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Advances in plant-based functional foods: Emerging trends, nutritional potential, and health implications

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Abstract: Plant-based functional foods (PBFFs) have emerged as a rapidly growing sector driven by consumer health awareness, technological innovation, and sustainability considerations. These foods, encompassing cereals, legumes, fruits, vegetables, nuts, seeds, and novel sources like microalgae and microgreens, are rich in bioactive compounds such as polyphenols, carotenoids, polyunsaturated fatty acids, dietary fibers, phytosterols, and bioactive peptides. Evidence from epidemiological, clinical, and mechanistic studies demonstrates that PBFFs can modulate metabolic pathways, reduce oxidative stress, enhance cardiovascular and metabolic health, and support gut microbiota functionality. Technological advancements, including nanoemulsions, hydrogels, and non-thermal processing, are improving the bioavailability, stability, and functional efficacy of these compounds. Despite promising health benefits, challenges remain in ensuring consistent bioactive delivery, addressing safety and regulatory disparities, and achieving consumer acceptance. This review synthesizes emerging trends, nutritional potential, and health implications of PBFFs, providing insights for researchers, industry stakeholders, and policymakers to optimize the development and adoption of functional foods. Future research should focus on strengthening clinical validation, improving bioavailability strategies, and developing personalized nutrition approaches to fully realize the potential of PBFFs in preventive healthcare and sustainable food systems.
Keywords: Plant-based functional foods, bioactive compounds, polyphenols, dietary fibers, microalgae

1. Introduction

In recent years, plant-based functional foods (PBFFs) have emerged as a transformative segment in the global food landscape, driven by evolving consumer preferences, technological innovations, and increasing awareness of diet-related health outcomes. Functional foods, defined as "whole foods along with fortified, enriched, or enhanced foods that have a potentially beneficial effect on health when consumed as part of a varied diet on a regular basis at effective levels" (Crowe & Francis, 2013). They are characterized by physiologically active components, including antioxidants, phenolic compounds, and omega-3 fatty acids (Arshad & Ahmad, 2021). Plant-based diets, in contrast, are broadly defined as "all diets based on plant foods, including an abundance of vegetables, fruits, beans, lentils, legumes, nuts, seeds, fungi, and whole grains, with limited or no animal products." (Flores-Balderas, 2023) or as regimens that encourage whole plant foods while discouraging meats, dairy, eggs, and processed foods (Tuso, 2013). These definitions, endorsed by authoritative bodies such as the Academy of Nutrition and Dietetics and the American Council on Science and Health, underscore the evidence-based health potential of PBFFs rather than marketing claims.

The development of PBFFs has been shaped by multiple emerging trends. Innovations in alternative proteins, precision fermentation, and functional formulations are expanding options for plant-based meat, cheese, milk, and egg analogs (Tachie, 2023), although adoption remains constrained by micronutrient deficiencies and beany

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flavors. Consumer trends are increasingly influenced by conscious and sustainable consumption, with purchasing behaviors guided by health, ethics, and digital engagement (Cuthbertson & Marks, 2008; Karunia, 2023). Alternative proteins are growing two to three times faster than traditional meat sources, though still represent less than 4% of the global protein market. Simultaneously, demands for food safety, transparency, and traceability continue to shape production and labeling practices (Bjørndal et al., 2014).

Health implications of PBFFs are increasingly substantiated by scientific evidence. Clinical studies indicate that bioactive compounds such as probiotics, flavonoids, and omega-3 fatty acids can reduce LDL cholesterol, enhance insulin sensitivity, and mitigate oxidative stress (Fekete et al., 2025). Epidemiological evidence further suggests that PBFFs may lower chronic disease risk, particularly cancer (Das et al., 2016). Nevertheless, persistent nutritional gaps and variability across products remain critical considerations. For instance, plant-based seafood alternatives show differing outcomes in nutritional parameters between dietary groups (Mahmud et al., 2024), and PBPs may offer inferior protein quality compared to animal-based counterparts, alongside allergen and food safety concerns requiring ongoing research (Tachie et al., 2023).

Overall, the robust evidence base spanning 2008–2024 indicates that PBFFs hold significant promise for promoting human health, environmental sustainability, and ethical food production. The purpose of this review is to comprehensively examine recent advances in plant-based functional foods, highlighting emerging trends, nutritional potential, and associated health implications. Its significance lies in synthesizing current knowledge, identifying gaps in clinical and nutritional evidence, and informing researchers, industry stakeholders, and policymakers on strategies to optimize the development, adoption, and health impact of PBFFs.

Even while research on plant-based functional foods is expanding, it frequently concentrates on food categories, particular bioactive chemicals, or restricted health outcomes, leading to a fragmented knowledge of their entire functional potential. Additionally, existing assessments do not adequately incorporate bioavailability issues, inconsistent clinical evidence, and new technology and regulatory factors. To close these gaps, a thorough and critically analyzed viewpoint is required. The categorization, bioactive content, technical developments, and health consequences of plant-based functional foods are all comprehensively examined in this study, which also highlights present constraints and potential avenues for future research. This study offers a comprehensive framework to enable the creation, optimization, and use of PBFFs in functional nutrition and sustainable food systems by combining findings from epidemiological, mechanistic, and clinical investigations.

2. Plant-Based Functional Foods: Classification and Sources

Plant-based functional foods are increasingly recognized for their potential to promote health beyond basic nutrition. These foods provide bioactive compounds that can modulate metabolic pathways, reduce disease risk, and improve overall well-being. In this section, we present a comprehensive overview of key categories of plant-based functional foods—cereals and grains, legumes and pulses, fruits and vegetables, nuts, seeds, oils, and emerging novel sources such as algae and microgreens, while critically synthesizing evidence from epidemiological, mechanistic, and clinical studies.

2.1. Cereals and Grains

Cereals and grains represent a foundational component of functional foods due to their nutritional richness and broad-spectrum bioactivity. Common cereals such as wheat, oats, barley, buckwheat, brown rice, millet, sorghum, and flaxseed have been extensively studied for their health-promoting properties (Otles & Nakilcioglu-Tas, 2022). These grains are rich in phenolic acids, flavones, flavonoids, phytosterols, dietary fiber, vitamins, and minerals, providing multiple avenues for functional food development (Sidhu et al., 2007).

Cumulative evidence underscores cereals' role in mitigating cardiometabolic risk. Charalampopoulos et al. (2002) highlighted their multifunctional benefits, including glucose regulation, lipid profile improvement, and gut health modulation. Epidemiological studies further indicate that habitual cereal consumption is inversely associated with cardiovascular disease, type 2 diabetes, obesity, and certain cancers (Otles & Nakilcioglu-Tas, 2022). Among cereals, barley is particularly notable; its β-glucan content has been validated in multiple regulatory frameworks as a soluble fiber capable of lowering blood glucose and LDL cholesterol (Bhat et al., 2023). Moreover, cereal-derived products, including beverages, baked goods, and breakfast cereals, can be strategically engineered to enhance functional properties and improve bioavailability (Otles & Nakilcioglu-Tas, 2022). Compared with other plant sources, cereals offer the advantage of well-characterized fibers like β-glucan with regulatory approval, providing a clear translational pathway from research to functional food applications, which remains less established for emerging sources.

2.2. Legumes and Pulses

Legumes and pulses are recognized for their dense nutrient profile and pronounced metabolic benefits. Evidence indicates that consumption of lentils, chickpeas, beans, and peas can modulate postprandial glycemia, enhance insulin sensitivity, and regulate lipid metabolism, positioning them as functional foods suitable for type 2 diabetes management (Bahadoran & Mirmiran, 2015).

Legumes are rich in proteins, bioactive peptides, polyphenols, and phytosterols, which confer antioxidant, anti-inflammatory, and cardioprotective effects Ferreira et al. (2022); (Kapoor, 2015) Further reported anti-aging and anti-cancer properties are associated with pulse-derived bioactives. However, most research remains in vitro or limited to compositional analyses, and controlled human studies are scarce. Ferreira et al. (2022) emphasized that large-scale clinical trials evaluating the biological effects of pulse-based foods are critically needed. Additionally, maintaining bioactive integrity during processing and storage continues to pose practical challenges. While cereals are primarily valued for their soluble fibers, legumes offer diverse macronutrient- and bioactive-driven functionalities. Yet the translational gap for legumes is more pronounced due to limited clinical validation, highlighting an area for targeted human studies.

2.3. Fruits and Vegetables

Fruits and vegetables are among the most extensively validated plant-based functional foods. They provide high concentrations of antioxidants, phenolics, and other phytochemicals, which act through additive and synergistic mechanisms to confer protection against oxidative stress and inflammation. Foundational work by Kaur and Kapoor (2001) demonstrated strong associations between fruit and vegetable intake and reduced disease risk. Liu (2003) further highlighted that whole foods exert more potent effects than isolated compounds, emphasizing the importance of dietary matrix interactions. Prospective cohort studies also link high consumption of plant-based foods to substantially reduced cardiovascular risk (Hu, 2003). Recent research corroborates these findings, demonstrating consistent antioxidant and anti-inflammatory activities (Madhab et al., 2023; Serafini & Peluso, 2016). Compared with cereals and legumes, fruits and vegetables offer a wider array of phytochemicals with demonstrated synergistic activity. However, variability in study design, dosage, and participant characteristics limits direct comparisons and highlights the need for standardized intervention trials.

2.4. Nuts, Seeds, and Oils

Nuts, seeds, and plant-derived oils provide concentrated sources of bioactive compounds, including unsaturated fatty acids, phytosterols, and antioxidants, with established cardiovascular benefits. Epidemiological evidence demonstrates that high consumption of these foods significantly lowers the risk of coronary artery disease and stroke Hu (2003); (Ryan et al., 2007) quantified bioactive content in various seeds, highlighting phytosterol levels between 24.9 and 191.4 mg/100 g and predominantly unsaturated fatty acid profiles. Flaxseed has been particularly well-studied, with both animal and human studies supporting its role in reducing cardiovascular disease, diabetes, and certain cancers (Goyal et al., 2014).

Nonetheless, limitations persist. For example, pumpkin seed oil demonstrates promising in vitro bioactivity, yet clinical evidence remains limited, often restricted to cardiovascular or hormonal outcomes in specific populations such as menopausal women (Šamec et al., 2022). Nuts and seeds provide a concentrated functional effect relative to cereals and fruits due to high bioactive density. However, the generalizability of their benefits is constrained by population-specific studies and reliance on observational data rather than robust clinical trials.

2.5. Novel Plant-Based Sources (Algae, Microgreens, Plant Proteins)

Emerging plant-based sources, including microalgae, microgreens, and plant-derived proteins, represent the frontier of functional food research. Microalgae, in particular, are notable for exceptionally high protein content (up to 70%) and complete amino acid profiles (Mosibo et al., 2024). They also provide polyunsaturated fatty acids, vitamins, minerals, and carotenoids, supporting diverse functional applications (Matos et al., 2017). Recent studies demonstrate cardiovascular, antioxidant, and anti-inflammatory benefits (Saeed et al., 2025).

Despite promising attributes, challenges remain. Taste and odor, limited bioavailability, and processing constraints hinder commercial adoption (Andrade-Bustamante et al., 2025). Moreover, most research has focused on microalgae, with little empirical evidence regarding microgreens or other plant proteins in functional food contexts. Novel sources like microalgae offer superior nutrient density and bioactive potential relative to traditional cereals, legumes, and fruits. However, translational and sensory limitations currently restrict their widespread use, underscoring a key area for future innovation and human clinical evaluation.

Table 1. Classification of Plant-Based Functional Foods, Key Bioactive Components, and Evidence Summary

Category	Major Sources	Key Bioactive Compounds	Reported Health Benefits	Strength of Evidence
Cereals and grains	Wheat, oat, barley, buckwheat, brown rice, millet, sorghum, flaxseed	Phenolic acids, flavonoids, phytosterols, dietary fiber (β-glucan), vitamins, minerals	Reduced risk of CVD, obesity, type 2 diabetes, and certain cancers; improved blood glucose and LDL reduction	Strong epidemiological & mechanistic evidence; highly cited reviews
Legumes and pulses	Lentils, chickpeas, beans, peas	Proteins, bioactive peptides, polyphenols, phytosterols	Improved glycemic control, insulin sensitivity, lipid regulation, antioxidant, and anti-inflammatory effects	Moderate–strong evidence; limited large-scale human trials
Fruits and vegetables	Fruits, leafy vegetables, and cruciferous vegetables	Antioxidants, phenolics, phytochemicals, flavonoids	Disease prevention, reduced cardiovascular risk, anti-inflammatory, and antioxidant effects	Very strong evidence from cohort studies and reviews
Nuts, seeds, and oils	Flaxseed, pumpkin seeds, nuts, plant oils	Phytosterols, unsaturated fatty acids, lignans	Cardiovascular protection, lipid regulation, anti-cancer, and anti-diabetic potential	Substantial observational evidence; fewer clinical trials
Novel plant-based sources	Microalgae, emerging plant proteins	High-quality proteins, PUFAs, carotenoids, vitamins, minerals	Antioxidant, anti-inflammatory, cardiovascular benefits	Emerging but promising evidence; challenges in processing and sensory acceptance

Overall, cereals and grains provide well-characterized fiber-driven benefits with strong regulatory support. Legumes contribute diverse bioactives but require more clinical validation. Fruits and vegetables offer a wide array of synergistic phytochemicals, whereas nuts, seeds, and oils deliver high-concentration bioactives primarily targeting cardiovascular health. Novel sources, such as microalgae, hold substantial promise but face practical adoption challenges. A critical trend across all categories is the need for standardized clinical trials, improved bioavailability strategies, and integration of these foods into functional products that retain their biological activity.

3. Bioactive Compounds in Plant-Based Foods

Plant-based foods are rich in bioactive compounds that contribute to health promotion and disease prevention. Key classes include phenolic compounds and flavonoids, carotenoids and vitamins, polyunsaturated fatty acids (PUFAs), dietary fibers and prebiotics, and phytosterols and bioactive peptides. These compounds act via multiple mechanisms—antioxidant, anti-inflammatory, cardioprotective, and gut-mediated—though their efficacy depends on bioavailability, food matrix, and processing.

3.1. Phenolic compounds and flavonoids

Phenolic compounds and flavonoids are widely distributed in cereals, legumes, nuts, olive oil, vegetables, fruits, tea, and red wine, and are recognized for antioxidant and disease-preventive properties (Naczk & Shahidi, 2003). Kris-Etherton et al. (2002) synthesized evidence demonstrating protective roles in cardiovascular disease and cancer. More recent studies confirm additional benefits, including antibacterial, anti-inflammatory, immune-enhancing, and anticancer effects (El Qarnifa & Alahyane, 2025; Sun & Shahrajabian, 2023). However, bioavailability is a key limiting factor. Factors such as the food matrix, processing, and individual metabolic differences influence absorption, meaning actual physiological benefits may vary considerably. Compared with other bioactives, phenolics and flavonoids exhibit broad-spectrum effects due to their multi-target antioxidant and anti-inflammatory mechanisms, yet their dependence on bioavailability differentiates them from more directly absorbed compounds such as certain PUFAs or phytosterols, highlighting the need for careful food formulation to maximize benefits.

3.2. Carotenoids and vitamins

Carotenoids—including β-carotene and lycopene—and vitamins C, K, and B-complex provide antioxidant, anti-inflammatory, and disease-preventive functions (Saini et al., 2021; Samtiya et al., 2021). Lycopene shows strong evidence for cancer prevention (Finley, 2005). However, bioavailability varies substantially: plant-derived vitamin C is ~76% bioavailable, while β-carotene reaches only ~15.6% compared with 74% for preformed vitamin A (Chungchunlam & Moughan, 2024). Absorption is influenced by dietary fat, food processing, and carotenoid species (Priyadarshani, 2017). While carotenoids and vitamins are more compound-specific than phenolics, they can produce potent effects when absorbed efficiently. Their narrower spectrum of activity contrasts with the multi-target functionality of phenolics, but their inclusion alongside broad-spectrum compounds may yield synergistic effects in functional food formulations.

3.3. Polyunsaturated fatty acids (PUFAs)

Plant-based PUFAs, including alpha-linolenic acid from flax, chia, and garden cress, and stearidonic acid and EPA/DHA from microalgae oils, support cardiovascular health, cell membrane integrity, and immune function (Saini et al., 2021). Omega-3 PUFAs provide anti-inflammatory and hypotriglyceridemic effects, whereas omega-6 PUFAs may be pro-inflammatory (Rincón-Cervera et al., 2022). Evidence for cardiovascular benefits is robust, but potential roles in diabetes, cancer, Alzheimer's disease, and dementia remain uncertain, highlighting the need for further clinical research (Rincón-Cervera et al., 2022). PUFAs differ from phenolics and carotenoids in that they act through lipid metabolism and inflammation pathways more specifically. While their cardiovascular benefits are well-established, their narrower mechanistic scope underscores the value of combining PUFAs with multi-target bioactives, such as phenolics and flavonoids, for comprehensive health promotion.

3.4. Dietary fibers and prebiotics

Dietary fibers and prebiotics modulate gut microbiota and generate bioactive metabolites, including short-chain fatty acids (acetate, propionate, butyrate), which exert systemic physiological effects (Holscher, 2017). Prebiotic compounds, such as inulin, fructooligosaccharides, and galactooligosaccharides, promote digestive health and glycemic control (Carlson et al., 2018; Macagnan et al., 2016). Some purported benefits, such as improved epithelial integrity and colorectal cancer risk reduction, remain debated due to insufficient clinical validation (Verspreet et al., 2016). Unlike PUFAs or carotenoids, fibers and prebiotics act indirectly through gut-mediated pathways, complementing directly acting compounds. Their inclusion in functional foods provides an additional mechanism that supports systemic health and can potentiate the effects of other bioactives such as polyphenols or phytosterols.

3.5. Phytosterols and peptides

Phytosterols are well-established for LDL-cholesterol reduction, supported by numerous clinical studies and meta-analyses, and may confer anti-obesity, anti-diabetic, anti-inflammatory, and immunomodulatory benefits, potentially reducing cancer risk by up to 20% (Moreau et al., 2018; Nattagh-Eshtivani et al., 2022). Plant-derived peptides exhibit antihypertensive, antioxidant, and immunomodulatory effects (Maestri et al., 2016), though practical applications are limited and require further preclinical and clinical validation (Yuan et al., 2022). These compounds provide highly targeted mechanistic effects, particularly in lipid metabolism and cardiovascular health. Compared with broader-spectrum bioactives such as phenolics or flavonoids, their effects are narrower, making them ideal partners in multi-component functional foods where synergistic interactions can amplify overall efficacy.

Across plant-based bioactive classes, complementary mechanisms emerge. Phenolics and flavonoids act broadly through antioxidant, anti-inflammatory, and immunomodulatory pathways. Carotenoids and vitamins provide more targeted but potent effects when absorbed efficiently. PUFAs contribute lipid- and inflammation-modulating functions, fibers and prebiotics act indirectly through the gut, and phytosterols and peptides deliver focused lipid-lowering and cardiovascular benefits. Collectively, these compounds form a network of synergistic interactions that maximize health outcomes beyond individual effects. Designing functional foods that integrate multiple bioactive classes, optimize bioavailability, and retain biological activity throughout processing represents a critical strategy for translating these bioactives into practical, efficacious interventions.

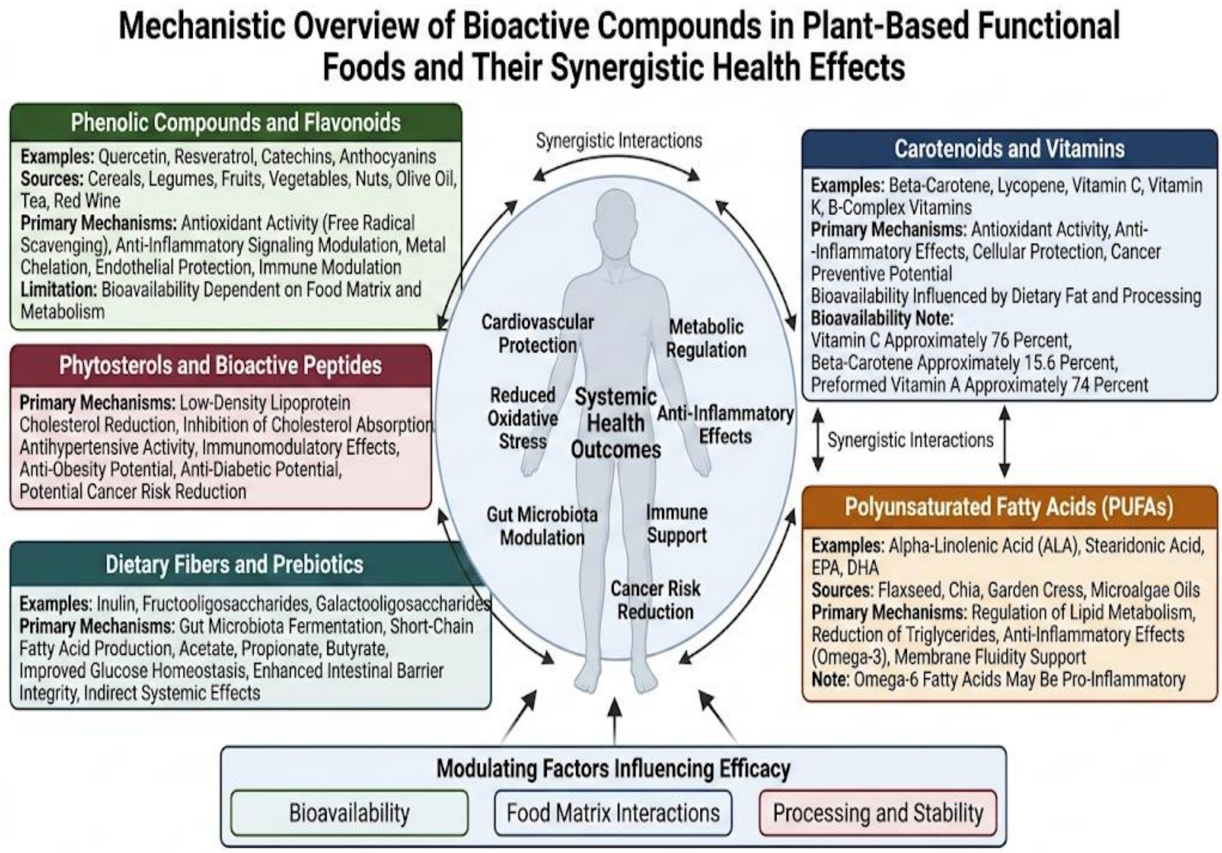

Fig. 1. Mechanistic overview of major bioactive compound classes in plant-based functional foods and their synergistic health effects.

4. Technological Approaches in Enhancing Functional Properties

Bioactive compounds present in plant-based foods, particularly phytosterols and peptides, have attracted considerable scientific interest due to their demonstrated ability to improve human health and their potential integration into functional food systems. Among these compounds, phytosterols and plant-derived peptides represent two major categories that contribute to the enhancement of physiological functions, especially those related to metabolic and cardiovascular health. Their relevance in food science lies not only in their biological activity but also in the increasing need to optimize their stability, delivery, and efficacy through technological interventions.

Phytosterols constitute one of the most extensively investigated classes of bioactive compounds, with substantial clinical evidence supporting their effectiveness in cholesterol reduction. Moreau et al. (2018) emphasized that numerous clinical investigations have consistently validated the low-density lipoprotein (LDL) cholesterol-lowering capacity of various phytosterol forms. The robustness of this conclusion is strengthened by the availability of more than ten meta-analyses synthesizing outcomes across multiple populations and study designs. Such repeated confirmation highlights the reliability of phytosterols as functional components within dietary interventions aimed at cardiovascular risk reduction. Beyond their established lipid-modulating effects, additional health-promoting roles have also been described. (Nattagh-Eshtivani et al., 2022) reported broader physiological impacts, including anti-obesity, anti-diabetic, anti-inflammatory, and immunomodulatory properties, suggesting that phytosterols may exert systemic effects beyond cholesterol metabolism. Furthermore, phytosterol-rich dietary patterns were associated with a potential reduction in cancer risk of approximately 20%, indicating their possible contribution to long-term disease prevention strategies.

In contrast to phytosterols, plant-derived bioactive peptides represent a rapidly emerging research area characterized by promising yet still developing evidence. These peptides originate from plant proteins and have been investigated for their diverse physiological activities. Maestri et al. (2016) identified at least 6,000 proteins capable of generating bioactive peptide sequences, illustrating the vast potential of plant resources as reservoirs of functional compounds. Reported biological activities include antihypertensive, antioxidant, and immunomodulatory effects, which collectively highlight their potential role in managing chronic conditions. However, despite these encouraging findings, challenges remain concerning their translational application. Yuan et al. (2022) noted that the practical and industrial utilization of bioactive plant-derived peptides remains limited, emphasizing that further pre-clinical and clinical investigations are required to validate health claims and establish consistent efficacy under real-world dietary conditions. This distinction between experimental potential and practical application underscores the need for technological innovations that can bridge laboratory findings and commercial implementation.

Technological advancements have therefore become essential in enhancing the functional performance of these bioactive compounds. Innovative delivery systems such as nanoemulsions, hydrogels, and biopolymer-based structures are increasingly employed to improve stability, protect sensitive compounds during processing, and enable controlled release during digestion. These approaches directly address common limitations associated with bioactive ingredients, including poor solubility, instability under processing conditions, and low bioavailability.

Nanoemulsion systems, typically characterized by droplet sizes ranging from 50 to 200 nm, have demonstrated considerable effectiveness in enhancing absorption and biological activity. Huang et al. (2010) reported that curcumin nanoemulsions achieved an 85% inhibition of inflammation, while dibenzoylmethane nanoemulsions exhibited a threefold improvement in oral bioavailability compared with conventional emulsions. These findings demonstrate how nanoscale structuring can significantly improve functional efficiency without altering the intrinsic properties of the compounds themselves. Supporting this concept, Prakasha and Vinay (2025) state that nanoemulsions not only protect sensitive bioactive molecules from adverse processing conditions but also facilitate enhanced absorption of vitamins, antioxidants, and proteins. As a result, nanoemulsion technology represents a critical strategy for maximizing the efficacy of functional ingredients within complex food matrices.

Hydrogels represent another promising technological approach, particularly for applications requiring sustained or controlled release mechanisms. Liu et al. (2021) demonstrated that polysaccharide–protein hydrogel systems improve the stability and bioavailability of key bioactive classes such as polyphenols, flavonoids, carotenoids, and vitamins. In addition to structural protection, hydrogels allow for the gradual release of phenolic compounds and aroma molecules, thereby improving functional performance while potentially enhancing sensory quality. This controlled delivery capability makes hydrogels especially relevant for food formulations where maintaining bioactivity throughout storage and digestion is essential.

Non-thermal processing technologies further contribute to the preservation of functional properties. Galanakis (2021) reported that such technologies help maintain the bioavailability of sensitive compounds while improving overall functional characteristics. However, the effectiveness of these methods depends strongly on careful optimization of operational parameters, as inappropriate processing conditions may lead to degradation or reduced activity. Therefore, technological design and process control remain central factors in ensuring successful implementation.

Table 2. Technological Approaches for Enhancing Functional Performance of Plant-Based Bioactives

Technology / Aspect	**System / Major Features**	**Functional Benefits**	**Mechanisms / Functional Effects**	**Evidence / Notes**
Nanoemulsion systems	Droplet sizes 50–200 nm; oil-in-water emulsions	Improved absorption of bioactives	Increased surface area improves solubility and digestion	Experimental evidence shows a strong enhancement of bioavailability
Nanoemulsion systems	Emulsifier-stabilized nanoscale droplets	Enhanced anti-inflammatory activity	Protection of sensitive compounds during digestion	Demonstrated improved biological activity in model systems
Nanoemulsion systems	Nano-scale delivery matrix	Increased oral bioavailability of compounds	Controlled release and improved intestinal uptake	Reported up to 3-fold improvement compared with conventional emulsions
Hydrogel-based delivery systems	Polysaccharide–protein hydrogel structures	Sustained release of polyphenols and vitamins	Gradual diffusion-based release during digestion	Effective controlled-release technology validated experimentally
Hydrogel-based delivery systems	Water-retaining structured gels	Improved stability of carotenoids and flavonoids	Structural protection against oxidation and degradation	Enhances shelf-life and functional retention
Hydrogel-based delivery systems	Biopolymer networks	Improved sensory quality alongside bioactivity	Controlled interaction with the food matrix	Promising for functional food formulation
Non-thermal processing	High-pressure processing	Preservation of heat-sensitive bioactives	Minimal thermal degradation	Strong potential for maintaining nutritional quality
Non-thermal processing	Pulsed electric fields	Improved functional characteristics	Cell membrane disruption enhancing extraction and stability	Requires optimization of processing parameters
Non-thermal processing	Cold plasma technologies	Maintenance of bioavailability	Reduced oxidation and microbial load without heat	Emerging technology; process control critical
Challenges: matrix interactions	Complex food matrices	Variable efficacy of bioactive delivery	Binding or interaction may reduce availability	Requires formulation optimization
Challenges: safety considerations	Novel delivery systems	Need for long-term safety validation	Potential toxicity or accumulation concerns	Knowledge gaps remain
Challenges: stability issues	Processing and storage conditions	Loss of functionality over time	Degradation under environmental conditions	Further research is required for industrial scalability

Despite the considerable progress achieved through these approaches, certain limitations and knowledge gaps remain unresolved. (Gasa-Falcon et al., 2020) highlighted concerns related to interactions between bioactive compounds and food matrices, potential toxicity issues, and the long-term implications of sustained consumption. These challenges indicate that while technological innovations have substantially improved the functional performance of plant-derived bioactives, further research is still required to fully understand their safety, efficacy, and long-term impact within dietary systems.

5. Health Benefits and Nutritional Impacts

5.1. Antioxidant and Anti-Inflammatory Effects of Plant-Derived Polyphenols

Plant-derived polyphenols represent one of the most extensively studied groups of bioactive compounds, largely due to their strong antioxidant and anti-inflammatory properties that contribute to protection against chronic diseases. Epidemiological investigations and meta-analyses demonstrate that long-term consumption of polyphenol-rich diets is associated with reduced risks of cancers, cardiovascular disorders, diabetes, osteoporosis, and neurodegenerative diseases (Pandey & Rizvi, 2009).

More recent studies reinforce these mechanisms, confirming antioxidant, anti-inflammatory, anti-carcinogenic, and cardioprotective activities (Adal et al., 2024). Clinical and nutritional evidence further suggests that dietary polyphenols improve lipid profiles, regulate blood pressure, reduce insulin resistance, and attenuate systemic inflammation, with compounds such as quercetin and resveratrol showing specific benefits for cardiovascular health (Rana et al., 2022). Despite the strength of observational and mechanistic evidence, quantitative comparisons remain limited because many available sources lack detailed participant numbers and precise effect sizes from controlled trials. Compared with other nutritional bioactives, polyphenols demonstrate broader multi-target biological activities; however, their variability in bioavailability and study design makes direct comparisons with nutrient classes such as fatty acids or fibers more challenging, emphasizing the importance of integrating polyphenols within complex dietary patterns rather than evaluating isolated compounds alone.

5.2. Gut Microbiota Modulation and Metabolic Health

Beyond direct antioxidant activity, plant-based foods exert substantial health effects through modulation of the gut microbiota. Dietary fibers and plant polysaccharides undergo microbial fermentation, producing short-chain fatty acids—including acetate, propionate, and butyrate—that contribute to improved glucose homeostasis, lipid metabolism, and endothelial function (Fava et al., 2019). Simultaneously, polyphenols are metabolized by intestinal bacteria into biologically active metabolites that further reduce the risk of metabolic diseases (Wang et al., 2022).

Evidence indicates that plant-based diets are associated with a lower incidence of cardiovascular events and type 2 diabetes (Wong, 2014). Specific plant compounds illustrate these benefits: cocoa flavanols have been linked to reduced risk of myocardial infarction and stroke, while quercetin and resveratrol contribute to cardiovascular improvement through anti-inflammatory and endothelial-supportive effects (Rana et al., 2022). Additionally, medicinal plants such as garlic, fenugreek, and chicory demonstrate glucose- and cholesterol-lowering properties alongside microbiota modulation.

Immunomodulatory effects are also observed, largely mediated through reduced intestinal inflammation and enhanced barrier integrity (Fava et al., 2019). Nevertheless, while mechanistic evidence is compelling, many studies still rely on observational data or experimental models, and robust clinical trials with quantified outcomes remain limited. When compared with direct-acting bioactives such as antioxidants, gut microbiota modulation represents a more indirect yet potentially longer-lasting pathway, emphasizing that plant-based health benefits often arise from combined systemic and microbial interactions rather than single mechanisms.

5.3. Integrated Nutritional Perspective

Collectively, evidence indicates that the health benefits of plant-based foods arise from overlapping mechanisms involving antioxidant defense, anti-inflammatory pathways, metabolic regulation, and microbiota-mediated effects. Polyphenols provide broad multi-system protection through direct biochemical interactions, while dietary fibers and microbiota-derived metabolites contribute indirectly by shaping gut ecology and metabolic signaling. These pathways are not independent; rather, they interact synergistically, with polyphenols influencing microbial composition and microbial metabolism, enhancing bioactive availability. This integrated perspective highlights that the nutritional impact of plant-based diets extends beyond individual compounds, suggesting that whole-food approaches may provide greater health benefits than isolated bioactive supplementation. Future research should therefore focus on well-designed clinical trials capable of quantifying effect sizes, clarifying mechanistic interactions, and strengthening translational applications in functional food development.

Table 3. Expanded Summary of Health Benefits and Nutritional Impacts of Plant-Based Dietary Components.

Health Aspect	Key Plant Components / Drivers	Reported Health Benefits	Mechanisms / Functional Effects	Strength of Evidence / Notes
Antioxidant protection	Polyphenols	Reduction of oxidative stress and cellular damage	Free-radical scavenging and metal chelation	Strong epidemiological and mechanistic evidence
Anti-inflammatory effects	Polyphenols (e.g., quercetin, resveratrol)	Reduced systemic inflammation and chronic disease risk	Modulation of inflammatory signaling pathways	Supported by clinical and nutritional studies
Cardiovascular protection	Polyphenols, cocoa flavanols	Improved lipid profile, blood pressure control, reduced myocardial infarction and stroke risk	Endothelial protection, antioxidant activity	Strong observational evidence; limited quantified effect sizes
Metabolic regulation	Polyphenols	Reduced insulin resistance and improved metabolic health	Regulation of glucose metabolism and oxidative pathways	Moderate–strong evidence; variability across studies
Gut microbiota modulation	Dietary fibers, plant polysaccharides	Improved gut health and metabolic outcomes	Fermentation by microbiota; SCFA production	Mechanistically strong evidence
SCFA-mediated metabolic effects	Fibers → acetate, propionate, butyrate	Improved glucose homeostasis and lipid metabolism	Microbial fermentation products affecting metabolism	Evidence growing; human trials still limited
Microbial metabolism of polyphenols	Gut microbiota + polyphenols	Formation of bioactive metabolites with systemic benefits	Biotransformation into absorbable compounds	Emerging evidence from experimental and clinical studies
Immunomodulatory effects	Fibers, microbiota-derived metabolites	Enhanced immune response and reduced intestinal inflammation	Improved gut barrier integrity and reduced inflammation	Mostly mechanistic and experimental evidence
Effects of medicinal plants	Garlic, fenugreek, chicory	Glucose- and cholesterol-lowering effects	Microbiota modulation and metabolic regulation	Promising but requires stronger clinical validation
Integrated dietary synergy	Whole plant-based diets (polyphenols + fibers)	Broad systemic health improvement beyond single compounds	Synergistic interaction between antioxidant and microbiota pathways	Supports whole-food approach; further clinical trials needed

6. Regulatory, Safety, and Consumer Acceptance Issues

Functional foods encounter multiple interconnected challenges that collectively influence their successful development, regulatory approval, and consumer adoption. These challenges operate across several dimensions, including safety and toxicological concerns, regulatory inconsistencies, and varying patterns of consumer perception and acceptance. Among these factors, regulatory fragmentation and botanical safety issues emerge as particularly significant barriers, limiting the efficient translation of functional food innovations into global markets.

Evidence from the literature demonstrates that these challenges are not isolated but rather form a complex network of interacting constraints. From a safety and toxicological perspective, the assessment of botanical ingredients remains particularly complicated due to the natural variability in plant composition and the diversity of bioactive compounds present in different species. Kroes and Walker (2004); Intrasook et al. (2024) highlighted that safety evaluation is hindered by factors such as compositional variation, potential food–drug interactions, and the presence of hazardous substances that may differ substantially among plant sources. This variability introduces uncertainty into risk assessment frameworks and complicates the establishment of standardized safety guidelines.

Furthermore, Colombo et al. (2020) noted that insufficient harmonization among international legislative systems further complicates safety oversight, suggesting that inconsistencies in regulatory approaches may increase challenges in ensuring consumer protection while supporting innovation. Regulatory frameworks represent another major determinant influencing the progress of functional foods within international markets. Differences in policy structure and approval procedures across regions create disparities in market development and commercialization opportunities. Annunziata and Vecchio (2013) documented that inconsistent legislative environments within Europe have limited market expansion compared with regions such as North America and Japan, where regulatory pathways have been comparatively more supportive or better established.

Similarly, Díaz et al. (2020) confirmed that approval mechanisms and regulatory requirements vary considerably among regions, creating barriers for global standardization. Despite these regulatory differences, the evidence suggests that consumers generally respond positively to health-related claims, indicating that regulatory inconsistency rather than consumer resistance may be a stronger limiting factor in certain contexts. This highlights the need for improved alignment between scientific evidence, policy frameworks, and market practices.

Consumer acceptance constitutes an additional critical dimension shaping the success of functional foods. Acceptance is influenced by a multifactorial set of determinants rather than a single driving variable. Baker et al. (2022), through the synthesis of seventy-five empirical studies, identified five major categories influencing consumer response: product-related attributes, socio-demographic characteristics, psychological factors, behavioral tendencies, and physical characteristics. The presence of these multiple determinants illustrates the complexity of consumer decision-making and emphasizes the importance of integrating social and behavioral perspectives alongside technological and nutritional considerations. Supporting this view, Frewer et al. (2003) emphasized that consumer acceptance largely depends on individual understanding of risk perception and health status, suggesting that communication strategies and perceived safety play central roles in shaping purchasing behavior and trust in functional food products.

Market-related evidence further demonstrates the growing economic significance of functional foods despite existing challenges. Rashidinejad (2024) reported that the global functional foods market reached approximately USD 280.7 billion in 2021 and is projected to expand at an annual growth rate of 8.5% through 2030. This growth trajectory reflects increasing consumer health awareness and demographic shifts such as aging populations, both of which contribute to rising demand for foods offering health-promoting benefits. The coexistence of strong market expansion alongside regulatory and safety challenges suggests that continued progress in this field will depend on balancing innovation with effective governance, safety assurance, and consumer education.

Collectively, the available evidence indicates that the advancement of functional foods is shaped by the interaction between scientific validation, regulatory coordination, and consumer perception. While the market demonstrates substantial growth potential, unresolved issues related to botanical safety assessment, legislative harmonization, and consumer understanding remain critical factors that must be addressed to support sustainable and responsible development within the functional food sector.

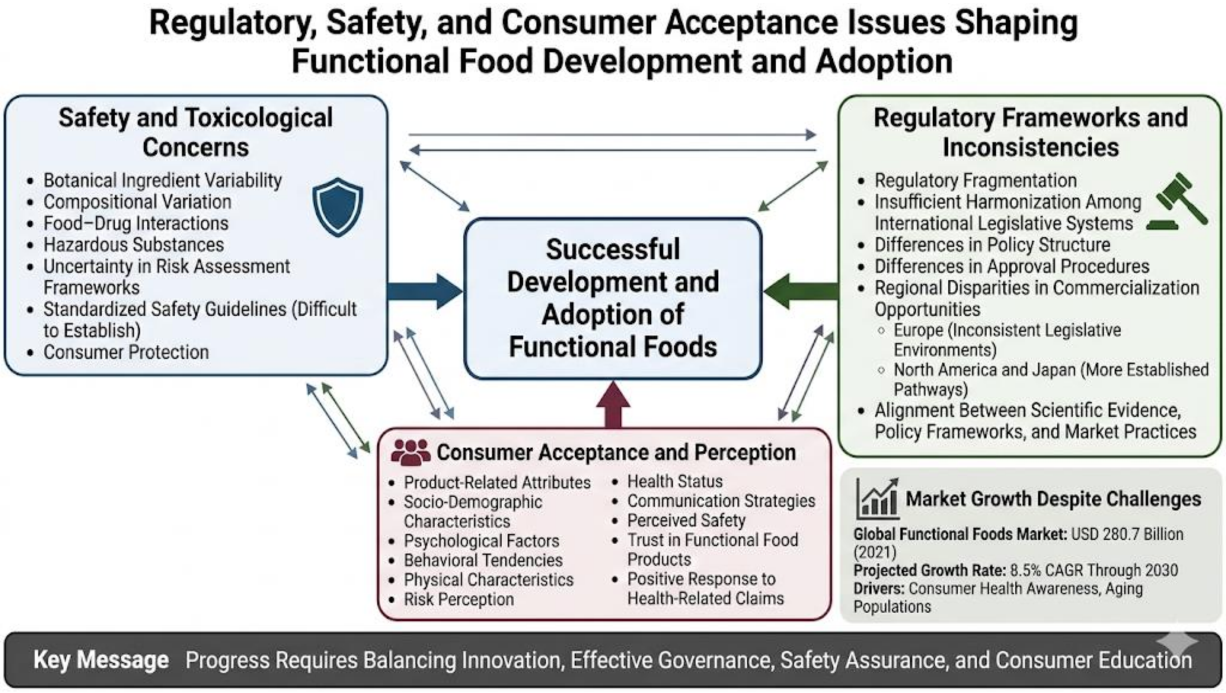

Fig. 2. Regulatory, safety, and consumer acceptance factors shaping functional food development and adoption.

The schematic highlights how safety/toxicological concerns, regulatory fragmentation, and consumer perception interact to influence successful commercialization, alongside continued market growth despite challenges.

7. Challenges and Future Directions

Functional plants represent a rapidly advancing area within food science and nutrition; however, their broader application continues to be constrained by several persistent challenges related to bioavailability, stability, and large-scale production. These limitations affect both scientific development and commercial translation, influencing how effectively functional plant components can be incorporated into food systems. At the same time, emerging technological advancements and evolving market demands provide significant opportunities for future progress, particularly in the areas of personalized nutrition and the development of novel product categories. The interaction between these constraints and opportunities defines the current direction of research and industrial innovation in the field.

The strength of available evidence varies across different aspects of functional plant development. Among the most consistently reported challenges are issues associated with bioavailability and stability, which are well documented across multiple studies. Rashidinejad (2024) and additional supporting sources identify poor solubility, reduced stability during processing and storage, and degradation within the gastrointestinal environment as primary factors limiting the functional effectiveness of plant-based bioactive compounds. These factors collectively reduce the proportion of bioactive ingredients that remain available for absorption, thereby limiting the intended physiological benefits. Consequently, improving stability throughout processing and ensuring effective delivery during digestion remain central priorities for both researchers and industry stakeholders.

Beyond physicochemical limitations, challenges related to scalability and regulation further restrict the widespread implementation of functional plant technologies. Rashidinejad (2024) emphasized that manufacturing processes often face technical and economic barriers when transitioning from laboratory-scale experimentation to industrial-scale production. In addition, the absence of clear and consistent regulatory frameworks introduces uncertainty regarding product development, approval pathways, and market entry. These combined manufacturing and regulatory constraints indicate that technological advancement alone may not be sufficient; coordinated regulatory development and standardized production approaches are equally necessary to support long-term growth.

Despite these challenges, the concept of personalized nutrition represents a particularly promising future direction for functional plant applications. (Rashidinejad, 2024) described personalized nutrition as a transformative approach with the potential to revolutionize health and wellness by aligning dietary interventions with individual needs. This perspective reflects a broader shift toward targeted nutritional strategies that move beyond generalized recommendations. However, the realization of personalized nutrition frameworks depends on overcoming existing scientific limitations, including improved delivery systems and reliable validation of health benefits, as well as resolving regulatory barriers that currently limit implementation.

Emerging market trends provide further evidence of expanding opportunities within the functional plant sector. Boukid (2021) documented the mainstream growth of plant-based meat analogues, demonstrating increasing consumer demand and market penetration. Nevertheless, formulation complexity and processing challenges remain critical issues requiring continued innovation to ensure product quality and functional performance. Similarly, Sharma et al. (2024) and additional studies highlighted the rapid expansion of functional beverages as an important product category, although ongoing concerns related to stability and bioavailability continue to influence product development strategies. These findings suggest that market growth is occurring alongside technological challenges, reinforcing the need for solutions that maintain functionality throughout processing, storage, and consumption.

Technological strategies aimed at addressing these challenges include microencapsulation and advanced delivery system innovations. There have been supporting studies that identified such approaches as promising solutions for improving stability, protecting sensitive bioactive compounds, and enhancing overall delivery efficiency. By enabling controlled release and reducing degradation during processing or digestion, these technologies provide practical pathways toward improving functional performance and expanding commercial feasibility.

Taken together, current evidence indicates that the future of functional plant-based products will depend on balancing scientific innovation with manufacturing scalability, regulatory clarity, and evolving consumer demands. While significant obstacles remain in relation to bioavailability, stability, and industrial implementation, emerging technological solutions and expanding market interest suggest substantial potential for continued advancement. As research progresses, integrating technological, regulatory, and market-oriented perspectives will be essential for realizing the full potential of functional plants within modern food and nutrition systems.

8. Conclusion

Plant-based functional foods represent a significant opportunity to promote health, sustainability, and ethical food production. Their diverse bioactive compounds act through complementary mechanisms—including antioxidant, anti-inflammatory, metabolic, and gut-mediated pathways—to provide systemic health benefits beyond basic nutrition. Technological innovations have enhanced the stability, bioavailability, and efficacy of these compounds, yet challenges in processing, sensory acceptance, safety, regulatory alignment, and clinical validation remain. Future progress will depend on integrating multi-component bioactives, improving translational research, advancing personalized nutrition strategies, and harmonizing regulatory frameworks. By addressing these challenges, PBFFs can fulfill their potential as a cornerstone of preventive nutrition and functional dietary interventions worldwide.

CRediT authorship contribution statement

Muhammad Abdullah Butt and Talha Riaz contributed to conceptualization, study design, and overall supervision of the review. Muhammad Abdullah Butt, Sawera Hayat, and Rabiya Riaz were involved in literature collection and preparation of the original draft. Muhammad Moeid Khan, Burhan Khalid, and Aliza Batool contributed to data curation, visualization, and manuscript drafting. Xianjiang Ye and Zhijun Xia provided supervision, critical review, and editing of the manuscript. Areeg Azhar and Sadia Ansar contributed to the literature review, data organization, and manuscript refinement. All authors contributed to writing the review and editing, approved the final manuscript, and agreed to be accountable for the content of the work.

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Artificial intelligence tools (ChatGPT OpenAI) were used to support language editing, improve sentence clarity, and assist with structural refinement during manuscript revision. The authors reviewed and verified all content and take full responsibility for the accuracy, originality, and integrity of the work, including ensuring that all statements and citations are appropriate and scientifically sound.

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