ISBN 978-1-960740-54-0

INNOVATIVE FOOD PRODUCTS - NUTRACEUTICALS AND FUNCTIONAL FOODS

Editors

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Review Based Book Chapter

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March 06, 2025

doi:10.5281/zenodo.14830046

Scientific Knowledge Publisher (SciKnowPub), USA

info@sciknowpub.com

REVIEW BASED BOOK CHAPTER

FUNCTIONAL FOODS, EFFICACY AND DISEASE PREVENTION

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Abstract

The increasing global trend of chronic diseases has promoted remarkable interest in functional foods, defined as foods with health benefits other than basic nutrition. This chapter provides comprehensive analysis of functional foods with respect to their classification, bioactive compounds, and mechanisms of functioning, with special emphasis on functional foods for cardiovascular diseases, cancer, diabetes, obesity, and cognitive impairment. Functional foods, derived from plant-based, animal-based, modified, and nutraceutical sources, contain bioactive compounds such as phytosterols, omega-3 fatty acids, antioxidants, and probiotics, which contribute to various physiological functions, including gut microbiota modulation, immune system enhancement, cognitive support, and physical performance optimization. The broader environmental and economic implications of functional foods are also explored, highlighting their potential to support sustainable health solutions. The emerging areas of research are expected to enjoin personalized nutrition, subsequent development of biotechnology, and new technological insights in nutrition to fast-track the effectiveness and affordability of functional foods. The chapter reinstates the scientific and real-life importance of functional foods and calls for their incorporation in mundane diets while acknowledging the need for sustained research toward optimizing their health-promoting potential.

Keywords
Functional Foods, Bioactive Compounds, Personalized Nutrition, Disease Prevention, Immune System

Introduction of Functional Foods

Functional foods are modified or fortified foods that provide a health benefit beyond their basic nutritional value. They are designed to improve overall health and well-being, reduce the risk of chronic diseases, or enhance physical and mental

performance [1]. The concept of functional foods was first introduced in Japan in the 1980s and has since gained popularity worldwide [2]. These foods typically contain added ingredients such as: Examples of functional foods includes yogurt with live cultures (probiotics), energy bars with added omega-3 fatty acids, fortified cereals with vitamins and minerals, juice beverages with added antioxidants, bread with added fiber (prebiotics). Following are characteristic functions that are played by functional foods in human body: Functional foods may assist in the prevention or management of long-term health conditions such as: heart disease (e.g., omega-3 fatty acids, plant sterols), type 2 diabetes (e.g., fiber-rich foods, probiotics) and certain cancers (e.g., antioxidants, phytochemicals) [3].

Functional foods are defined as foods that provide additional health benefits beyond basic nutrition. Our daily needs for macronutrients (proteins, fats, and carbohydrates) and micronutrients (vitamins and minerals) can be met by a traditional diet, however, functional foods benefits are above all this and they yield benefits such as improved health conditions successively less chances of getting diseases. Encompassing sustained immunity, bolster gut health, lower cholesterol levels, and layout horde of other advantages, making them a vital part of the diet of people who care about their health [4]. Consumers are incorporating functional foods into their diets more frequently as evidence shows their impact on overall health. The market for these foods has grown significantly, providing a diverse selection of options, ranging from probiotic-rich yogurts to antioxidant-packed berries. Integrating functional foods into one's diet is not just a matter of following trends; it's a conscious decision that is based on understanding their profound benefits.

Functional foods can be characterized in various ways which include conventional foods and modified foods. By definition conventional foods are unmodified foods that can be used by individuals in daily life such as vegetables, grains, nuts, seeds, dairy, fish, meat and legumes. On the contrary, modified foods are described as foods that have been modified through various processes which include fortification, enrichment this can be done at various level of processing which can be at agricultural level by enzymatic, chemical or technological means. Examples of modified foods includes

calcium fortified orange juice, margarine that has been enriched with omega 3 fatty acid, eggs enriched with omega-3 fatty acids and fermented foods. There is a third class of functional food which involve isolated or synthesized food ingredients i.e., indigestible carbohydrates (e.g. resistant starch and oligosaccharides) these compounds provide prebiotic effects [5]. Figure 1 shows the classification of functional foods.

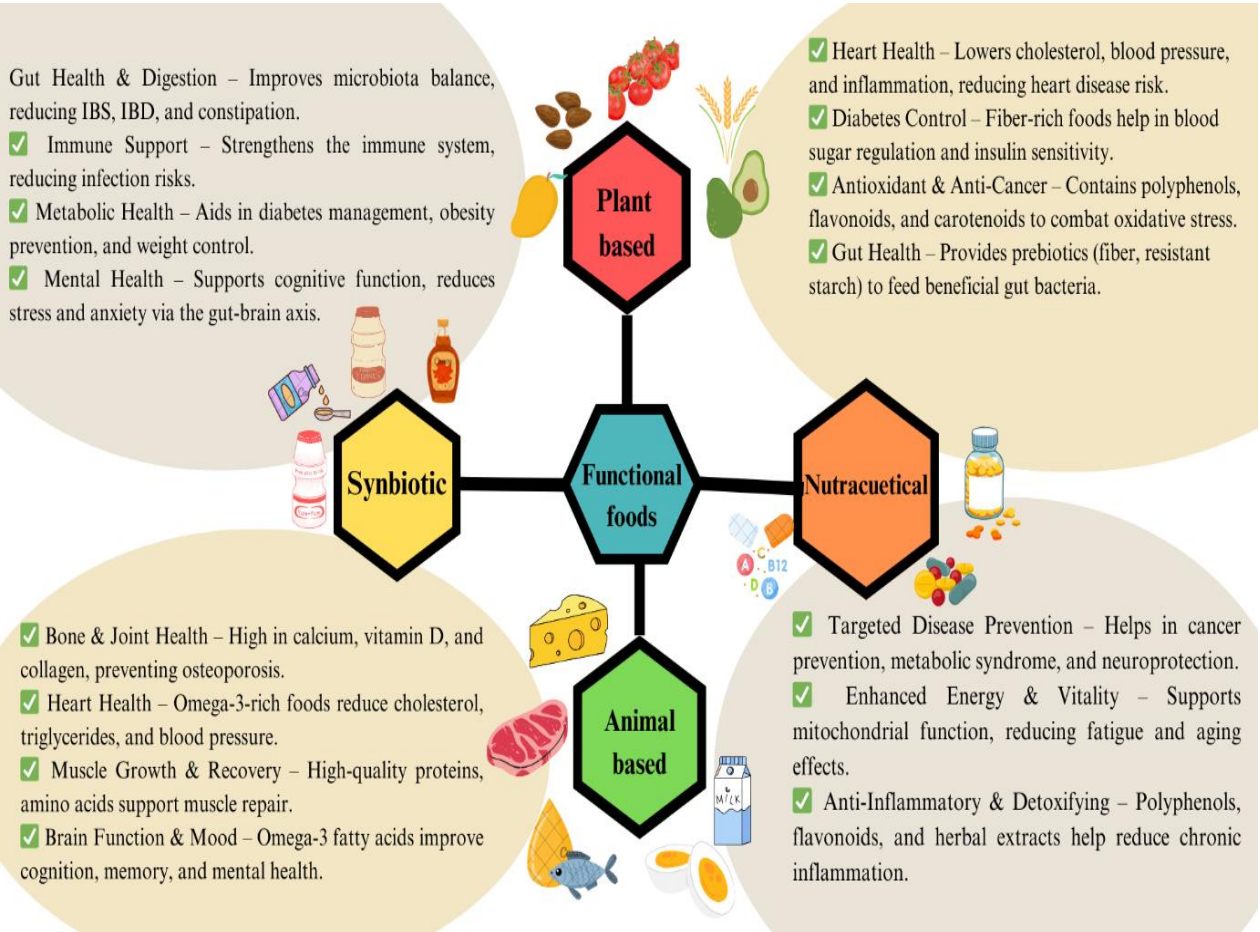

Figure 1. Classification of Functional Foods

Functional foods comprising of prebiotics, probiotics and fiber can contribute to improved gut microbiome, which is prerequisite for, immune system function, digestion and nutrient absorption and production of certain vitamins. In addition, functional foods can aid in improving physical performance by; supplying energy and endurance (e.g., sports drinks, energy bars), assisting muscle growth and repair (e.g., protein-rich

foods, creatine) and improving mental focus and concentration (e.g., omega-3 fatty acids, caffeine). Functional foods also support mental health and cognitive function by lowering stress and anxiety (e.g., adaptogenic herbs, omega-3 fatty acids), improving mood (e.g., serotonin-boosting foods, vitamin D) as well as enhancing cognitive function (e.g., omega-3 fatty acids, antioxidants). Functional foods can allow a suitable and approachable way to assimilate essential nutrients and health-promoting elements into an industrious lifestyle. Customized functional foods can be used to meet individual nutritional needs and health goals, conceding personalized approach to nutrition. Functional foods can proceed toward sound aging by: reducing inflammation (e.g., omega-3 fatty acids, antioxidants), supporting bone health (e.g., calcium, vitamin D) and enhancing cognitive function (e.g., omega-3 fatty acids, antioxidants). Amalgamation of functional foods and balanced diet can subsequently result in advanced health conditions and overall well-being of individuals [6]. Figure 2 shows the key health benefits of functional foods.

1. Bioactive Compounds in Functional Foods

The two types of bioactive compounds in functional foods are from plant-based sources and animal-based sources.

1.1 Bioactive Compounds from Plant-based Sources

Plant based bioactive compounds present in food are beneficial to human health via lowered disease risk. These bioactive compounds are what gives plant-based foods their numerous health benefits. These bioactive compounds are phytosterols, glucosinolates, terpenes and terpenoids, alkaloids, isothiocyanates and polysaccharides to name a few.

1.1.1 Phytosterols

Phytosterols are natural plant compounds that are structurally similar to cholesterol and are from triterpene family. Phytosterols have many health benefits such as anti-inflammatory properties, lowering cholesterol and improving immunity via antioxidant properties. Till now, approximately 250 phytosterols have been identified. Most common phytosterol type in diet is campestral, β-sitosterol and stigmasterol. They are essential

structural components of the cellular membrane and have many important functions, which include membrane fluidity and permeability modulation. They promote health by their antioxidant properties and cholesterol lowering effects by lowering cardiovascular disease risk. They are present in fruits and vegetables, nuts, sunflower seeds, whole grains vegetable oils and legumes [7].

Figure 2. Health Benefits of Functional Foods

1.1.2 Terpenes and Terpenoids

Terpenes are naturally occurring compounds that have simple hydrocarbons structures while terpenoids are known as modified class of terpenes, which have different structure. Terpenes are pinene, myrcene, terpinene, p-cymene and limonene. They have shown antimicrobial activities against the different bacterial strains including antibiotic resistant bacteria and antibiotic susceptible strains of bacteria. Their antimicrobial potential is due to their ability to inhibit synthesis of DNA and protein as well as their ability to enhance cell rupture. Staphylococcus aureus is bacterial species against which terpenes (geraniol, thymol, eugenol, carvone and carvacrol) have shown antibacterial action. Terpenoids on the other hand are the aromatic and medicinal plants secondary compounds and have shown disease resistance. For instance, terpenoids such as monoterpenoids caused microbial population to decrease via interfering with microbial metabolic activities as well as disruption in microbe multiplication and development thus justifying its' antimicrobial action [8].

1.1.3 Alkaloids

These are naturally occurring phytochemicals present as secondary metabolites in plants and animals. Alkaloid's chemical structure contain nitrogen. In plants, alkaloids concentrate in various organs such as fruits, roots, leaves, tubers. They have a significant role in protecting the plant against parasites, specifically bacteria and fungi. Studies show that alkaloids concentrate in the unripe fruit of lobeira plant. Extracts from lobeira fruit that were rich in alkaloids as well as extracted and isolated alkaloids have many health benefits including antiparasitic effects as well as hypoglycemic and anticarcinogenic effects [9].

1.1.4 Glucosinolates

Glucosinolates are naturally occurring phytochemicals commonly found in cruciferous vegetables such as broccoli and cauliflower. They have many health benefits such as protection from various cancers like breast cancer, colorectal and prostate cancer. They are also cardioprotective providing protection against myocardial infarction. Glucosinolates are compounds that contain sulfur (S) and nitrogen (N) and are generally present in vegetables as well as plants. They primarily derived from glucose

and amino acids. They are extracted from Brassica genus which includes Brussels sprout, kale, cabbage, broccoli, turnip, swede and cauliflower. They are hydrolyzed in human gut into isothiocyanates. The breakdown products of glucosinolates which are indole and isothiocyanates products have shown to prompt apoptosis (cell death) thereby lowering the growth of tumor via alteration of estrogen metabolism and by blocking the cell cycle as well as by blocking phase 1 enzyme. They also have inflammation lowering capacity via blocking histamine release [10].

1.1.5 Isothiocyanates

Isothiocyanates are byproducts of hydrolysis of glucosinolates in human gut. They are phytochemicals that are highly reactive. Glucosinolates are present mainly in the cruciferous vegetables. Isothiocyanates are possessing health promoting qualities such as neuroprotective properties as well as anti-inflammatory and anti-cancer properties. According to experimental evidences and epidemiological evidences, isothiocyanates lower oxidative stress and acts as antioxidants indirectly and they also show anti-microbial potential, thus, recently they have been shown increased attention due to their research potential and industrial application to different fields such as pharmacy and food industry. Irrespective of these benefits, their application is very challenging due to their volatile nature and increased sensitivity to heat. Also, processing of these bioactive compounds makes them less bioavailable due to sub-optimal conditions of processing. Isothiocyanates shows many health benefits and disease lowering potential due to their antimicrobial activity. This is due to their potential to lower oxygen consumption as well as depolarizing the membrane of mitochondria the bacterial cells. Isothiocyanates are commonly safe compounds (GRAS generally recommended as safe) and therefore are safe to be used in food industrial application as food preservatives. Isothiocyanates are also incorporated to food-packaging films due to their antimicrobial activity. They are also applied to food industry due to their potential of extending shelf life. This is due to their acting as a substrate in order to activate lactoperoxidases (LPO) for shelf-life extension of various dairy-products; which can be attributed to their bacteriostatic properties and bactericidal properties [11].

1.1.6 Polysaccharides

Polysaccharides are naturally existing biochemical compounds that are made up of greater than 10 monosaccharide units which are interconnected via glycosidic linkages. They are the most abundant and commonly available carbohydrates type present in different organisms such as algae, fungi and plants. Their classification is dependent on composition of monosaccharides. Polysaccharides are having two classes which are: heteropolysaccharides, that comprise of two or more than two different monomeric units (like pectin) and homo-polysaccharides, that consists of a single type of monosaccharide (like starch). Polysaccharides are structurally complex and can store carbohydrates in plants. Oral consumption of polysaccharides is followed by absorption and utilization in intestines. Polysaccharides are beneficial for the human bowel movements. Polysaccharides consists of fibers which is beneficial for gut health and is fermented in human gut by the microorganisms present in gut. The microbiota of human gut as well as their derived metabolites positively impacts human health. Hence research focuses on the interaction between microbes and polysaccharides. Deficiency of dietary fiber deficiency negatively impacts gut microbiota and is a precursor to diseases such as metabolic diseases and gut dysbiosis. This also leads to higher resistance of insulin thus increasing obesity. This is primarily due to inflammation caused by excretion of endotoxins by bacterial cells. Improving gut health via consumption of polysaccharide to positively impact gut microbiota can have a beneficial effect on metabolic disease [12].

1.2 Bioactive Compounds from Animal Sources

Like the bioactive compounds that are sourced from plants, bioactive compounds of animal origin are also having positive health benefits. For instance, Marine fishes contain a variety of bioactive compounds; such as increased amount of long chain omega 3 PUFAs (polyunsaturated fatty acids). These PUFAs are beneficial as they can become a part of cell membranes which lowers the inflammation. This is done by lowered synthesis of pro inflammatory cytokines. Another animal derived bioactive compounds from meat and its products are peptides, vitamins, fatty acids and minerals, that have a positive impact on human health. In addition, meat contains essential amino acids, thus

giving essential and quality proteins. Bioactive compounds rich in meat are coenzyme Q10, bioactive peptides, l-carnitine, choline, glutathione, taurine, alpha-lipoic acid, conjugated linoleic acid, and creatine. Milk produced by mammals contains bioactive peptides that positively impacts immunity. Cow produces milk that has whey protein rich in bioactive peptides that modulates immune responses. Similarly, Bioactive compounds in egg have anti-inflammatory effects. Egg whites are rich in bioactive proteins, which includes avidin, ovalbumin, Ovo transferrin, ovomucin and lysozyme; which have shown positive effect on immunity as well as anti-bacterial effects. Therefore, animal derived bioactive compounds should be studied and isolated to maximize their health benefits [13].

2. Role of Functional Foods in Disease Prevention and Management

A functional food provides potential health benefits owing to essential nutrients they encompass. These foods are valuable for the inhibition, prevention and treatment of various maladies. The body utilizes minerals, vitamins, omega 3 fatty acids, fiber, phenolic compounds and antioxidants existing in plants-based food items including vegetables, nuts, fruits, beans and herbs to combat numerous illnesses like cancer, diabetes, obesity and cardiovascular diseases [14].

2.1 Cardiovascular Diseases

Cardiovascular ailments (CVDs) are the primary reason of mortality and morbidity globally and a noteworthy contributor to disability, particularly coronary heart disease (CHD) and stroke. Data reclaimed from the World Health Organization have publicized that in the last two eras, the total of deaths instigated by CVDs amongst adults exceeded 350,000,000 internationally [15].

To reduce the rate of morbidity and mortality attributable to cardiovascular diseases it's significant to lessen the ingestion of sodium and fat. Scientific researches have proven in various studies that vitamin E reduces the risk of cardiovascular diseases. It is also demonstrated the vitamin E supplementation lessen the severity of atherosclerosis by reducing lipid composition of plaque [16]. Vitamin E enriches food sources comprise of lupin, pea, cowpea, moonbeam, soyabean and lentils have several health benefits. Frequent consumption of legumes reduced LDL, VLDL and cholesterol levels of blood

and HDL levels improved. Hydrolysates protein of beans drops cholesterols levels of blood showed hypocholesterolemia activity and also prevented inflammation and oxidative stress by improving the regulation of a compound adipocytokines. It displayed hypoglycemic activity by inhibiting SGLT1 and GLUT2 glucose transporters. Black beans protein hydrolysates also displayed hypoglycemic activity [17]. Polyphenols including flavones, flavonoids, flavanones and flavanols are bioactive compounds of legumes. These bioactive compounds improve the hyperglycemia and hypercholesterolemia. Since, it enhances the activity of adenosine monophosphate protein kinase [18]. Chickpeas comprise of saponins which decreases activity of pancreatic lipase. Also decline the deposition of lipid in 3T3-L1 and adipocytes. Functional foods are beneficial for the promotion of the functionality of HDL-C and the advancement of its levels. The mechanisms comprise of their influence in reverse cholesterol transfer and the enhancement of anti-inflammatory effects and anti-oxidant effects of HDL-C [19].

2.2 Cancer

Cancer is vigorous and long-term process with the involvement of many factors leading to growth of uncontrolled and inactive cells know as cancerous cells. The uncontrolled spread of cells is through the progression of metastasis. Dietary phytochemicals, generally flavonoids, polyphenols, isothiocyanates, organosulfur compounds, and tetraterpenoids, characterized biologically active compounds present in vegetables, medicinal plants, fruits, and beverages. These natural organic bioactive compounds display epigenetic modulatory properties by inducing the activity of epigenetics crucial enzymes, for instance histone acetyltransferases, DNA methyltransferases, demethylases, deacetylases and histone methyltransferases. Owing to the reversibility of the alterations that they induce, their insignificant adverse effects, and their effective epigenetic regulatory property, dietary bioactive phytochemicals hold noteworthy potential as antitumor agents [20]. Cereals are beneficial for the deterrence of spread of cancerous cells. Cereals food items comprise of barley, wheat and rice are the key source of macronutrients required for providing energy daily. Whole grains reduce the risk of progress of cancer cells. One of the whole grain bioactive compounds lunasin isolated from rice, barley, and wheat is a peptide which is valuable for reducing

inflammation and cholesterol in blood and also has cancer preventive outcome. Highest levels of lunasin are present in oat named ivory [21].

Various bioactive components are present in wheat straw including phytosterols, triterpenoids, policosanols and phenolics, have numerous health benefits like anti-inflammatory, antioxidants, anticancer, antiatherogenic, antiallergic, antimicrobial, antiviral, vasodilatory and cardioprotective effects. Germinating brown rice is a common functional food. It has numerous health beneficial bioactive compounds which have various physiological effects including antioxidant, hypoglycemic, anticancer, hypocholesterolemia effects. Brown rice contains tannins, sterols, GABA, essential oils, amino acids, sterols and flavones. Rice bran is also considered as functional food, have anticancer properties. It also encompasses bioactive components phytochemicals for instance tocopherols, ferulic acid, γ- oryzonals, β – sitosterol, phytic acid, tricin and phytic acid. Additional bioactive component of rice bran is cycloartenyl ferulate which has the anticancer properties by impeding human colorectal adenocarcinoma [22].

2.3 Type 2 Diabetes

It is a metabolic disorder, also identified as diabetes mellitus, is a collection of common endocrine ailments considered by continued enhance blood sugar levels. Various factors are involved in development of diabetes including unhealthy diet, stress, excess body weight, infection, physical inactivity, family history and high blood pressure. Functional foods have their prospective health benefits and have been systematically demonstrated; they have protective effectiveness along with physical activity in diabetes type 2 prevention [23]. Mediterranean diet augmented with functional foods is health beneficial meal plans for the prevention and management of Type 2 diabetes; this diet is exceedingly valued in American Diabetes Association reference for T2DM prevention and management. MD diet is enriched with polyphenols bioactive compounds such as fruits, olive oil vegetables, tree nuts and these bioactive components have health protecting benefits. Alongside with polyphenols, alkaloids, flavonoids, terpenoids, pigments, unsaturated fatty acids and sterols displays an essential part in sustaining wellbeing and helping to elude diseases like cancer, asthma depression, obesity, diabetes, and cognitive decline [24]. Nutraceuticals with

mediterranean diet such as, omega 3 PUFA in tree nuts and EPA, oleic acid in olive oil and DHA found in oily fish and high amounts of fiber found in whole grains with a low glycemic index, this sort of acids and antioxidants inhibits the oxidation, inflammation, and supports to enhancement of the endothelial micro and macro vascular function [25].

2.4 Obesity

Obesity is common all over the world. Owing to the energy disproportions problem of obesity upsurges whereby energy ingestion exceeds energy spending. Functional foods, when taken as a major part of a balanced diet, have been suggested as a potential substitute method of weight management and obesity prevention and of improving metabolic concerns of obesity, as well as augmented glucose and lipid levels in blood [26]. In current years, numerous animal studies, along with human clinical trials and epidemiological researches, have been executed to observe the potential outcome of particular functional foods and their bioactive compounds on weight control and numerous mechanisms of its effect on health have been suggested [27]. Obesity is considered as multifactorial prolonged diseases mostly instigated by an inequity in kcalories intake and expenditure. Obesity and its linked complications are the fifth foremost reason for worldwide mortality. The remunerations of the present obesity treatment routine have been masked by increase several adversarial effects [28]. Consequently, numerous researchers concentrate on plant-derived bioactive compounds, natural products and changed dietary pattern for the treatment, prevention and management of obesity and its related complications (co-morbidities). Numerous epidemiological researches have inveterate that the ingestion of functional foods and nutraceuticals could significantly lessen possibility of numerous chronic and acute diseases like obesity, diabetic mellitus, cardiovascular and cancer [29].

2.5 Immune System

Immune function is influenced by the nutrition. Bioactive compounds in functional foods are responsible for the strengthening of immune system like vitamins, antioxidants, trace elements (zinc, copper and manganese), omega 3 and 6 polyunsaturated fatty acids, nucleotides, l-arginine, nucleosides, probiotics, prebiotics and synbiotics [30]. Immune dysfunction in the body can be initiated by numerous factors. To solve this problem,

plant-based functional foods are utilized for their wide immune-enhancing activities. Consequently, numerous studies have been carried out to interpret the molecular and cellular regulatory mechanisms and signaling pathways of immunoactive constituents to analyze the immune strengthening properties of these active constituents. Contrasting from current synthetic drugs, which are costly and can have numerous side effects, plant-based functional foods have fewer side effects, are constant, stable, and tend to display a permanent effectiveness. Bioactive compounds demonstrate immune strengthening properties by various mechanisms for instance it regulates the levels of cytokines to enhance immunity, by regulating natural killer cells and propagation of T lymphocytes and stimulate cellular and humoral responses to increase immunoregulative effect [31].

2.6 Gut Health

The GI tract is an understandable mark for the bioavailability of functional foods as it is considered crossing point amid the bioactive compounds of diet and all other metabolic roles. GI function depends on a suitable steadiness of healthy microflora to inhibit the entry of harmful and pathogenic bacteria. An utmost promising area for the formation of functional foods lies in the utilization of constituents to amend the metabolic action of the gut residing microflora such as probiotics, prebiotics and symbiotic (mixtures of probiotics and prebiotics) [32].

The health-related benefits of probiotics include decreased in occurrence or severity of GI infections and diseases as well as improvement of lactose intolerance and enhancement in gut function, including decrease in the frequency of constipation and diarrhea. Prebiotics are non-digestible food constituents that can fuel growth of microflora and alter the metabolic related activity of particular bacterial species already residing in the gut and reduces the growth of pathogenic bacteria, leads to improvement of gut health. Microflora also decreases the risk of development of colon cancer. Their capability to upsurge production of short chain fatty acids in the colon is related with amplified absorption of particular minerals for instance magnesium and calcium. Dairy products, baked goods, table spreads and breakfast cereals, breads, and bars, meat products, salad dressings and about confectionery items contain prebiotics [33].

3. Mechanism of Action of Bioactive Compounds

Bioactive constituents are extra-nutritional components that are present in fewer quantities in foods enhance health benefits beyond the basic nutrients. They are being thoroughly considered to assess their impact on health, and bioactive compounds appeared to have favorable behavioral, physiological, and immunological properties. Up to the present time, several bioactive constituents have been investigated and discovered. These compounds differ extensively in chemical structure and function and are assembled accordingly.

Examples related to bioactive compounds are flavonoids, choline, carotenoids, carnitine, phytosterols, polyphenol, phytosterol, dithiolthiones, phytoestrogens, taurine and glucosinolates. Subsequently, vitamins and minerals displayed beneficial pharmacological properties; they can be characterized as bioactive compounds too. These compounds certainly are present in numerous foods, have antioxidant, anti-inflammatory, antitumor, anticarcinogenic, and antimicrobial properties.

3.1 Modulation of Gut Microbiota

The human gastrointestinal gut entails around 100 trillion microorganisms, containing up to 5000 various types of bacteria, in addition to Archaea, parasites, viruses, Eukarya and bacteriophages that collectively called the "gut microbiome". Alterations in gut microorganism composition (dysbiosis) can lead to numerous diseases [34]. Functional foods and natural herbs encompass bioactive molecules capable of enhancing the immune system, anti-bacterial and anti-viral functions. Functional foods, for instance probiotics, prebiotics, and dietary fibers, have been displayed to have beneficial effects on gut microbiota and immune function. The utilization of functional foods has been related to improved regeneration of cells, enhanced cognitive function, strengthen immunity, maintenance of gut microflora, and substantial improvement in overall health [35].

Probiotics are microorganisms that can optimally change the stability of intestinal microflora, improve digestion, inhibit the growth of harmful bacteria and upsurge the body's resistance by reinforcement the immune system. Studies displayed that probiotics are health beneficial owing to antioxidant properties. Antioxidants are

complexes that decrease the hazard of numerous ailments. These compounds, indeed, prevent the action of free radicals and stop their oxidation [36]. The body cells are protected from the disparaging effects of these compounds owing to the antioxidant properties of probiotics. Oxidative stress is a state that happens as a consequence of upsetting the antioxidant-prooxidant equilibrium in the cell, which ultimately leads to apoptosis and cell death. Ingestion of probiotic strains with antioxidant activity can profit human health by decreasing oxidative harm. Meanwhile the usage of probiotics benefits, improves immune responses, hemostasis and stops numerous disorders produced by oxidation in the host [37].

3.2 Anti-inflammatory Effects

Prolonged inflammation is related to various human diseases. Dietary intake of plant-based products full of antioxidant is an approach and a growing trend for fighting the inflammatory responses of numerous communicable and non-communicable ailments and their risk factors [38]. Fruits, herbs, vegetables, spices, and their extracts demonstrated a functional activity enhancing antioxidant status and at the same time improving inflammatory and oxidative stress. It is highly suggested to entirely utilize the "functional heritage" of the extensive collection of diverse phytochemicals with multi-factorial synergistic interactions confined in fruits, herbs, vegetables, and spices and their extracts to capably stop the raise of inflammatory and oxidative stress, major reasons of deteriorating ailments [39].

3.3 Antioxidant Activity

In the preceding era, antioxidants have got a great deal of publicity for their role in decreasing oxidative stress and free radicals, as well as treatment and prevention of cancer. In such situations, polyphenols and phenols are often of great concern; they can be identified by means of enzymes including phenol oxidases, tyrosinase, and even with the plant tissue carrying such enzymes [40]. Some illnesses for instance cancer, hypertension, obesity, coronary heart diseases, type 2 diabetes, and cataract are induced by increase in free radicals leads to increase in oxidative stress and fruits, legumes, cereals, vegetables, provide the greatest defense in contradiction of these diseases [41]. The food related natural antioxidants present in fruits and vegetables have an advantageous health benefit. Some of the antioxidants present in dietary

plants comprise of carotenoids, phenolic compounds, coumarins, stilbenes, flavonoids, benzoic acid derivatives, lignans and proanthocyanidins. Blackberries, walnuts, artichokes, raspberries, strawberries, brewed coffee, cranberries, blueberries, pecans, grape juice, unsweetened chocolate and ground cloves categorized at the highest of the classification owing to normal serving quantities. Antioxidants for instance vitamin C, polyphenols, vitamin E, lycopene and beta-carotene are ample in beverages and fruit juice, have been displayed to lesser mortality and morbidity related with deteriorating illnesses [42].

3.4 Modulation of Gene Expression

Diet related bioactive constituents, in the notion of nutrigenomics and nutrigenetics comprise of food phytochemicals and nutraceuticals, which can transfer information from the exterior atmosphere and impact gene expression in the cell and therefore the function of the organisms. It is vital to honor diet not only as the foundation of calories and basic nutrition, essential for living and development, but also as the feature persuading health, biochemical mechanisms, and activation of pathways. Bioactive constituents of the food control gene expression through variations in the chromatin structure (including DNA methylation), instigation of transcription factors by signaling cascades, non-coding RNA, or straight ligand binding to the nuclear receptors [43]. Bioactive diet related components effect gene expression through diverse mechanisms, mostly by chromatin structure modification, non-coding RNA, direct ligand binding to the nuclear receptor and initiation of transcription factors by signaling cascades. Identifying of these bioactive complexes and elucidating their mechanism of function will permit more actual food recommendation for entire population [44]. Bioactive diet constituents show a significant part in prevention and treatment of many illnesses, for instance circulatory system ailments, cardiovascular diseases, diabetes, cancers and obesity. It appears significant to advance additional awareness on nutrigenetics and nutrigenomics and to inspire dieticians to utilize this information for more effective dietary references and recommendations [45].

4. Safety Considerations of Functional Foods

Functional foods safety considerations include; ingredient safety: be certain that all the ingredients, including additives and supplements, are safe for consumption. Potential

allergens are supposed to be clearly mentioned on the product label for consumer safety such as gluten, nuts etc. While execution of Good Manufacturing Practices (GMPs) is vital to prevent contamination and ensure cleanliness. Stability assessments to verify that products remain safe and effective for the duration of their shelf life and at the end examine the possible interactions between ingredients in functional foods and prescribed medications.

4.1 Regulatory Considerations

Adhere to labeling laws, which encompass nutrition information, ingredient listings, and health assertions. Verify that health assertions are backed by scientific proof and adhere to regulatory standards. Ensure that ingredients used in specific product have GRAS status or has gained acceptance from regulatory agencies. Comply with regulations for novel foods, including approval processes and labeling requirements. Food and Drug administration is the regulatory body in United States for functional foods. European food safety authority Is the regulatory body in Europeans union. In Canada, Health is the one who regulates functional foods. National health and medical research council is the regulatory body in Australia for functional foods. Make certain that safety protocols and regulations are fully met. Regulatory changes should be monitored constantly. Collaboration with experts ensure adherence and addresses concerns. Investment in scientific research and development is highly important to support health claims and that to ensure safety. Effective communication with the consumer is important and that being said transparency throughout is important in responding to concerns of consumers and for that products should be labeled properly [46]. In Pakistan, the safety regulations for functional foods are governed by several authorities and regulations. PFA Pakistan food authority was established in 2017 which is responsible for safety and quality of food products which also include functional foods. Ministry of National Health Services, Regulations and Coordination (NHSR&C) is another ministry that keep an eye on the regulations of functional foods and food products. Though, the main role of Drug Regulatory Authority of Pakistan (DRAP) is to monitor the development of pharmaceuticals however, it also observes the regulations of functional foods and food products.

4.2 Safety Requirements

Manufacturers of functional food products must establish ways that certain safety and quality of their products this involves Good Manufacturing Practices GMPs. There is a systematic way to identify and control potential hazards in foods that are identified by HACCP (Hazard Analysis and Critical Control Points). Product producer must specify that their products are allergens and contaminants free this is done by ACC (Allergen and Contaminant control). Production house product labels and advertising claims should be in compliance with the regulations [47].

Table 1. Bioactive Compounds in Functional Foods and their Health Benefits

Food Name	Functional Compound(s)	Health Benefits	References
Turmeric	Curcumin	➢ Reduces inflammation and joint pain ➢ Acts as a powerful antioxidant, combating oxidative stress ➢ Supports brain health by enhancing BDNF levels	[48]
Garlic	Allicin, Sulfur Compounds	➢ Lowers blood pressure and cholesterol levels ➢ Boosts immune system function, reducing infections ➢ Exhibits anti-cancer properties by inhibiting tumor growth	[49]
Green Tea	Catechins, Polyphenols	➢ Provides strong antioxidant protection ➢ Enhances fat burning and weight management ➢ Lowers the risk of cardiovascular diseases	[50]
Yogurt (Probiotic)	Probiotics (*Lactobacillus, Bifidobacteria*)	➢ Improves gut microbiota balance, enhancing digestion ➢ Strengthens the immune system ➢ Helps in reducing symptoms of lactose intolerance	[51]

Fatty Fish (Salmon, Mackerel)	Omega-3 Fatty Acids (EPA, DHA)	➢ Reduces inflammation, lowering risk of chronic diseases ➢ Supports heart health by reducing triglycerides and blood pressure ➢ Enhances brain function and reduces cognitive decline	[52]
Blueberries	Anthocyanins, Flavonoids	➢ Improves memory and cognitive function ➢ Protects against cellular damage with antioxidants ➢ Supports heart health by reducing blood pressure	[53]
Tomatoes	Lycopene	➢ Lowers risk of prostate and other cancers ➢ Protects skin from UV damage ➢ Supports cardiovascular health by reducing oxidative stress	[54]
Nuts (Almonds, Walnuts)	Omega-3, Vitamin E, Fiber	➢ Reduces inflammation and oxidative stress ➢ Supports brain health and cognitive function ➢ Improves heart health by lowering cholesterol levels	[55]
Whole Grains (Oats, Brown Rice)	Beta-glucan, Fiber	➢ Lowers LDL cholesterol, reducing heart disease risk ➢ Supports digestive health by enhancing bowel function ➢ Provides sustained energy and aids in weight management	[56]
Dark Chocolate (Cocoa)	Flavonoids, Theobromine	➢ Enhances mood and reduces stress ➢ Improves blood flow and lowers blood pressure ➢ Provides antioxidant protection, reducing inflammation	[57]

Table 2. Effect of Antioxidants and Bioactive Compounds on Health

Bioactive Compounds	Food Sources	Health Benefits	References
Lutein	Green leafy vegetables (spinach, kale, etc.)	Antioxidant (AOX), anti-inflammatory, antiatherogenic, antihypertensive, antidiabetic, antiulcer, reduces cancer risk, prevents eye diseases	[58]
Curcumin	Curcuma (turmeric)	Antioxidant (AOX), reduces diabetes mellitus (DM) risk, neurodegenerative diseases (NDs), cardiovascular diseases (CVD)	[59]
Inulin	Asparagus, garlic, chicory, onion	Prebiotic effect, reduces atherosclerosis, increases satiety	[60]
β-glucan	Yeasts, oats, bacteria	Reduces CVD, controls diabetes, stimulates the immune system	[61]
Isothiocyanates	Brassica family: Brussels sprouts, cabbage, broccoli	Reduces NDs, reduces cancer risk	[62]
Sterols and Stanols	Wheat germ, rapeseed oil, peanuts	Lowers LDL-C, anti-inflammatory, reduces triglycerides (TG), reduces NDs	[63]
Resveratrol	Red grape, blueberries, blackberries, cocoa	Reduces CVD, lowers LDL-C	[64]
Isoflavones	Soy, miso, tofu, soy-based foods, flaxseeds	Reduces CVD, lowers LDL-C, prevents osteoporosis, reduces DM risk, reduces liver disease	[65]
Fructooligosaccharides	Chicory, onions, garlic, Jerusalem artichoke, dandelion	Alleviates depression symptoms, bifidogenic effect, reduces atherosclerosis, increases	[66]

	greens, leeks, asparagus	satiety	
Glucosinolates	Brassica family: Brussels sprouts, cabbage, cauliflower, etc.	Reduces cancer and metastasis risk, protects cells from redox imbalance, reduces chronic inflammatory diseases	[67]
Zeaxanthin	Egg yolk, spinach, kale	Antioxidant (AOX), provitamin A, anti-inflammatory, improves cognitive function, reduces cancer risk, reduces CVD risk	[68]

Table 3. Observed Effect of Bioactive Compounds and Their Mechanisms [69]

Compounds	**Observed Effects**	**Mechanisms**
Omega 3 PUFA	Decrease TNF, IL-6, PGE2	Inflammatory pathway inhibition
Anthocyanin	Increase BDNF, lowers the oxidative damage	Cell signaling, antioxidant activity, anti-inflammatory
Inulin	Increase mineral absorption and Bifidobacterium	Prebiotic effect, maintain lipid levels
Ellagitannins	Decrease inflammation	Microbiome modulation
Lycopene	Inhibited tumor growth, prevent DNA mutation	Apoptosis induction
Neoxanthin	Potent antioxidant properties	Antioxidant actions, modulation of signaling pathways
Punicalagin	Supports in decreasing arthritis, hypertension, cancer, oxidative stress, hyperglycaemia and maintaining cholesterol and lipids levels in blood	Processes for instance deglycosylation, demethylation and ring cleavage lead to the generation of bioactive compounds that demonstrate antioxidant, anti-inflammatory, and metabolic modulatory properties
Ellagic acid	Potent antioxidant and anti-inflammatory properties	Improving insulin secretion, insulin receptor substrate protein 1 expression, triglyceride, glucose transporter 4, total cholesterol, LDL, HDL and decreasing TNF-a, interleukin-6 (IL-6), (ROS), malondialdehyde (MDA), and oxidative stress in related tissues

Conclusion

Functional foods represent a promising approach to enhancing health and preventing chronic diseases by providing bioactive compounds with targeted physiological benefits. Despite their significant health benefits, the development and consumption of functional foods require careful consideration of safety aspects, including ingredient stability, allergenicity, and potential interactions with medications. Regulatory legislation assumes a key role in determining product efficacy, safety, and consumer confidence; in the future, personalized nutrition and biotechnological advances, and scientific research will drive the evolution of functional foods and their ability to efficiently address individual health needs. With the enhancement of public understanding of the benefits derived from functional foods and a deeper scientific knowledge of their mechanisms, functional foods will be recognized and integrated into daily diets and healthcare plans, serving a significant purpose in promoting long-term health and well-being. To maximize the global health impact of functional foods, sustained interdisciplinary research efforts and regulatory progress will be imperative in unlocking their full potential for improving public health outcomes worldwide.

Acknowledgement
The authors are highly obliged to their departments and institutes for access to journals, books and valuable database.

Authors Contributions
Introduction and Safety regulations, A.Z; classification of functional foods and bioactive components, M.F; disease management and mechanism of action, A.S; abstract, conclusion and figures, Z.A; Conceptualization, review and validation, F.S.

Conflict of Interest
The authors declared that they have no conflict of interest.

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