properties and physicochemical attributes. Similarly, according to the study's findings, Altamash et al. [83] developed a pineapple and beetroot juice candy using a mixture of juices in four ratios. Sugar and agar-agar were added to improve texture and flavor. The mixture was gently heated and cooled before being poured into molds and refrigerated. The candy with 90% pineapple juice and 10% beetroot juice had the best overall quality.

The study conducted by Purba et al. [42] experimented with pineapple-based candies mixed with moringa leaf juice at five different concentrations. The best quality candy was achieved with 25% moringa leaf juice and 75% pineapple juice. The process involved heating and stirring the mixture with sugar, jelly powder, and Arabic gum until it reached 90°C. The mix for the jelly was poured into molds and left to solidify at room temperature for 1 hour. After that, it was refrigerated at 10°C for 12 h and dried in an oven at 50°C for 2 days. Finally, the jelly candy was packed into plastic clips for further observation.

The experiment conducted by Baviera et al. [85] found that using vacuum impregnation, the mild-temperature pineapple candying process can yield high results with no weight loss. This includes using a low-concentration osmotic solution (25 °Brix) for 30 min, followed by two dehydration steps using progressively concentrated osmotic solutions (55 °Brix for 24 h and 65 °Brix for 48 h). Reducing the temperature to 15°C enhances product quality by reducing shrinkage and increasing process yield. The smaller sample size also reduces weight loss.

Compounds such as gelatin, pectin, starch, agar, alginates, and gums are prominently used to prepare candies. These act as gelling agents and improve the candies' textural properties. The addition of these compounds also causes potential changes in the nutritional profile of the candies. A recent study by Pereira et al. [94, 95] used gelatin (500°C) and sucrose (400°C) to develop Tepache jelly candies made from pineapple peel and concluded a decrease in vitamin C content, which is due to the retention of water content and antioxidant activity with an increase in augmentation of sucrose and gelatin. In contrast, there was no change in reducing sugar content with the addition of gelatin alone, and this is due to the lack of sugar in gelatin. Also, an increase in the concentration of gelatin and sucrose led to an increase in moisture content due to the hydrocolloid nature of gelatin, pH, and ash content. Another study by Pillai et al. [78] used pineapple peel extract with gelatin as a gelling agent for preparing guava gummies, which led to a reduction in moisture content and a pH increase with the addition of the extract. In contrast, an increase in ash content was observed. In the case of reducing sugar, no change was reported.

A gummy candy was prepared from pineapple juice, beetroot juice, agar-agar, and sugar, and an increase in fat, acidity, ash, and moisture content was found. The parameters of protein, β -carotene, and ascorbic acid content were reported to be reduced. The content of β -carotene was decreased due to the addition of beetroot. No significant change was noted regarding carbohydrates and reducing sugar by Rathnavelu et al. [96]. Another study by Efe et al. [97] developed gummy candies from pineapple peel powder and cornstarch, indicating low pH and water activity. The TSS showed a higher content in pineapple-based candies. Guava and pineapple jellies were prepared using honey as a sweetener. The lowest moisture content was recorded after the candy preparation, and the total soluble content, pH, and ash content were reduced, respectively, while the highest vitamin C and β -carotene content was due to the addition of lemon by Benucci et al. [98].

7. Textural and Color Properties of Pineapple-Based Candies

Carotenoid and xanthophyll pigments in pineapple peel extract can act as natural food colors. Carotenoids produce yellow, orange, and red tones when added to substances. A high concentration of carotenoids can cause a product to turn red or have a reddish hue. Gummy candies are bright yellow without pineapple peel extract paste, and adding this extracted peel paste drastically changes the color from bright

yellow to orange [99]. Subsequently, the higher amount of the peel paste addition makes the color of the gummy candies darker. The color change is due to the light yellowish-brown shade of peel paste, which reduces the brightness of the candies. Adding pineapple peel extract paste gives gummy candies the highest texture qualities, such as gumminess, chewiness, and hardness, similar to commercial products [27].

Gummy candies prepared with pineapple powder were less bright, had more intense color saturation, and appeared yellow-brown. The texture analysis showed these modified candies were firmer and more elastic but less intense than the control samples [88]. Elif Savaş and Melih Manav [100] analyze the fracturability of freeze-dried pineapple treats, pointing out that specific textural parameters such as chewiness and adhesiveness cannot be assessed due to their brittle structure. Although the hardness measured 33 ± 2.05 N, the amorphous components did not meet the desired fracture strength. The force-time curves show high deformability with a clear fracture point. The lightness of jelly candy was influenced by the ratio of moringa leaf juice to pineapple juice, with higher amounts of pineapple juice resulting in a lighter color [42].

Colors shift in freeze-dried pineapple treats. Lightness (L^*) and yellowness (b^*) rose during freeze-drying, but WPC reduced lightness in predried samples. Gum Arabic (GA) and other hydrocolloids influenced brightness, and linseed oil (LO) also contributed. Freeze-drying increased brightness due to surface porosity and microbubbles. The greenness (a^*) value increased after drying due to structural changes caused by vacuum sublimation [101]. Pineapple powder addition did not significantly affect the lightness (L^*), but it caused a notable increase in the yellow hue (b^* value) [89]. The taste and texture of freeze-dried pineapple treats. The fruity flavor dominated; however, some samples were rancid due to LO and propolis oxidation. Whey protein concentrate (WPC) enhanced smoothness and chewiness, whereas GA marginally reduced brittleness and oiliness. Freeze-drying preserves flavor but may result in unpleasant scent alterations. Thermal characteristics of the components were also investigated [102].

8. Nutritional and Health Benefits of Pineapple-Based Candies

Herbal pineapple candy: Herbal pineapple candy is a nutritious and delicious treat that contains vitamin C, manganese, fiber, and various minerals. It also includes enzymes such as bromelain and chlorophyll from both pineapple fruit and basil leaves. These elements contribute to its taste, flavor, and health benefits [32]. The nutritional profile of herbal pineapple candy includes the following components: TSS content of 73.75 °Brix, total sugar content of 65.30%, reducing sugar content of 57.70%, acidity of 0.10%, and ascorbic acid content of 6.10 mg/100 g pulp. These values were obtained after 90 days of storage and are specific to the herbal pineapple candy prepared in the study. The pineapple-based candy's health benefits (Figure 4) may include reducing the chances of heart disease and cancer,

preventing kidney stones and blood clots, relieving arthritis and nausea, treating skin acne, and acting as a natural energizer and stress buster. Moreover, sodium alginate has been used as a carrier material, along with positively charged amino acids as stabilizing agents, for the controlled release of bromelain in *in vitro* studies [86, 95].

Pineapple and beetroot gummy candies: Incorporating pineapple and beetroot juice in producing gummy candy presents numerous health advantages. The nutrition profile of gummy candy prepared using pineapple and beetroot juice is diverse. In a 100 g serving, the candy provides approximately 43 kcal of energy, 1.61 g of protein, 0.17 g of total lipid, and 9.56 g of carbohydrates. Additionally, it contains 2.8 g of fiber and various essential minerals such as potassium, magnesium, phosphorus, sodium, calcium, and iron. The candy also offers a range of vitamins, including vitamins B1, B2, B3, B5, B6, C, and A, as well as folate and betaine. It is also low in cholesterol and fat and is renowned for its digestive aid [90, 92].

On the other hand, beetroot is packed with fiber and helps grow good bacteria in the digestive system, which strengthens the immune system. It also has betanins, which provide several health benefits, like promoting cardiovascular health and reducing the risk of skin and lung cancer. Consequently, including pineapple and beetroot juice in gummy candy offers consumers an abundance of nutrients and a high β -carotene content [83].

Flavored pineapple candy: This candy is made from pineapple, sugar syrup, and a variety of extracts, including mint, ginger, tulsi, and cardamom. It contains essential nutrients such as vitamins C, A, and B, along with organic acids that promote overall health and well-being. The high vitamin C content may help alleviate symptoms of colds and coughs, while both calcium and vitamin C contribute to stronger bones and teeth. Additionally, the candy is rich in antioxidants and compounds that are associated with a reduced risk of certain types of cancer. The bromelain enzyme found in pineapple may also help reduce redness, swelling, and pain, potentially alleviating symptoms of arthritis. Moreover, consumption of pineapple candy may help prevent hypertension and reduce the risk of blood clots [95]. It is important to note that individual results may vary, and it is always recommended to consume candy in moderation as part of a balanced diet. The extracts, such as mint, ginger, tulsi, and cardamom, add flavor and contribute potential health benefits through their bioactive compounds and antioxidants [33].

The study by Achumi et al. [87] prepared pineapple and carrot gummy candies. These candies offer a delightful combination of flavors while delivering many nutritional benefits. It provides abundant vitamin C, β -carotene, manganese, and bromelain. Manganese is crucial in strengthening bones and connective tissues, contributing to overall skeletal health. Vitamin C, coupled with bromelain—an enzyme found in pineapple—is a powerful antioxidant that helps prevent cell damage and protect against diseases like heart disease, microbial infections, arthritis, and various cancers. The infusion of carrot juice enhances the nutritional profile due to the presence of β -carotene, which is converted into vitamin A. Vitamin A is essential for

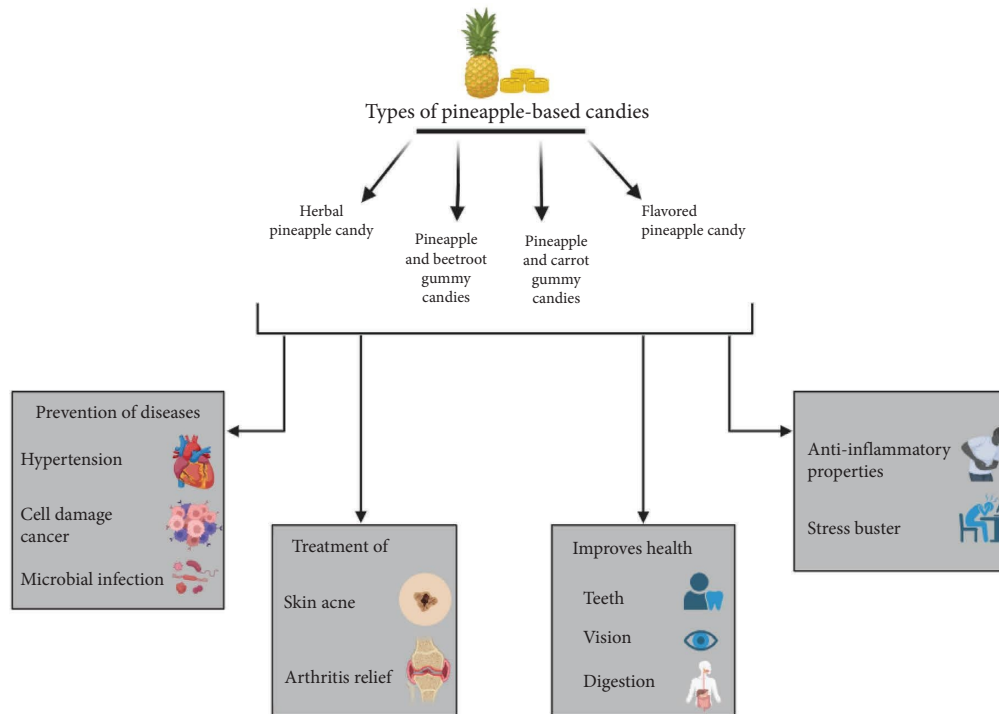


FIGURE 4: Health benefits of different pineapple-based candies.

maintaining rhodopsin, a light-sensitive protein in the eyes, contributing to improved vision [30, 74].

Furthermore, the α -carotene and lutein present in carrots improve eye health. Additionally, the soluble fiber from both pineapple and carrots aids in reducing cholesterol levels, promoting cardiovascular health. These gummy candies containing the bromelain enzyme not only support overall well-being but also contribute to healthy teeth by inhibiting the occurrence of tooth decay [30]. Varieties of pineapple-based candies, their nutritional composition, and their health benefits are shown in Table 3 and Figure 2. Pineapple candy is a delicious and beneficial option for those seeking to support their overall health [90]. It is always advisable to consume candy in moderation as part of a balanced diet. Pineapples have gained significant attention due to their nutritional value. The use of pineapple has led to the creation of various products that may serve as functional foods. However, the process of making pineapple candy involves high temperatures and varying pH conditions that can denature the enzyme bromelain and flavonoids, potentially diminishing their functional and biological properties. Notably, bromelain retains its proteolytic activity up to 60°C, but it loses its effectiveness beyond this temperature [53]. Consequently, consuming bromelain in candy form may not offer the same health benefits as consuming it from raw pineapple or in supplement form.

9. Industrial Feasibility of Bromelain-Infused Candies

The large-scale production of bromelain-enriched candies offers both opportunities and challenges. From a cost perspective, the extraction and purification of bromelain remain

relatively expensive compared to conventional flavoring or texturizing additives, which could increase the overall production cost of these fortified candies [15, 16, 40]. However, advancements in enzyme immobilization, encapsulation techniques, and the use of pineapple by-products, such as stems and peels, could significantly lower raw material costs and enhance process economics [2, 23, 44, 86, 94, 95].

In terms of scalability, confectionery manufacturing lines can integrate bromelain with minimal modifications, particularly in gummy and jelly systems that operate at lower processing temperatures. Nonthermal technologies, such as spray drying with carriers or microencapsulation, also enhance scalability by ensuring greater retention (Table 4) of enzyme activity during mass production [15, 16, 23, 44].

Consumer acceptance is another critical factor. With the increasing demand for functional foods and clean-label products, bromelain-fortified candies may attract health-conscious consumers looking for digestive and anti-inflammatory benefits in convenient formats [15, 16]. However, potential issues, such as changes in texture, alterations in taste due to enzyme activity, and allergenicity, must be carefully addressed through fully experimental formulation and transparent labeling. Therefore, successfully balancing cost, process feasibility, and consumer expectations will be essential for the industrial adoption of bromelain-based candies.

10. Emerging Insights

Bromelain is a thermolabile enzyme, which means its structure can be destabilized and its activity reduced under certain conditions. Its incorporation into confectionery

TABLE 4: Comparative synthesis of bromelain retention in different processing methods.

Processing method	Description	Bromelain retention (%)	References
Fresh pineapple	Raw edible fruit pulp	100	[13, 103]
Thermal processing (pasteurization, canning)	Juice heating at 85°C–95°C for 15–20 min	5–15	[47, 103, 104]
Spray drying	Encapsulation of pineapple juice powder	25–40	[44, 105]
Microwave drying	600 W power, 10–12 min	20–35	[106, 107]
Nonthermal processing			
High-pressure processing (HPP)	400–600 MPa for 5–10 min	70–85	[47, 108]
Pulsed electric field (PEF)	20–30 kV/cm field strength, 100 pulses	65–80	[46, 109]
Ultrasound treatment	20–40 kHz, 10–15 min	60–75	[45, 107, 110]
Freeze-drying	Pineapple juice powder under low temperature/vacuum	55–70	[44, 105, 111]

products presents unique challenges due to the high sugar concentration, low water activity, and acidic pH levels typically found in these systems [48]. Traditional high-temperature processes, such as boiling sugar, make bromelain inactive for therapeutic use [49]. Additionally, the enzyme's proteolytic activity may interact with proteins like gelatin or milk derivatives, affecting texture, mouthfeel, and overall sensory acceptance. However, there is a lack of systematic studies examining these interactions in bromelain-infused candies [72, 73, 84].

To address these challenges, innovative stabilization approaches have been explored. Encapsulation using biopolymers shows promise in protecting bromelain from thermal and pH-induced degradation while allowing for controlled release in the gastrointestinal tract [50, 51]. Nonetheless, a critical gap in research exists regarding comparative studies across different candy matrices—such as boiled sugar, gummy, and jelly systems—to determine which formulation best preserves enzyme bioactivity [53]. Consequently, future work should focus on standardizing formulation strategies, optimizing encapsulation efficiency, and conducting in vivo validation to ensure both functional stability and consumer acceptance of bromelain-fortified confections.

Additionally, future research on bromelain should address three broader areas: (i) the standardization of extraction and purification techniques, as current methods yield variable purity and activity, limiting consistency in functional foods [13, 44]; (ii) bioavailability, since while animal studies show partial absorption, there is a lack of human pharmacokinetic and dose-response data [32, 84]; and (iii) regulatory compliance, as international disparities in labeling, safety thresholds, and substantiation of health claims restrict global acceptance [112]. Furthermore, optimizing nonthermal processing technologies such as freeze-drying, spray drying with encapsulants, and PEFs remain essential for enhancing the stability of bromelain in pineapple-based functional foods.

11. Conclusion

Pineapple candy as a functional food enhances its significance in the confectionery world. Bromelain-infused pineapple candies represent a promising category of functional confections, combining nutritional appeal with therapeutic potential. Pineapple, rich in vitamin C, antioxidants, and dietary fiber, contributes to flavor- and wellness-oriented product development. Including bromelain, a proteolytic enzyme known for its anti-inflammatory, anticoagulant, and digestive benefits, enhances the health value of these candies. However, effective commercialization requires overcoming key formulation and processing challenges such as bromelain's sensitivity to heat and pH, its allergenic potential, and the need for dosage consistency. Advances in low-temperature processing and encapsulation technologies—like pectin-based or low-heat systems—have shown promise in retaining up to 85% of bromelain activity while enhancing stability. Standardized analytical methods for enzyme activity and in vivo studies validating health outcomes are

essential to support functional claims. Furthermore, consumer acceptance research, cost optimization, and regulatory compliance will determine market success. As consumer demand for healthier sweet products grows, pineapple candies fortified with bromelain offer a unique, convenient vehicle for delivering essential nutrients and functional benefits, positioning them as a valuable innovation in the evolving landscape of functional foods [113, 114].

Data Availability Statement

Data sharing is not applicable to this article, as no datasets were generated or analyzed during the current study.

Ethics Statement

The authors have nothing to report.

Consent

The work has been submitted to the Journal of Food Quality for publication with the consent of all authors.

The undersigned hereby consents to the publication of the work in the aforementioned journal.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Muhammed Anjal Thondiyil: investigation and writing—original draft. Praveen Kumar Dubey: investigation, project administration, conceptualization, visualization, supervision, and editing. Swarup Roy: visualization, review, editing, and supervision. Aparajita Bhasin: visualization and editing. Atul Anand Mishra: visualization and supervision. Gayatri Mehta: visualization and editing.

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