

Review

Functionalization of Chocolate: Current Trends and Approaches to Health-Oriented Nutrition

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Abstract: Expanding the range of healthy food products is one of the most promising areas in the field of food science. In recent years, there has been an active development of the global trend of functional nutrition aimed at strengthening general health, as well as preventing common non-communicable diseases and metabolic disorders. Chocolate, occupying a leading position among confectionery products, continues to demonstrate a steady growth in consumption on a global scale, which is due to its unique taste and sensory and functional properties. Modern trends in the food industry are aimed at further improving the composition and properties of chocolate, which makes it a promising object for scientific research and innovative developments. This review is devoted to the systematization and study of modern research aimed at developing functional types of chocolate that meet the principles of healthy nutrition. The paper considers the potential of bioactive components, such as polyphenols, probiotics, prebiotic components, dietary fiber, polyunsaturated fatty acids, and plant extracts, for use in the functionalization of chocolate. These compounds have pronounced antioxidant, anti-inflammatory, antimicrobial, and cardioprotective properties. Particular attention is paid to the role of bioactive components of cocoa and chocolate in the prevention of chronic non-communicable diseases, strengthening the cardiovascular system, improving cognitive functions, and normalizing the composition of intestinal microbiota. In addition, promising areas in the field of production technologies and innovative solutions aimed at creating functional types of chocolate with improved consumer properties are considered. The relevance of these developments is due to the growing demand for food products that combine high taste qualities and functionality, which opens up new opportunities for health-oriented nutrition.

Keywords: functional food products; cocoa products; chocolate; bioactive compounds; health-oriented nutrition



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1. Introduction

Malnutrition is referred to as the imbalance in the nutritional and biological value of consumed foods, as well as the deficiency of essential micronutrients in the daily diet [1]. According to the estimation of the Food and Agriculture Organization of the United Nations (FAO), unhealthy dietary patterns lead to significant hidden costs in global agrifood systems, primarily due to the rise of non-communicable diseases [2]. Currently, a natural correlation has been established between balanced nutrition and the prevalence of diseases

such as neoplasms [3], diabetes mellitus [4], hypertension (with predominant damage to the heart muscle) [5], ischemic heart disease [6], gastric and duodenal ulcers [7,8], and various other pathological conditions. Optimal nutrition, balanced in essential micronutrients, plays a key role in maintaining high work capacity, preventing a wide range of diseases, strengthening the body's immune reserves, and enhancing resilience to adverse environmental factors [9].

A deficiency of vitamins, macro- and microelements, essential amino acids, dietary fiber, and polyunsaturated fatty acids in the body leads to a decline in the physical and cognitive abilities of a person. Additionally, it contributes to an increased impact of unfavorable environmental factors, the accumulation of heavy metal salts in the body, the development of stress, neuro-emotional tension, and disruption of metabolic reactions [10–12].

In recent years, the trend of functional nutrition has been actively developing throughout the world, aimed at enhancing the general condition of the body, preventing common non-communicable diseases, and improving the quality of life of the population [13]. The concept of functional nutrition originated in Japan in the 1980s [14]. Today, the functional food market is represented by a wide range of food products, which are divided into four main categories: natural food products containing a functional component, food products in which the concentration of certain components that negatively affect the general health of a person is reduced, products enriched with functional components, and food products, the component composition of which has been modified by restoring, replacing, or removing a certain ingredient [15].

When developing new functional food products, the main criterion for choosing a base ingredient for its modification and enrichment, as well as the subsequent application in healthy nutrition, is its widespread use and mass consumption among various population groups [16,17]. This approach ensures not only the availability of raw materials, but also a high probability of product acceptance by consumers, which is especially important when creating products for dietary and preventive nutrition [18]. One such product is undoubtedly chocolate, which is included in the daily diet of many people and is in high demand due to its taste and energy characteristics [19].

Chocolate is a confectionery product obtained by processing a mixture of cocoa derivatives (*Theobroma cacao* L.), milk components, sugars or sweeteners, and various food additives, and it is characterized as a high-calorie product [20]. The chemical composition of cocoa beans is distinguished by high levels of carbohydrates (31%), proteins (11%), fats (54%), fiber (16%), and minerals [21]. Chocolate has a stimulating effect on metabolic processes in the body due to the bioactive components of cocoa, such as theobromine, caffeine, and polyphenols [22]. These bioactive components contribute to mood enhancement, increased productivity, and the stimulation of metabolic activity.

Cocoa and its derivatives (chocolate, cocoa liquor, and cocoa powder) contain different amounts of polyphenols and have different levels of antioxidant potential [23]. Cocoa polyphenols include flavonoid and non-flavonoid compounds, and their total content, ranging from 12% to 18%, is based on the dry mass of beans [24]. Among the main groups of cocoa polyphenols are catechins (37%), anthocyanins (4%), and proanthocyanidins (58%) [25]. The antioxidant properties of these compounds play an important role in protecting the body against oxidative stress. Specifically, polyphenols inhibit lipid peroxidation processes, prevent the oxidation of low-density lipoproteins, and enhance the body's resistance to the effects of free radicals [26]. In addition, there is evidence of the modulating effects of cocoa and dark chocolate polyphenols on the intestinal microbiota, promoting the growth of bacteria that activate the tolerogenic anti-inflammatory pathway in the host body [27].

However, it should be noted that most chocolate products developed using traditional technology contain significant amounts of sugar, fat, and artificial flavoring additives [28]. The excessive consumption of these components can have an adverse effect on the body and, in particular, contribute to the development of chronic diseases, such as obesity, diabetes, and cardiovascular pathologies.

2. Technological Features of Chocolate Production

Chocolate production is a complex process involving numerous chemical reactions [29]. The chocolate production process is shown in Figure 1. The main stages during which the most important reactions that determine the taste characteristics of chocolate products occur include the fermentation, drying, and roasting of cocoa beans and the conching of chocolate [30].

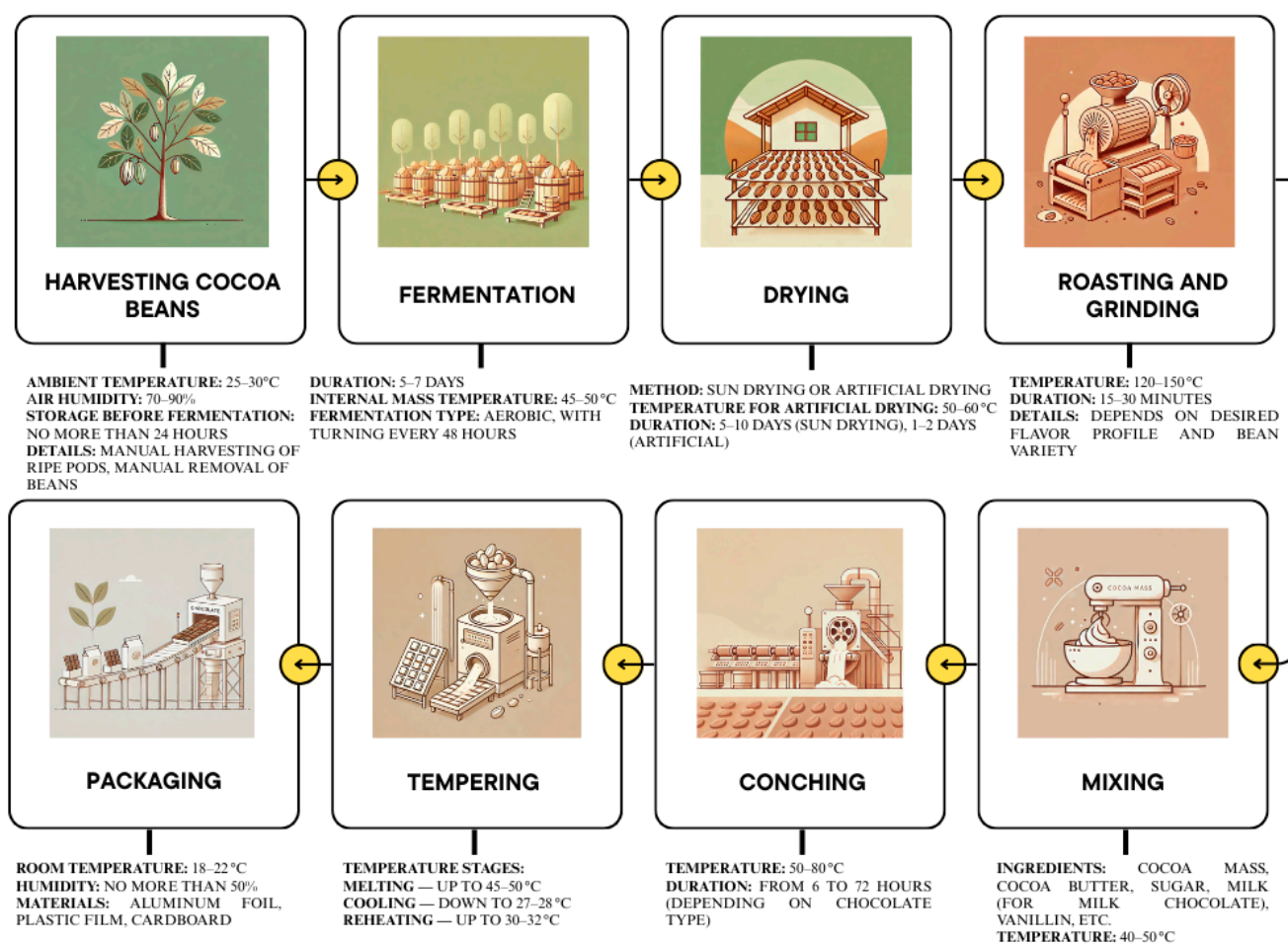


Figure 1. Technological process of chocolate production.

The fermentation of cocoa beans is still a largely spontaneous process. The main purpose of this process is to facilitate the subsequent drying of substandard cocoa beans by removing the pulp. Fermentation is a critical process responsible for the formation of volatile compounds such as alcohols, esters, and carboxylic acids [31]. A recent study revealed the temperature-dependent nature of cocoa fermentation, where 40 °C promotes the retention of bioactive compounds and 60 °C accelerates the formation of aroma precursors, demonstrating the need to optimize temperature conditions to achieve target product quality characteristics—either functional properties or organoleptic properties [32]. Temperature and pH are key factors regulating both enzyme activity and microbial sequence and metabolite formation, which together determine biochemical changes in beans [33].

The initial fermentation parameters of cocoa beans include low pH (3.3–4.8), high sugar content, and limited oxygen availability, with yeast and lactic acid bacteria playing a key role by metabolizing sugars, citric acid, and pectins, resulting in the formation of ethanol, organic acids, and pH changes [34]. The concentrations of metabolites (ethanol, lactic acid) vary depending on the fermentation region, while the pH dynamics are determined by the balance between the formation of acids by yeast and lactic acid bacteria and their subsequent utilization.

The optimal moisture content of cocoa beans is achieved with drying over 20 h and fermentation up to 200 h, while the pH is stabilized with 168–180 h of fermentation and drying at 60–65 °C, and the minimal fragmentation of the beans is ensured by short drying (10–20 h) and fermentation less than 80 h [35]. Optimal parameters of post-harvest processing, including fermentation for 6 days and 11 h and drying at 50.25 °C for 45 h, provide cocoa beans with commercial quality with a moisture content of 7.49%, a pH of 5.06, and fragmentation of 83 beans per 100 g.

The fermentation process contributes to the formation of the characteristic color and flavor properties of fermented cocoa beans [36]. This process includes two main stages: in the first anaerobic stage, yeast and lactic acid bacteria ferment the sugars and organic acids of the pulp, forming ethanol and lactic acid. They also produce organic acids and volatile compounds that form the aroma of cocoa. Next, lactic acid bacteria reach maximum growth, reducing the pH of the environment. In the second aerobic stage, acetic acid bacteria oxidize ethanol to acetic acid, which is accompanied by an increase in temperature to 45–50 °C. Their population reaches a peak and then decreases due to the effect of high temperature. In the later stages, heat-resistant bacteria of the genus *Bacillus* appear, which can produce enzymes and form compounds that impair the taste and aroma of cocoa beans. These processes determine the organoleptic properties of cocoa [37].

The next stage of chocolate production is drying and roasting the cocoa beans. The parameters of these processes, including temperature conditions and duration, have a significant impact on the formation of taste characteristics, color, and texture of the final product [38]. The most common methods of drying cocoa beans are natural drying in the open sun, drying in solar dryers, ovens, and microwave units, and using the sublimation method. The best results are achieved by drying in an oven at 45 °C, preserving the quality of the cocoa beans and providing a balance between reducing acetic acid and free fatty acids [39]. Alternatively, solar drying in a greenhouse at a temperature range of 21–52 °C allows for reaching 5.3% moisture in 7 days, minimizing the risks of contamination, but requires optimization to reduce time and improve organoleptic properties.

The purpose of the roasting process is to transform dry fermented beans into microbiologically safe raw materials with a characteristic aroma and the necessary fragility. The most widely used roasting method is the convection method, in which cocoa beans are treated with a stream of hot air. The temperature regime of convection roasting usually varies within the range of 130–150 °C, and the duration of the process is from 15 to 45 min [40]. After drying and roasting, the cocoa beans are ground into a fine paste called cocoa mass or cocoa liquor using various equipment, such as ball mills, conches, or roller mills [41].

Conching is a processing step in which chocolate undergoes prolonged exposure to high temperatures, mechanical forces, and the addition of fats and emulsifiers [42]. This process results in significant changes in the physicochemical, rheological, and sensory properties of chocolate [43]. One of the primary objectives of conching is to achieve optimal fluidity and texture of the product, which is necessary for its subsequent technological processing [44]. In addition, an important role in the conching process is played by the removal of undesirable volatile compounds formed as a result of oxidative and carbonyl reactions catalyzed by heat and aeration [45]. This is achieved by the intensive mixing

and prolonged heating of the chocolate mass for several hours. The conching process goes through three main phases: dry, pasty/plastic, and liquid. During conching, solid particles are coated with a fat phase, which changes the rheological properties of chocolate. Viscosity decreases as the layer of sugar particles and cocoa mass increases, reducing the interaction between particles [46]. Time and temperature are the key parameters determining the degree of influence of conching on the formation of the flavor characteristics of chocolate. However, factors such as aeration, energy supply to the chocolate mass, and the design features of the conching machine also have a significant impact on individual physicochemical mechanisms associated with flavor modification. Conching affects the flavor properties of chocolate by changing the concentration of key flavor compounds or their distribution in the chocolate matrix. This, in turn, affects the interaction of these compounds with other components, as well as the kinetics of their release during consumption of the product [47].

After conching is complete, the process of tempering the chocolate mass begins. Tempering is a complex technological stage aimed at the controlled crystallization of cocoa butter with the formation of fat crystalline networks with a certain polymorphism, nano- and microstructure, melting temperature, as well as specified indicators of surface gloss and mechanical properties [48]. The tempering process begins with heating the chocolate mass to a temperature of 43–46 °C, at which all fat crystals completely melt. Then, the chocolate is cooled to 24–29 °C with constant stirring to create a mixture of stable and unstable crystalline nuclei, and reheated to 30–31 °C to melt the unstable nuclei while maintaining the stable ones before further processing [49]. Tempering parameters may vary depending on the characteristics of the cocoa beans used. The need for tempering is due to the complex polymorphism of cocoa butter and the aim to obtain a product that is stable during storage and has high-quality characteristics. Tempered chocolate can be used for molding and glazing.

After all these processes are completed, the chocolate is slowly cooled: first to 18 °C, and then to 7 °C. Cold-sealing technology is usually used for packaging chocolate, using low-odor, water-based adhesives. Packaging materials must provide reliable protection of the product from the effects of oxygen, moisture, and light. It is recommended to store finished chocolate at a temperature of 18–20 °C and a relative humidity of less than 50%, excluding and minimizing contact with direct light to preserve its quality and consumer properties [50].

3. Composition of Traditional Types of Chocolate

Chocolate is a semi-solid suspension of fine particles of sugar, cocoa, and milk (depending on the type of chocolate), which make up about 70% of the total mass of the final product. These particles are uniformly distributed in a continuous fat phase, which consists mainly of cocoa butter [51].

Chocolate confections, as processed cocoa bean products, are characterized by low protein content and high fat levels [52]. The average protein content in chocolate varies within 5–10% of the total mass, which is due to the technological features of its production and the composition of the used raw materials. The energy value of chocolate can exceed 3000 kcal/kg of product, which is due to the high level of carbohydrates and fats in its composition [53]. Carbohydrates in chocolate are mainly represented by sugars, the content of which reaches up to 45% of the total mass of the product [54]. The fat profile of chocolate is mainly represented by cocoa butter, which is the main source of lipids in the product, while the fat content can reach 30–40%. This high proportion of cocoa butter determines the texture and consumer properties of chocolate [55,56]. As the proportion of cocoa solids increases, the relative content of carbohydrates decreases, compensated by an increase in the total fat content.

These characteristics indicate the high energy value of chocolate but emphasize its limited benefits in terms of nutritional balance. The chemical composition of various types of chocolate is given in Table 1. Chocolate is also a source of a number of minerals, such as magnesium, potassium, copper, and iron [57,58]. These microelements play an important role in maintaining physiological functions. The content of these bioactive components varies depending on the percentage of cocoa solids in the product.

Table 1. The chemical composition of different chocolate types.

Compounds	Value		
	Dark Chocolate	Milk Chocolate	White Chocolate
Protein, %	8.5–10.4	5.0–8.4	5.3–6.0
Fat, %	40.0–42.0	28.0–41.0	31.0–32.5
Carbohydrate, %	31.0–35.0	43.0–58.0	55.5–60.0
Ash, %	1.2–1.5	1.3–2.6	1.2–1.6
Moisture, %	0.4–0.9	1.0–1.2	0.7–1.1
Energy, kcal	518–560	539–575	522–539
TPC *, mg CAE **/100 g	573.6–583.7	153.9–167.2	118.5–134.3
References	[59–61]	[52,59–63]	[59,60,64,65]

* TPC—total phenolic content; ** mg CAE—milligrams catechin equivalents.

The main categories of chocolate are dark, milk, and white chocolate, which are differentiated based on the content of cocoa solids, milk fat, and cocoa butter. These differences result in variations in the proportions of essential nutrients, such as carbohydrates, fats, and proteins.

Dark chocolate with a high content of cocoa products retains a significant number of polyphenols, flavonoids, procyanidins, and theobromine, as well as vitamins and minerals that help strengthen the immune system and maintain overall health [66]. Unlike dark chocolate, milk and white chocolate contain less cocoa, which leads to a decrease in the concentration of bioactive compounds in their composition. This is especially true for white chocolate, which is made from cocoa butter, sugar, milk, and emulsifiers and contains virtually no phenolic compounds [67]. In this regard, white chocolate produced using traditional technology is not considered a healthy food product. However, approaches to its modification are currently being developed aimed at improving its nutritional properties and functional characteristics [68].

The milk chocolate system is a dispersion of solid particles (cocoa, sugar, and milk powder) in a fat phase consisting mainly of cocoa butter [69]. Milk chocolate is characterized by a high energy value, which indicates an imbalance of macro- and micronutrients in its composition. The nutritional and biological value of milk chocolate is determined by its recipe composition and the characteristics of the raw materials. It should be noted that milk chocolate is characterized by a high content of added sugar and fat, as well as a low antioxidant potential [70]. At the same time, the level of protein in its composition remains insignificant.

The presented data indicate that traditional chocolate products contain different amounts of nutrients depending on the type of chocolate. These differences highlight the importance of choosing the type of chocolate according to individual consumer preferences and goals. Given the high popularity of chocolate and its significant impact on the diet, an important area of food science is improving the recipes and technologies for the production of chocolate products in order to enhance their functional characteristics. This approach involves enriching chocolate with biologically active substances that promote health while reducing the potential negative impact on the body.

4. Advancing Technologies in Functional Chocolate Development

The chocolate industry is constantly changing to meet consumer demands and adapt to modern healthy lifestyle trends. The development of technologies for creating functional types of chocolate as part of scientific research demonstrates exponential growth on a global scale [71]. This contributes to the widespread introduction of new functional products that expand traditional ideas about chocolate [72]. As a result of such modifications, chocolate is acquiring a new status as a smart choice for people who follow healthy eating principles.

The term “functional”, as applied to chocolate and confectionery products, is defined as “a product in which standard ingredients are replaced, removed, or supplemented by a component that performs a specific physiological function or has potential benefit for humans” [73]. Functional types of chocolate can be enriched with bioactive components that perform various functions: supplementing the main diet (dietary supplements) or having a pharmacological effect (nutraceuticals) [74].

Chocolate is an optimal matrix for the delivery of bioactive compounds, which is primarily due to its high consumer appeal [75]. A key aspect of creating functional chocolate is the selection of biologically active ingredients, including raw materials of plant, animal, and microbial origin. An important stage of research is determining the optimal dosages and stage of introducing these additives into the chocolate matrix, which ensures the preservation of their functional properties and bioavailability at all stages of the production process and ensures the high-sensory properties of the final product. In this context, special attention is paid to modern technological processing technologies, including the encapsulation of bioactive compounds, three-dimensional printing, and the replacement of traditional ingredients with more nutritious and functional alternatives. These technologies help to increase the nutritional value of chocolate products and improve the bioavailability of active components, enhancing the therapeutic and prophylactic effect (Figure 2).

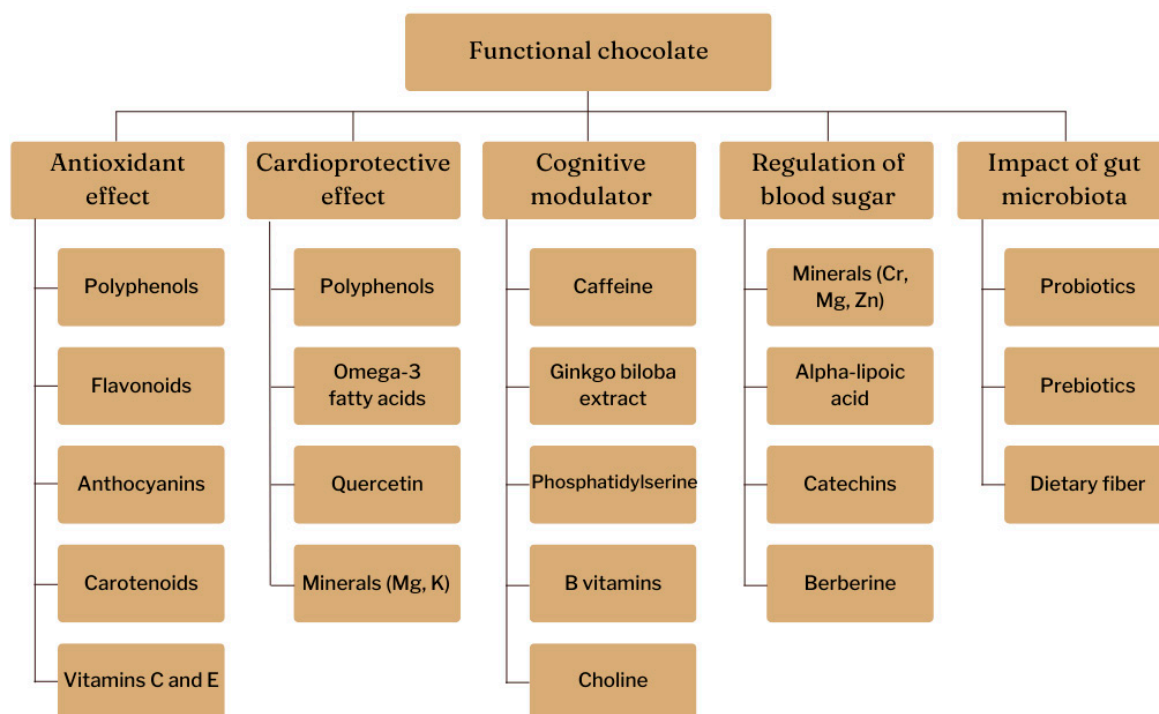


Figure 2. Potential Bioactive Components for Chocolate Fortification with Proven Physiological Effects Supporting Health Maintenance.

4.1. Encapsulation of Bioactive Components

Currently, there is evidence of the destruction of the structure of polyphenols, vitamins, probiotics, and other bioactive components during the processing and storage of chocolate products due to their sensitivity to the effects of exogenous factors, such as high temperatures, oxygen, light conditions, and the pH of the environment [76–78]. One of the effective areas in the field of the stabilization of bioactive substances in functional products is encapsulation technology based on the formation of a protective matrix or shell around the active substance, which minimizes its loss due to evaporation, chemical degradation, or migration in food systems [79]. In this case, the particles obtained in the encapsulation process can vary in size from several nanometers to several millimeters. However, preference is given to smaller particles, since they have a larger specific surface area, which contributes to a more efficient release of encapsulated active compounds and improves their interaction with biological tissues [80]. Table 2 shows the technologies for the production of chocolate products using encapsulated bioactive components.

Table 2. Encapsulation of bioactive compounds in chocolate production.

Bioactive Substance	Polymers	Encapsulation Method	Chocolate Type	Objective	References
<i>Morus nigra</i> extract	Liposomes	Spray drying	Dark chocolate	Enhancement of antioxidant activity	[81]
Chlorogenic acids	Pectin/Gelatin	Coacervation	Dark chocolate	Improvement of sensory and functional properties	[82]
<i>Vitex agnus castus</i> L. extract	Vegetable fat	Spray drying	Dark chocolate	Alleviation of premenstrual syndrome (PMS) symptoms	[83]
Herbal extracts <i>Crocus sativus</i> L., <i>Rosa damascena</i> , <i>Melissa officinalis</i> L., <i>Echium amoenum</i>	Gum arabic/Chitosan	Complex formation followed by spray drying	Dark chocolate	Improvement of preventive effects	[84]
Fish oil	Soy/Whey/Potato Protein	Emulsification followed by spray drying	Dark chocolate	Increase in omega-3 fatty acid content	[85]
β-Carotene	Whey protein isolate/Pullulan	Spray drying, freeze-drying/coaxial electrospinning	White chocolate	Shelf-life extension	[86]
Green tea extract	Maltodextrin	Spray drying	White chocolate	Increase in polyphenol content	[87]
Probiotics	Dry milk/Maltodextrin/Trehalose/Fructooligosaccharide/Starch	Spray drying	White chocolate	Formulation of probiotic chocolate	[88]
Probiotics and inulin	Sodium alginate	Microencapsulation	Milk chocolate	Formulation of synbiotic chocolate	[89]
Chia seed oil	Soy protein isolate/Maltodextrin/Inulin	Spray drying	Milk chocolate	Enrichment of chocolate with a plant-based source of Omega-3 fatty acids	[90]
Polyphenols	Maltodextrin	Spray drying	Chocolate bar	Enhancement of antioxidant activity	[91]
<i>Moringa oleifera</i> Leaf extract	Sodium alginate	Microencapsulation	Chocolate beads	Enhancement of antioxidant activity	[92]

In the production of functional chocolate products, various polymers are used as encapsulating agents, including liposomes, alginates, caseinates, pectin, gelatin, pullulan, maltodextrin, soy and whey protein isolates, vegetable fats, milk powder, starch, inulin, potato protein, fructooligosaccharides, chitosan, and acacia.

The key factors affecting the stability of encapsulated active ingredients are the production methods and types of wall material (carrier) [93]. Modern advances in food engineering have led to the development of a variety of encapsulation methods, each with unique advantages and limitations. The most common encapsulation methods are spray drying, coacervation, emulsification, lyophilization, cocrystallization, and complexation. Polymers used as wall material play an important role in ensuring biocompatibility and release of encapsulated bioactive substances, facilitating their targeted delivery and increased availability in functional foods and dietary supplements. These factors collectively

affect the functional characteristics and applicability of micro- and nanocapsules in the production of functional chocolates.

4.2. Technology of the 3D Printing of Chocolate

The use of 3D printing technologies in the food industry is of growing interest in applied scientific research. Chocolate is one of the most common products for 3D printing due to its ability to be extruded in a molten state, as well as its popularity with consumers [94]. The widespread implementation of 3D printing technology in the chocolate industry is due to the possibility of creating personalized forms, adapting to individual nutritional requirements, and accelerated prototyping. In addition, the use of 3D printing technology allows for the modification of the composition of traditional chocolate, including regulation of the cocoa content, as well as the integration of bioactive components and medicinal substances into the structure of chocolate products [95].

A recent study evaluated the preferences and perceptions of texture-modified chocolate produced using 3D printing technology [96]. To conduct textural and sensory analysis, experimental samples of 3D-printed chocolate products with different filling structures (patterns and filling levels) were made for subsequent textural and sensory evaluation. The geometric parameters of the samples, such as length, width, and thickness, demonstrated a high degree of compliance with the design values, which indicates the accuracy of 3D food printing (3DFP) technology and its potential for creating products with individual characteristics. A direct dependence of the product weight on the filling level was observed, which caused a change in their textural properties and could affect the economic indicators of production and the nutrient composition of the product. The results of the consumer survey showed a positive response from respondents, most of whom were already familiar with 3D food printing technology.

Another study examined the mechanical and rheological processes of white chocolate 3D extrusion printing by comparing the operation of a commercial printer and a syringe extruder [97]. The experimental data indicate high stability of the extrusion process, despite the presence of static zones in the bending area of the syringe. In all tests, the establishment of a quasi-stationary extrusion pressure was observed after a displacement of 10–20 mm. In the course of the study, the optimal parameters for the 3D printing of chocolate products were determined, including key indicators such as extrusion pressure and processing temperature. A temperature of 36 °C was recognized as a critical parameter, ensuring maximum extrusion stability. Deviations from the optimal temperature regime caused characteristic defects: nozzle clogging and damage to the layered structure of the product.

Another study demonstrated the feasibility of modifying chocolate composition using advanced testing methods. Using a 3D printer, chocolate products with a reduced sugar content and desired sensory characteristics were developed by layering chocolate with different sugar concentrations [98]. This technology achieved a 19% reduction in sugar content without changing the perceived overall sweetness or preference level. This demonstrates the feasibility of successfully using 3D printing technology to modify chocolate composition without significantly altering sensory characteristics, which is important for the development of functional chocolate products.

In the context of improving the functional properties of chocolate, the effect of adding carob extract to a dark chocolate recipe on 3D printing parameters, sensory and rheological properties, and product safety indicators was studied [99]. The developed three-dimensional chocolate sample with 30% carob extract demonstrated compliance with established standards of consumer properties and microbiological safety and received positive feedback from the tasting panel.

Based on the above, 3D printing technologies demonstrate high potential in solving public health and economic problems, offering innovative solutions in the field of functional food production while considering the properties of macro- and micronutrients, bioactive components, and printing parameters. Further research in this area should be aimed at expanding the range of functional food products and the cost-effectiveness of using additive technologies in food technology.

4.3. Sugar-Free Chocolate

Traditional chocolate is characterized as a high-calorie product (about 500 kcal/100 g) due to its high content of saturated fat and sugar [100]. The development of the concept of healthy eating has led to a change in consumer preferences: consumers who follow the principles of healthy eating avoid high-calorie products, giving preference to products with reduced sugar and fat content [101]. In this regard, the confectionery industry, in particular the chocolate industry, faces serious challenges associated with the need to reduce sugar content, as well as the development of chocolate with a complete absence of sugar, while maintaining the high-quality characteristics of the finished product, such as rheological properties, texture, taste, and aroma [55].

Sucrose has traditionally been used as the main sweetener in chocolate production. However, the high sugar content in the product has necessitated the search for alternative solutions characterized by reduced caloric value, a low glycemic index, and the ability to use chocolate products in healthy eating [102]. The creation of new functional types of sugar-free chocolate, which involves replacing sucrose with alternative ingredients, is a promising area in the field of food science and technology [103,104]. A recent study demonstrated the possibility of developing milk chocolate with a low glycemic index by using natural sweeteners. The following sugar substitutes were used as sweeteners: fructooligosaccharides (FOS), inulin, sorbitol, palm sugar, and xylitol [105]. The results of the studies showed that the experimental milk chocolate samples have high sensory characteristics and a low glycemic index ($GL < 10$) compared to the control sample containing sucrose. This confirms the effectiveness of using these sugar substitutes in the production of chocolate products.

Another study analyzed the nutritional and sensory profiles of two chocolates containing plant-based milk powder substitutes and alternative sweeteners [106]. In the first formulation, milk powder was replaced with a mixture of coconut copra, almonds, and soy protein isolate. In the second formulation, developed using dark chocolate, sucrose was replaced with coconut sugar, stevia, and erythritol, resulting in a reduction in caloric content of approximately 8%. The use of coconut sugar with a low glycemic index ($GL = 35$) makes the product a healthier alternative to traditional dark chocolate containing sucrose. The results of this study highlight the potential of alternative sweeteners in creating functional chocolates.

A study of the steady-state and dynamic rheological properties of molten dark chocolate using sorbitol, isomalt, and inulin as sugar substitutes showed that such a substitution significantly affects the structure of the final product [107]. In this regard, the use of mixtures of bulk sweeteners in the recipe is recommended as an effective approach to preserve the functional properties and textural characteristics of chocolate products.

Another study examined the effects of sugar substitutes (maltitol and xylitol) in different concentrations on the rheological properties of milk chocolate [108]. As a result, the optimal ratios of the sugar substitutes used were determined to achieve the most acceptable rheological properties similar to the control sample, which makes them promising as alternative options.

4.4. Low-Fat Chocolate

Another important factor limiting the use of chocolate products in a healthy diet is the high content of saturated fats, due to the significant proportion of cocoa butter in the composition. In this regard, consumers increasingly prefer chocolate products with a reduced fat content [109]. Fats are widely used in the confectionery industry, primarily to impart certain textural characteristics to products, as well as a carrier of fat-soluble aromatic substances [110]. Cocoa butter and milk fat are traditionally used as fat components of chocolate. A number of studies have proposed approaches to creating low-calorie dark and milk chocolate by partially or completely replacing the fat components with alternative ingredients. Cocoa butter equivalents, cocoa butter substitutes, and cocoa butter analogues, as well as vegetable fats and oils characterized by a balanced fatty acid composition, are used as fat substitutes [111].

A recent study analyzed the effect of replacing the fat component of chocolate on the sensory and rheological properties of the final product [112]. Palm olein and cottonseed oil were used as alternative fat components in various ratios and concentrations (25–100%). The results of the study showed that replacing fat with 25% palm olein did not have a significant effect on the rheological properties of chocolate, while increasing the proportion of the fat substitute led to significant changes in the characteristics of the samples.

Another study examined the functional role of limonene in reducing the viscosity and hardness of low-fat chocolate [113]. Limonene binds to cocoa butter, altering its crystallization structure and reducing the level of solid fat in the product. In addition, it was found that the addition of limonene in small quantities to cocoa butter leads to a significant decrease in the viscosity of liquid fat.

The possibility of partially replacing the fat phase of chocolate using a cocoa-based water-in-oil emulsion has also been demonstrated [114]. The use of this approach allows the development of reduced-calorie chocolate containing 40% less fat, without significantly changing the sensory and rheological properties of the finished product.

A promising direction for partial or complete fat replacement in chocolate products is the use of oleogels as alternative components. A recent study examined the properties of an oleogel obtained using hydroxypropyl methylcellulose (HPMC) as a structure-forming agent for sunflower oil [115]. The results of the study indicate the potential for replacing up to 70% of cocoa butter with oleogel without significant impact on the perception of chocolate, with the optimal substitution level being 50%.

The use of oleogels to reduce fat content is possible both in the production of solid chocolate and in the preparation of chocolate paste. One study examined the possibility of modifying the composition of chocolate butter using an oleogel based on cold-pressed walnut oil structured with 10% wax and monoglycerides as a replacement for milk fat [116]. The results of the study demonstrated that both versions of oleogels containing candidaceous wax and monoglycerides successfully reproduced the sensory properties of commercial chocolate butter taken as a control sample, which confirms the potential for their use as an alternative to traditional fat components.

Current research points to significant potential in using alternative fat components, such as oleogels, vegetable oils, and emulsions, to develop reduced-fat chocolate products, opening up new possibilities for creating functional chocolates for healthy eating.

4.5. High Protein Chocolates

Another trend in the field of healthy nutrition is the growing interest of consumers in products with a high protein content. Food proteins play an important role, exerting a significant influence on the functional properties of the final products. Modern approaches in food technology make it possible to produce a wide range of high-protein ingredients with

specified functional and technological properties [117,118]. The enrichment of chocolate with protein components is of interest from the standpoint of increasing its nutritional and biological value. The additional inclusion of milk proteins in the composition of chocolate products affects the bioavailability of polyphenols [119].

A number of studies have demonstrated the development of functional chocolate products with high protein content. A bioactive component based on high-protein sunflower flour and whey protein concentrate was developed for inclusion in the chocolate mass formula [120]. The developed protein composition provides a wide range of essential amino acids, close to the profile of an ideal protein. The inclusion of this additive in the formula saw an increase in the content of complete protein in the chocolate.

Another study evaluated the possibility of replacing sugar with milk protein and the effect of the ash-to-protein ratio on the properties of chocolate [121]. This replacement of sugar with milk protein resulted in chocolate with acceptable organoleptic characteristics, provided that the ash-to-protein ratio remained close to the control sample.

The approach to increasing the protein content of chocolate products is of interest not only in the context of their use in healthy nutrition but also for the development of specialized types of chocolate intended for athletes. One study assessed the possibility of developing functional chocolate with the inclusion of whey protein isolate and erythritol intended for the nutrition of athletes and diabetics [122]. The use of this composition contributed to the improvement of its nutritional value and provided protection against fat blooming (anti-blooming effect), which eliminated the tempering process.

Thus, the development of functional chocolate is a complex interdisciplinary task that requires the integration of knowledge in the fields of food technology, nutrition science, and applied biotechnology. When designing new functional chocolate products, it is necessary to take into account not only their potential health benefits but also such important aspects of consumer perception as sensory characteristics, cost, and ease of use, which are also characteristic of traditional products [123]. These developments can make a significant contribution to the prevention of alimentary-related diseases and improving the quality of human life.

5. Bioactive Components in Functional Chocolate

5.1. Alternative Types of Milk

Traditionally, dry cow's milk is used in the production of milk chocolate to give the product its characteristic creamy taste and rich milky aroma. However, in recent years, against the background of changing consumer preferences towards healthier and more environmentally sustainable nutrition, there has been a growing interest in the use of alternative types of milk of both animal and plant origin. This direction is becoming especially relevant in the development of functional types of chocolate.

The use of animal milk in the development of new types of functional chocolate involves replacing cow's milk with non-traditional types of milk, such as buffalo, goat, and mare's milk [124–126]. These types of milk have unique properties that can significantly improve the functional and organoleptic characteristics of the finished product. In addition, these types of milk are characterized by a balanced micronutrient composition, which contributes to their nutritional value. An important advantage of the non-traditional types of milk under consideration is their low allergenic potential, which makes them a safe alternative for consumers with allergies to cow's milk proteins.

Of particular interest is the use of alternative plant milk in the production of chocolate products due to the need to meet the needs of consumers with various dietary preferences. In particular, this approach is a relevant alternative for people with lactose and milk protein intolerance, as well as for those who adhere to a vegan lifestyle. Plant analogues,

such as soy, peanut, pea, and oat milk, are used as an alternative to cow's milk [127–129]. Alternative plant milk is characterized by a high content of dietary fiber, including prebiotic oligosaccharides, as well as the presence of essential amino acids, vitamins, and macro- and microelements. These components help to normalize intestinal microflora, reduce the level of triacylglycerides and cholesterol in the blood, and prevent a number of non-communicable diseases [130].

5.2. Polyphenols

The enrichment of chocolate products with valuable plant components can be aimed at increasing their beneficial properties, improving the micronutrient composition, and extending shelf life [131]. As noted earlier, the key component of chocolate—cocoa—is characterized by a high level of polyphenols, which have pronounced antioxidant activity. The content of polyphenols depends on the type of chocolate, its composition, and the technological process of processing. Some types of chocolate products, in particular white and milk chocolate, are produced with a low content of cocoa products, which significantly reduces the level of polyphenols in their composition. As a result, these products cannot be considered a valuable source of these bioactive compounds. In this regard, an urgent task of food technology is the additional enrichment of chocolate with polyphenols in order to develop functional chocolate products with high nutritional and biological value.

Various extracts and by-products of food production are considered a source of polyphenols. According to research results, green tea extract, characterized by a high phenolic profile and pronounced antioxidant effect, can serve as an additional source of polyphenols [132]. The inclusion of green tea extract in chocolate helps to increase the total concentration of phenolic compounds while reducing the sugar level and caloric content of the final product. Another promising source of phenolic compounds is peanut peel, which, despite its high phenolic profile, remains a little-used processed product and is practically not used in the food industry. Research results demonstrate the high antioxidant potential of this ingredient as a source of natural antioxidants for enriching chocolate products [133]. In addition, dry grape pomace and grape seed powders, traditionally waste products of winemaking, can be highly valuable sources of polyphenols. According to literature data, up to 70% of polyphenols are retained in the pomace after squeezing the grape juice [134]. The addition of only 3.5% dried grape pomace to milk chocolate can significantly increase the total polyphenol content without significantly changing the rheological and sensory properties of the final product [135]. Wild berries are also valuable sources of polyphenols, which allows them to be used as bioactive components in the chocolate industry. For example, studies show that the addition of blueberry juice can significantly increase the phenolic profile of white chocolate [136]. A similar effect is observed when using other berries in the production of functional chocolate, such as blackberries, raspberries, and pomegranates [137,138].

5.3. Probiotics

Probiotics are defined as live microorganisms that, when administered in adequate amounts, confer a health benefit on the host. The human gastrointestinal tract microbiota plays a key role in maintaining nutritional status and overall health [139]. Currently, the majority of products containing probiotic bacterial strains are fermented dairy products, including yogurts, fermented milk drinks, cottage cheese, sour cream, and cheeses. However, due to the increasing prevalence of lactose intolerance among the population, the development of new products enriched with probiotics is becoming especially relevant. One of the promising areas in this area is the creation of chocolate products containing probiotic cultures. Such products may become an attractive alternative for consumers who

limit their consumption of dairy products due to individual health conditions. Table 3 presents the results of scientific research devoted to the creation of functional types of chocolate with the inclusion of probiotics.

There are two main methods for enriching chocolate products with probiotics. The first method involves the direct introduction of lyophilized powders containing probiotic cultures into the chocolate matrix [140]. The second method involves the encapsulation of probiotics using various polymers that provide protection of microorganisms from adverse environmental conditions [141].

The health benefits of probiotics are strain-specific. Additionally, the viability of these microorganisms during production, storage, and passage through the gastrointestinal tract is a key factor determining their biological activity and effectiveness [142].

Table 3. Current research on probiotic chocolate.

Probiotic Strains	Delivery System	Chocolate Type	Survival of Probiotics	References
<i>Lactobacillus plantarum</i> 564	Spray Drying Encapsulation	Dark Chocolate	1×10^8 CFU/g in the first 60 days of storage 1×10^6 CFU/g after 180 days	[143]
<i>Lactobacillus rhamnosus</i> LGG	Encapsulation via Freeze-Drying	Dark Chocolate	1×10^7 CFU/g after 120/180 days of storage	[144]
<i>Lactobacillus delbrueckii</i> subsp. <i>bulgaricus</i>	Encapsulation Using the Emulsion Freeze-Drying Method	Dark Chocolate	1×10^7 CFU/g after 120 days of storage	[145]
<i>Lactobacillus plantarum</i> HM47	Spray Drying Encapsulation	Milk Chocolate	1×10^8 CFU/g after 180 days of storage	[146]
<i>Lactobacillus acidophilus</i> LH5/ <i>Streptococcus thermophilus</i> ST3/ <i>Bifidobacterium breve</i> BR2	Microencapsulation	Milk Chocolate/Semisweet Chocolate/ Dark Chocolate	1×10^8 CFU/g/ 1×10^9 CFU/g after 360 days of storage	[147]
<i>Lactobacillus acidophilus</i> NCFM/ <i>Bifidobacterium lactis</i> HN019	Freeze-Dried Powders	Dark Chocolate/ Milk Chocolate	2×10^9 CFU/g	[148]
<i>Lactobacillus paracasei</i>	Freeze-Dried Powders	Milk Chocolate	1×10^8 CFU/g after 180 days of storage	[149]
<i>Lactobacillus helveticus</i> MTCC 5463	Freeze-Dried Powders/Frozen Concentrates	Milk Chocolate	2.42×10^8 CFU/g after 15 days of storage	[150]
<i>Lactobacillus acidophilus</i> LDMB-01	Freeze-Dried Powders	Milk Chocolate	1×10^6 CFU/g after 90 days of storage	[151]
<i>Bifidobacterium breve</i> NCIM5671	Freeze-Dried Powders	Dark Chocolate	1×10^9 CFU/g after 90 days of storage	[152]
<i>Bifidobacterium animalis</i> subsp. <i>lactis</i> BB-12® <i>Akkermansia muciniphila</i> DSM 22959	Freeze-Dried Powders	Dark Chocolate/ Milk Chocolate	1×10^8 CFU/g/ 1×10^6 CFU/g after 28 days of storage	[153]
<i>Lactobacillus paracasei</i> / <i>Lactobacillus acidophilus</i>	Freeze-Dried Powders	White Chocolate	1×10^7 CFU/g after 90 days of storage	[154]

The prospects for the development of chocolate products enriched with probiotics may take functional foods to a new level. A number of studies demonstrate the effectiveness of the introduction of probiotics in combination with prebiotics, omega-3 fatty acids, and cocoa polyphenols [89,155,156]. Such combinations of bioactive components enhance the synergistic effect, contributing to the improvement of the intestinal microbiome, strengthening the immune system, and reducing the risk of developing chronic non-communicable diseases. The introduction of chocolate products enriched with probiotics into the diet corresponds to modern trends in healthy eating and preventive medicine.

5.4. Dietary Fiber and Prebiotics

Along with probiotics, the regular consumption of dietary fiber and prebiotics that can be metabolized by gastrointestinal microorganisms is one of the key dietary strategies aimed at modulating the intestinal microbiota [157].

The introduction of dietary fiber into the composition of functional chocolate improves its nutritional profile due to the inclusion of prebiotic components and reduces the sugar content in the final product. The prebiotic effect is a selective stimulation of the growth and metabolic activity of one or a limited number of microorganisms that are part of the intestinal microbiota, which helps to improve the health of the host. The most common types of prebiotics used to enrich functional foods are fructooligosaccharides (FOS) and inulin [158]. These types of prebiotic components are also widely used in the chocolate industry. A recent study examined the effect of packaging materials on the preservation of the quality of milk chocolate containing hygroscopic dietary fibers (inulin and FOS) [159]. The results of the study showed that the characteristics of milk chocolate (with and without the addition of hygroscopic dietary fibers) remain stable for 270 days at 20 °C and at 75% relative humidity when using packaging materials, such as biaxially oriented polypropylene (BOPP)/metallized BOPP and BOPP/white BOPP.

In addition, an effective way to enrich the product with dietary fiber and reduce the sugar content is to introduce polydextrose, which has potential prebiotic properties, into the composition of functional chocolate. Research results demonstrate a positive effect of polydextrose on the rheological properties of milk chocolate, as well as an increase in the content of dietary fiber in the finished product [160]. This effect is enhanced by the use of finer grinding and an increase in conching time, which allows for optimization of the texture and consistency of the finished product.

Another promising source of dietary fiber in functional chocolate may be resistant starch. This is especially important for white chocolate, which, unlike other types of chocolate, does not contain low-fat cocoa products, which are a traditional source of dietary fiber. According to research, the introduction of resistant starch helps improve the nutrient composition of white chocolate by increasing the proportion of dietary fiber without negatively affecting the color characteristics as well as the rheological and organoleptic properties [64].

D-tagatose and galactooligosaccharides (GOS) can be used as prebiotic components in functional chocolate. A recent study examined the effect of these prebiotic compounds on the physicochemical and organoleptic properties of milk chocolate [149]. The results of the study determined the optimal ratios of GOS and tagatose in milk chocolate that did not have a negative effect on the viability of probiotic cultures of *Lactobacillus paracasei*. This allows us to consider these prebiotics as promising bioactive components for the development of functional types of chocolate that combine high-sensory characteristics and functional properties.

The results of these studies allow us to consider prebiotics and dietary fibers as promising bioactive components for the development of functional types of chocolate that combine high sensory characteristics and pronounced functional potential.

5.5. Polyunsaturated Fatty Acids

As noted above, the functional properties of food products are largely determined by their chemical composition, including the fatty acid profile. The fat fraction of chocolate is predominantly represented by triglycerides and fatty acids and also contains minor amounts of minor compounds, such as tocopherols, triterpenols, and sterols. The fatty acid profile of chocolate includes saturated fatty acids (SFA), such as stearic acid (34%) and palmitic acid (27%), as well as a monounsaturated fatty acid (MUFA)—oleic acid (34%).

This fatty acid profile determines the ability of chocolate to maintain a solid consistency at room temperature (20–25 °C) and to form a homogeneous suspension consisting of solid particles evenly distributed in cocoa butter and milk fat [56].

According to the literature, consumption of ω -3 polyunsaturated fatty acids demonstrates significant potential in reducing the intensity of inflammatory processes, as well as in the treatment and prevention of metabolic syndrome [161]. In accordance with the recommendations of the Food and Nutrition Board of the National Academy of Medicine, the level of adequate intake (Adequate Intake, AI) of omega-3 polyunsaturated fatty acids varies depending on age, gender, and physiological state. For men, the intake rate is set at 1.6 g/day; for women—1.1 g/day; for pregnant women—1.4 g/day; and for nursing mothers—1.3 g/day [162]. However, despite these standards, there is currently a deficit in the consumption of ω -3 PUFAs in the diet of the population, which is due to the insufficient inclusion of foods rich in these bioactive compounds [163].

In this regard, the additional fortification of food products with polyunsaturated fatty acids may become an effective dietary strategy to overcome the existing deficiency and contribute to achieving the recommended level of their consumption. A number of studies have been devoted to studying the possibility of fortifying food products, such as dairy products, juices, chocolate milk, dark chocolate, white chocolate, and milk chocolate, with omega-3 polyunsaturated fatty acids [164–169].

The enrichment of chocolate products with polyunsaturated fatty acids can be achieved by introducing individual omega-3 and omega-6 fatty acids or in combination with other bioactive components, such as probiotics and water- and fat-soluble vitamins [155,170]. The stability of the introduced PUFAs in the chocolate matrix is influenced by various factors, such as fat content, low water activity, oxidation state, moderate temperatures, processing conditions, and the phenolic profile of the cocoa products used. Studies show that chocolate, being an effective delivery system for omega-3 fatty acids, ensures the preservation of the introduced polyunsaturated fatty acids both in the form of free-flowing powder and in microencapsulated form using various polymers [169].

5.6. Plant Extracts

Biologically active compounds of plant origin are widely used in various industries, including the pharmaceutical, food, and chemical fields [171]. Plant extracts are considered promising sources of bioactive substances that can be used to enrich functional types of chocolate. The inclusion of plant extracts in the composition of chocolate is aimed at improving its functional properties, such as the content of phenolic compounds and antioxidant activity. To date, more than 8000 different phenolic compounds have been identified, with fruits and vegetables being the main sources of natural antioxidants [172].

The use of plant components in the development of functional chocolate can make it an effective carrier for the delivery of bioactive components with high added value [67,123]. In addition, this approach helps to increase the shelf life of the finished product.

The potential of using plant extracts such as elderberry (*Sambucus nigra*) and chokeberry (*Aronia melanocarpa*) extract to improve the functional properties of dark chocolate with a high zinc lactate content was studied [173]. It was found that the addition of these extracts contributed to an increase in the antioxidant activity of chocolate, with the most pronounced effect observed in the sample with the addition of chokeberry extract. The inclusion of these plant extracts affected the physicochemical parameters, in particular, the moisture, fat content, and viscosity of chocolate.

In addition, the enrichment of chocolate with plant extracts improves the antimicrobial properties of the final product [174]. The effectiveness of commercially available plant extracts and essential oils, widely used as flavoring agents in the confectionery indus-

try, against pathogenic microorganisms was studied. It was found that the extracts and essences of lemon (*Citrus limon*), magnolia vine (*Schisandra*), plum (*Prunus*), and strawberry (*Fragaria × ananassa*) inhibit the growth and development of microorganisms such as *E. coli* O157:H7, *S. Aureus*, *B. Cereus*, and *L. Monocytogenes*. The above samples of plant extracts demonstrated a pronounced antimicrobial effect when storing chocolate at a temperature of 20 °C, which indicates the possibility of their use as a protective component to ensure product stability.

Seaweed extracts, which are rich sources of bioactive compounds, polysaccharides, antioxidants, minerals, and essential nutrients, such as fatty acids, amino acids, and vitamins, can also be used to fortify functional chocolate [175]. Commonly used types of seaweed in the chocolate industry include spirulina (*Arthrospira*) and kelp (*Laminaria*) [176,177]. Research in this field indicates the high potential of macroalgae and microalgae extracts as bioactive components for functional chocolate enrichment, opening new possibilities for developing innovative products with enhanced nutritional and functional properties.

6. The Health Benefits of Chocolate

6.1. Antioxidant and Anti-Inflammatory Properties

Polyphenols present in chocolate play a significant role in providing beneficial effects on the body (Figure 3). The antioxidant activity of cocoa products and chocolate products is determined by flavonoid compounds, such as catechin, epicatechin, and procyanidins [178,179]. The unique tricyclic structure of these compounds provides their ability to neutralize reactive oxygen species, bind Fe^{2+} and Cu^+ ions, inhibit enzyme activity, and enhance the endogenous antioxidant defense of the body [180].

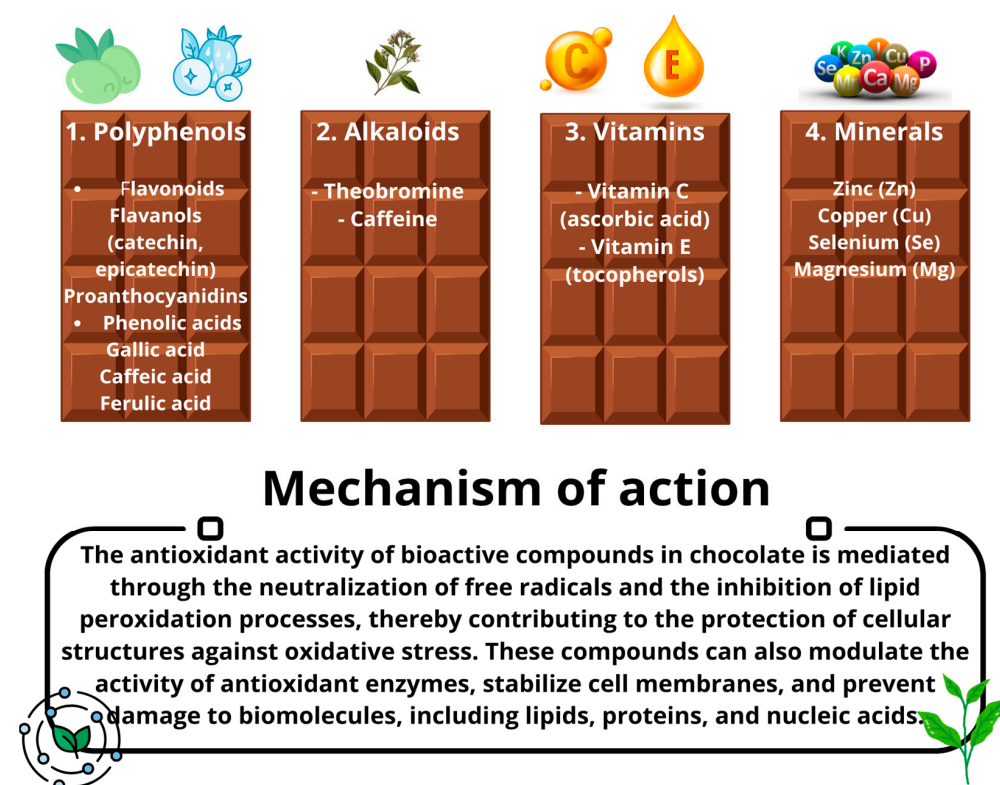


Figure 3. Bioactive compounds and antioxidant potential of chocolate.

Consumption of dark chocolate with a high cocoa content contributes to the intake of significant amounts of bioactive compounds, as well as essential macro- and microelements, which, according to scientific data, have a positive effect on human health [58]. Higher

cocoa content in chocolate correlates with increased levels of phenolic compounds, which play a key role in neutralizing free radicals and reducing oxidative stress.

In vivo, the antioxidant activity of flavonoids may be reduced by interactions with other food components. Studies show that dark non-milk chocolate significantly increases the antioxidant activity of blood plasma compared to milk chocolate [181]. This is due to the inhibitory effect of milk components on the absorption of antioxidants, which reduces the potential beneficial health effects.

The antioxidant properties of chocolate may help reduce the negative effects of toxic poisoning with heavy metal salts. A recent study showed that the co-administration of chocolate with cadmium chloride (CdCl₂) in mice led to a significant reduction in DNA damage, decreased apoptosis, and cell necrosis, as well as a decrease in oxidative stress and the restoration of mitochondrial function [182]. These results indicate a significant potential for chocolate products in reducing cadmium-induced toxicity.

In addition to polyphenols, cocoa and its derivatives contain bioactive compounds such as methylxanthines (caffeine, theobromine), peptides, and minerals, which can have both enhancing and suppressing effects on the antioxidant properties of the product [183]. Research suggests that the magnitude of the beneficial effects of cocoa may depend on a number of factors, including the bioavailability of polyphenols, the initial antioxidant status of the body, and the health status of the study participants (Table 4).

Table 4. Studies of the effects of chocolate intake on health.

Type of Evidence	Chocolate Type	Duration of Intake	Recommended Amount or Frequency of Intake	Health Benefits	Mechanism of Action	References
Clinical trials	Dark chocolate (containing 84% cocoa)	8 weeks	30 g per day, in combination with Therapeutic Lifestyle Changes (TLC) recommendations	Regulation of metabolism	Reduction in glycemic parameters (glucose, HbA1c), improvement in lipid profile (LDL, triglycerides), and attenuation of systemic inflammation (TNF- α , IL-6, hs-CRP) are mediated by the effects of flavonoids on glucose metabolism, oxidative stress, and endothelial function.	[184]
Clinical trials	Dark chocolate (containing 99% cocoa)	6 months	10 g per day (Polyphenol content: 65.4 mg)	Fat-lowering effect	The reduction in both absolute fat mass and relative body fat percentage in postmenopausal women is attributed to the modulation of lipid metabolism.	[185]
Clinical trials	Dark chocolate (containing 78% cocoa)	8 weeks	12 g per day	Mood modulation	The anxiolytic effect is mediated through the modulation of serotonergic neurotransmission, without significant effects on sleep parameters or anthropometric measures. The antioxidant effect was associated with a transient increase in plasma epicatechin concentration and a concurrent reduction in oxidative DNA damage in peripheral blood mononuclear cells, without any significant changes in total antioxidant capacity.	[186]
Clinical trials	Dark chocolate	2 weeks	45 g per day	Antioxidant effect		[187]

Table 4. Cont.

Type of Evidence	Chocolate Type	Duration of Intake	Recommended Amount or Frequency of Intake	Health Benefits	Mechanism of Action	References
Clinical trials	Dark chocolate	3 weeks	75 g per day	Lipoprotein-protective effect	An increase in HDL cholesterol levels induced by components of cocoa mass, along with a potential modification of LDL lipid composition by chocolate-derived fatty acids, may contribute to a reduction in lipid peroxidation in vivo.	[188]
Clinical trials	Dark chocolate	Single dose	25 g of dark chocolate with high and low polyphenol content	Improvement of cognitive functions	Improved cognitive performance associated with reduced activity in brain regions responsible for executive functions suggests a more efficient use of neural resources during prolonged task performance.	[189]
Clinical trials	Dark chocolate (containing more than 85% cocoa)	1 months	40 g per day (administered as 20 g every 12 h)	Gut health maintenance	Reduced intestinal barrier permeability achieved through the restoration of tight junction protein expression (occludin), decreased levels of zonulin and lipopolysaccharides (LPS), and suppression of LPS-induced oxidative stress in epithelial cells.	[190]
Clinical trials	Dark chocolate (containing more than 85% cocoa)	2 weeks	40 g per day	Gut health maintenance	“Reduced levels of lipopolysaccharides and zonulin, reflecting improved intestinal epithelial integrity and decreased gut barrier permeability, mediated by the interaction of cocoa bioactive compounds with regulators of intercellular junctions.”	[191]
Clinical trials	Dark chocolate (containing 70% cocoa)	4 weeks	60 g per day	Gut health maintenance	Decreased subjective hunger associated with elevated plasma levels of short-chain fatty acids, which influence appetite regulation through modulation of gut-brain axis activity.	[192]
Clinical trials	Dark chocolate combined with cocoa powder	4 weeks	43 g of dark chocolate plus 18 g of cocoa powder per day	Cardioprotective effect	A reduction in total cholesterol, LDL cholesterol, and apolipoprotein B levels, including atherogenic small dense LDL fractions, attributed to the synergistic effects of flavanols, monounsaturated fatty acids, and dietary fiber on lipid metabolism and lipoprotein structural modification.	[193]
In vitro and In vivo studies	Milk chocolate (containing 30% cocoa solids)	4 days	50 g per day	Immunomodulatory anti-inflammatory effect	Enhanced production of the pro-inflammatory cytokines IL-1 β and TNF- α in response to <i>P. acnes</i> stimulation, along with increased secretion of the immunomodulatory cytokine IL-10 following exposure to <i>S. aureus</i> .	[194]

Table 4. Cont.

Type of Evidence	Chocolate Type	Duration of Intake	Recommended Amount or Frequency of Intake	Health Benefits	Mechanism of Action	References
Ex Vivo and In Vivo studies	Milk chocolate/dark chocolate/cocoa powder/chocolate milk/chocolate syrup/cocoa butter	Acute (1-day) and chronic intervention (10 weeks)	For short-term effects: 22 g of cocoa powder/16 g of dark chocolate/For preventive effects (10 weeks): an equivalent of 2–40 g of dark chocolate per day	Antioxidant effect	Manifestation of antioxidant and anti-atherogenic effects mediated by the binding of polyphenols to low-density lipoproteins, enhancing their resistance to oxidation, without increasing oxidative stress or lipid load.	[195]
In vivo study in male Sprague–Dawley rats	Dark chocolate	3 months	Daily oral administration at a dose of 500 mg per kg of body weight	Improvement of cognitive functions	Reduction of hyperglycemia and oxidative stress, inhibition of acetylcholinesterase activity, and restoration of neuronal integrity in the hippocampus, collectively contributing to improved cognitive function in animals.	[196]

In addition, in vivo studies confirm the anti-inflammatory and immunomodulatory effects of cocoa products [197]. Long-term cocoa consumption affects intestinal and systemic immunity in rats. Research in this area shows that high doses of cocoa in young animals promote the activation of the T-helper 1 type (Th1) immune response and an increase in the number of $\gamma\delta$ T-lymphocytes in the intestine, while simultaneously reducing antibody production [198].

Thus, chocolate products with a high cocoa content have pronounced antioxidant and anti-inflammatory effects. However, further research, including long-term clinical trials involving various population groups, is required to fully understand the mechanisms of their effect on the body and optimize the use of these products in the prevention and treatment of diseases.

6.2. Impact on the Cardiovascular System

According to the data obtained in the course of experimental and clinical studies using cocoa and chocolate-based products, it was established that these products, rich in flavanols, play a significant role in cardioprotection and maintaining the health of the vascular system. The key physiological effects of chocolate include antioxidant activity, improvement of endothelial function due to vasodilation, reduction in blood pressure, inhibition of platelet aggregation, a decrease in the risk of coronary heart disease, heart failure, and cerebrovascular diseases, as well as a decrease in the severity of inflammatory processes [199,200]. The results of short-term randomized studies show that moderate consumption of chocolate has an anti-inflammatory and antiplatelet effect and also helps to increase HDL levels and reduce LDL oxidation [201].

The beneficial effects of chocolate on the cardiovascular system are associated with the biological activity of flavanols and procyanidins, which are found in significant quantities in cocoa and cocoa-based products [202]. The protective properties of these compounds in cardiovascular diseases are due to their ability to trap free radicals and chelate metals and interact with lipids and proteins, as confirmed by in vitro and in vivo studies [203–205]. Thus, the levels of flavanols and procyanidins observed in human and animal tissues correlate with their antioxidant and cardioprotective properties [125].

Studies in this area have shown that high doses of flavanols can induce both short-term and long-term increases or restoration of endothelium-dependent vasodilation in a variety of patient groups [206]. These groups include healthy individuals with cardiovascular risk factors (e.g., smoking, hypertension, hypercholesterolemia, or diabetes mellitus), cardiac transplant recipients, and patients with clinically evident coronary artery disease. The consumption of high-flavanol chocolate also results in significant improvements in flow-mediated vasodilation in both the short term (2 h) and long term (4 weeks) in patients with heart failure, compared to a control chocolate sample [207].

The results from another randomized, placebo-controlled trial ($n = 84$) showed that the daily consumption of 2 g of dark chocolate (70% cocoa) for six months reduced genotoxicity by reducing DNA damage and maintaining the integrity of cell nuclei, which is associated with the antioxidant activity of flavonoids [208]. In addition, improvements in biochemical parameters (reduction in total cholesterol, triglycerides, and LDL cholesterol) and anthropometric parameters (reduction in waist circumference) were noted, confirming the potential role of dark chocolate in reducing the risk of cardiovascular disease and metabolic syndrome.

Flavanols in *Theobroma cacao* contribute to the bitter and astringent taste of chocolate and confectionery products, which is often masked through intensive processing and the addition of flavoring agents. Numerous studies have suggested that the properties of dark chocolate vary depending on its composition and production technology, which poses challenges in assessing its potential health benefits [209]. The technological processing of cocoa products affects the content of monomeric flavonoids [(+)-catechin and (−)-epicatechin] and flavanols (quercetin and its derivatives). In particular, alkali processing leads to a 60% reduction in total flavonoid content, with the highest losses observed for (−)-epicatechin (67%) and quercetin (86%), indicating the impact of processing on polyphenol bioavailability as well as antioxidant and cardioprotective properties [210]. Given these findings, a comprehensive study of all processing stages and the development of chocolate products optimized for bioactive compound retention may enhance their positive health effects, including metabolic regulation, antioxidant activity, and cardioprotective benefits.

6.3. Effect on Cognitive Function

Different functional foods can have different effects on brain function. The identification of specific nutrients and analysis of their biological effects allow the development of evidence-based dietary interventions aimed at optimizing neuropsychological health and improving cognitive function (Figure 4). A number of studies have demonstrated that the consumption of foods high in flavanols has a significant neurobiological effect, contributing to the improvement of learning, memory, and cognitive function in general [211,212]. As mentioned earlier, cocoa and chocolate products are rich sources of flavonoids, particularly flavanols, which exhibit strong antioxidant and anti-inflammatory properties. Beyond their well-documented cardiovascular benefits, recent research has focused on their role in modulating neurocognitive functions, such as memory, attention, and cognitive flexibility, offering new insights into their potential applications in health-oriented nutrition [213].

The results of individual studies confirm that both short-term and long-term consumption of cocoa and cocoa-based products have a positive effect on various cognitive functions [214]. In the case of acute cocoa intake, the observed beneficial effects are probably associated with increased cerebral blood flow and increased cerebral oxygenation. In the case of the chronic consumption of cocoa flavanols in young people, an improvement in cognitive performance is observed, as well as an increase in the concentration of neurotrophic factors.

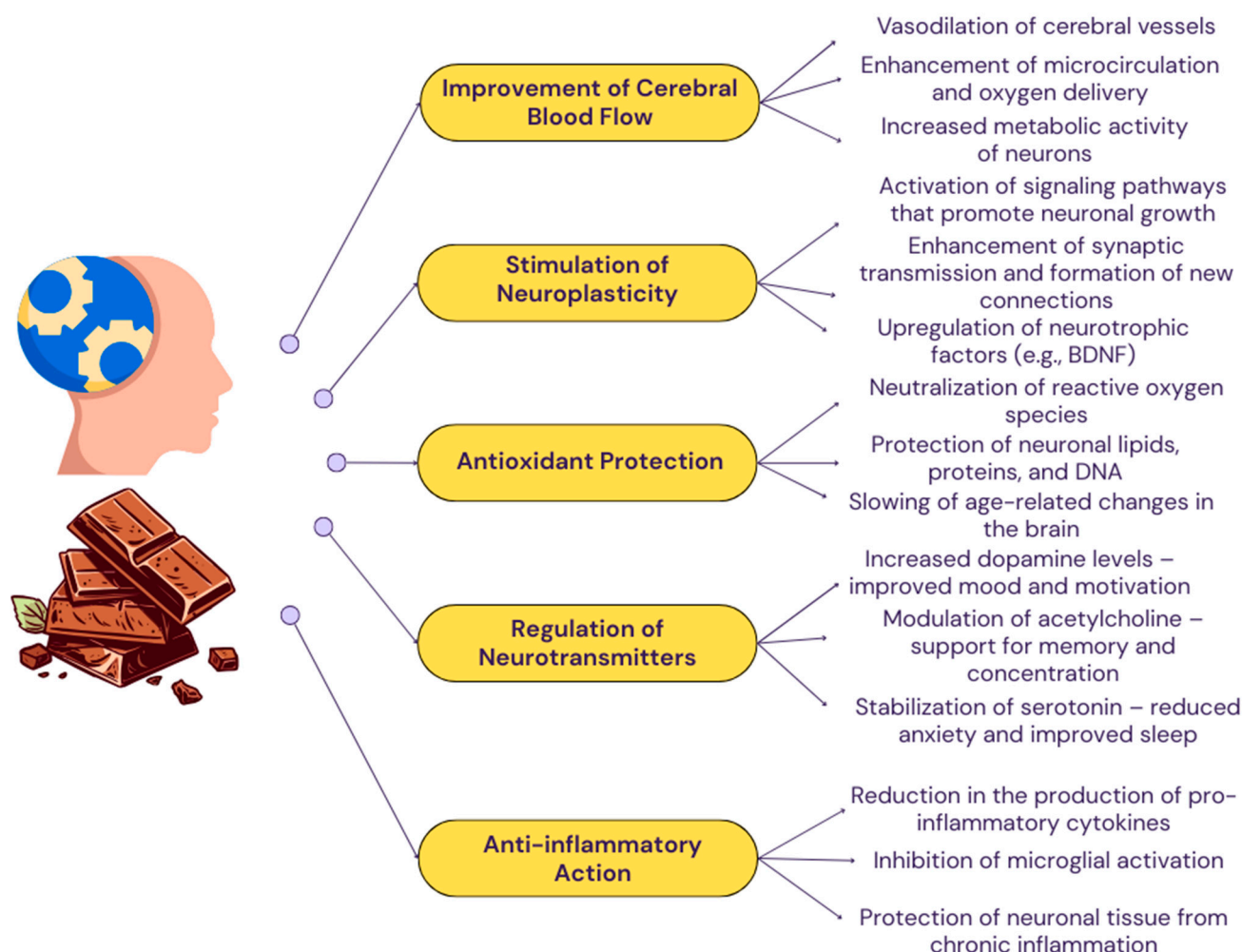


Figure 4. Mechanisms of Chocolate’s Neuroprotective Effects on Cognitive Health.

Although flavanols exhibit antioxidant activity *in vitro*, their effects on the brain largely depend on the ability of these molecules to cross the blood–brain barrier (BBB). The bioavailability of flavanols may be limited by various factors, such as environmental conditions, food properties, and individual host characteristics. In particular, catechin and especially epicatechin are able to penetrate the BBB, which has been confirmed in studies on human cell lines [215].

Taking into account the presented data, cocoa and dark chocolate may have a beneficial effect on the elderly, contributing to the improvement and restoration of neurovascular conductivity. The long-term protective effect of cocoa on cognitive function is likely to be more pronounced in individuals with early signs of cognitive decline or at increased risk for its development than in older adults with preserved cognitive abilities [216].

6.4. Impact on Gut Health

The potential of chocolate to improve emotional well-being is also associated with the modulation of the gut microbiota, including increased diversity and changes in the abundance of key taxa, highlighting the importance of the gut–brain axis in mood regulation [217]. Dark chocolate, containing cocoa proteins and dietary fiber, promotes the growth of butyrate-producing bacteria (e.g., *Faecalibacterium*, *Megamonas*, *Roseburia*), improving gut health [218]. Furthermore, dark chocolate consumption can induce cumulative changes in the excretion of microbial metabolites, including an increase in m-hydroxyphenylacetate

and a decrease in phenylacetylglutamine and p-Cresyl sulfate, demonstrating adaptation of the gut microbiota to chocolate components [219].

Cocoa polyphenols interact with the intestinal microbiota, modulating its composition and exerting a prebiotic and immunomodulatory effect, which helps improve the health of the intestine and the body as a whole [220]. Intestinal microbiota and polyphenols interact within a complex mechanism that affects the health of the host: polyphenols modulate the composition of the microbiota, stimulating the growth of beneficial bacteria and suppressing pathogenic microorganisms, and the microbiota, in turn, increases the bioavailability of polyphenols, converting them into biologically active metabolites. Polyphenols promote the production of short-chain fatty acids, which strengthen the intestinal barrier, reduce inflammation, and regulate metabolic processes [221].

An important aspect is the two-way nature of the interaction between polyphenols and the intestinal microbiota, which consists of the fact that intestinal microorganisms participate in the hydrolysis of polyphenols, thereby influencing their absorption [222]. Moreover, the hydrolysis products can have both a stimulating and inhibitory effect on the growth of various types of bacteria in the intestine. The metabolism of cocoa polyphenols by the intestinal microbiota leads to the formation of bioactive metabolites such as hydroxyphenylpropionic and phenylacetic acids, which are found in biological fluids and can have an anti-inflammatory effect [223].

During the roasting process of cocoa beans during chocolate production, melanoidins are formed, which are actively fermented by intestinal bacteria after 5 h, producing short-chain fatty acids (SCFAs) and branched-chain fatty acids (BCFAs) [224]. Cocoa melanoidins contribute to the improvement of the intestinal microbiota balance by stimulating the growth of non-pathogenic bacteria such as *Bacteroides* sp. and enhancing the production of SCFAs and BCFAs, which causes their indirect antibacterial effect.

Theobromine contained in chocolate inhibits the growth of certain bacterial groups, including *Firmicutes*, *Bifidobacterium* spp., and *E. coli*, while promoting the increase in the abundance of other taxa, such as *Erysipelotrichaceae* and *Candidatus Arthromitus*, and stimulates the synthesis of butyric acid, which highlights its role in modulating the intestinal environment and metabolic activity [225]. In this case, cocoa polyphenols and dietary fiber interact with theobromine, forming a complex effect that is different from the action of individual components, which opens up new prospects for the study of cocoa and chocolate as a functional product for maintaining intestinal health and body weight control.

7. Conclusions

The functionalization of chocolate products is a promising area in the food industry that meets modern requirements for the production of food products with improved consumer properties and functional focus. Modern achievements in food science and engineering make it possible to modify the composition of chocolate, reducing the content of sugar and fat, as well as enriching products with bioactive components, which helps prevent chronic diseases and improve overall health.

Numerous studies have confirmed the antioxidant, anti-inflammatory, and cardio-protective properties of traditional chocolate due to the high content of cocoa products. These properties are due to the presence of flavonoids, which help reduce oxidative stress, improve vascular endothelial function, and reduce the risk of developing cardiovascular diseases. In addition, the positive effect of chocolate on cognitive functions has been proven, which is explained by the neuroprotective effect of the bioactive components of cocoa.

The enrichment of chocolate with food polyphenols of plant origin not only enhances its antioxidant properties but also has a modulating effect on the composition of the intestinal microbiota, which is confirmed by the research results. The inclusion of probiotic

microorganisms helps to normalize the microbiocenosis, improving the condition of the gastrointestinal tract and strengthening the immune system. The addition of prebiotic components and dietary fiber stimulates the growth of beneficial microflora, creating a synergistic effect in combination with probiotics. The use of polyunsaturated fatty acids in the composition of functional chocolate enhances its cardioprotective, anti-inflammatory, and neuroprotective properties.

Thus, the use of bioactive components opens up new prospects for the development of innovative functional food products aimed at a healthy lifestyle.

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Abbreviations

The following abbreviations are used in this manuscript:

FAO	Food and Agriculture Organization of the United Nations
FOS	Fructooligosaccharides
HPMC	Hydroxypropyl methylcellulose
BOPP	Biaxially oriented polypropylene
GOS	Galactooligosaccharides
SFA	Saturated fatty acids
MUFA	Monounsaturated fatty acid
PUFA	Polyunsaturated fatty acids
AI	Adequate Intake
HDL	High-density lipoprotein
LDL	Low density lipoprotein
BBB	Blood–brain barrier
SCFAs	Short-chain fatty acids
BCFAs	Branched-chain fatty acids

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