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## Unveiling the nutraceutical mechanisms of vegetables in promoting health and managing chronic diseases

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### Abstract

Vegetables are indispensable components of the human diet, providing not only essential nutrients but also a rich array of bioactive phytochemicals with profound nutraceutical potential. In recent years, increasing scientific attention has been directed toward understanding the molecular mechanisms through which vegetable-derived compounds contribute to the prevention and management of chronic diseases. This review synthesizes current knowledge on the phytochemical composition, mechanistic pathways and emerging innovations that underscore the health-promoting roles of vegetables. Vegetables contain diverse classes of bioactives flavonoids, phenolic acids, carotenoids, glucosinolates, alkaloids and saponins that exert multiple physiological effects. These compounds act through intricate biochemical mechanisms involving antioxidant defense, anti-inflammatory modulation, metabolic regulation and cellular signaling. Key molecular pathways, including the activation of Nrf2/ARE, inhibition of NF-κB and COX-2, enhancement of insulin sensitivity and regulation of apoptosis and lipid metabolism, collectively contribute to reducing the risk of cardiovascular diseases, diabetes, cancer, neurodegenerative disorders and metabolic syndrome. Furthermore, omics-based approaches such as metabolomics, nutrigenomics and proteomics have deepened insights into gene-nutrient interactions, while advances in nanoencapsulation and food fortification have improved bioavailability and functional efficacy. Despite substantial progress, challenges remain in translating experimental evidence into clinical application due to variability in bioactive content, limited standardization and insufficient clinical validation. Integrating molecular nutrition with sustainable agricultural practices and personalized nutrition strategies can enhance the reliability and accessibility of vegetable-based nutraceuticals. Overall, this review emphasizes that vegetables, through their multifaceted mechanisms of action, hold immense promise as natural, sustainable and scientifically validated agents for health promotion and chronic disease prevention.

### 1. Introduction

Vegetables occupy an essential position in the human diet as they supply a wide range of nutrients necessary for maintaining health and physiological balance. They provide carbohydrates, proteins, vitamins, minerals and dietary fiber in addition to a multitude of naturally occurring phytochemicals that contribute to overall well-being. Beyond their basic nutritional role, vegetables have drawn growing scientific attention for their protective effects against several chronic and degenerative disorders. Epidemiological evidence consistently shows that populations consuming higher quantities of

vegetables tend to have lower incidences of lifestyle-related diseases, including cardiovascular ailments, diabetes, cancer and neurodegenerative conditions. Recognizing this, the world health organization (WHO) recommends a daily intake of at least 400 g of fruits and vegetables to safeguard against non-communicable diseases and nutrient deficiencies. Such recommendations underline the critical importance of vegetables not only as dietary essentials but also as key components of preventive healthcare. In recent decades, the term nutraceuticals, derived from the combination of “nutrition” and “pharmaceutical,” has gained prominence in food and health research (Adefegha, 2018). Nutraceuticals refer to natural bioactive compounds present in foods that deliver physiological or therapeutic benefits beyond their caloric or nutrient value. Vegetables are among the richest natural sources of these compounds. They contain a variety of phytochemicals such as flavonoids, carotenoids, phenolic acids, glucosinolates, alkaloids, saponins and organosulfur molecules, all of which exhibit strong biological activities. These compounds play vital roles in scavenging free radicals, suppressing inflammation,

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modulating enzyme systems and influencing cell signaling pathways involved in disease development. Closely related to this concept is that of functional foods, which are conventional dietary items that impart additional health-promoting effects when consumed regularly. Vegetables, therefore, serve as natural functional foods, capable of contributing both to nutrition and disease prevention through their bioactive profiles (Tufail *et al.*, 2025).

Nutritional science has evolved significantly from its earlier emphasis on preventing deficiencies to a more advanced understanding of how specific dietary molecules affect cellular and molecular functions. This shift from traditional nutrition to molecular nutrition has opened new avenues for exploring how vegetable-derived compounds influence gene expression, regulate metabolic processes and maintain redox balance. The emergence of technologies such as metabolomics, nutrigenomics and proteomics has revealed that these phytochemicals can interact with molecular targets, alter transcriptional responses and even modulate gut microbiota composition, collectively contributing to improved physiological resilience and reduced disease risk. This evolution in understanding highlights a fundamental transition from quantity-focused nutrition to quality- and functionality-driven dietary science (Saiwal *et al.*, 2019). The rising global prevalence of chronic diseases such as cardiovascular disorders, type 2 diabetes, obesity, cancer and neurological conditions poses serious challenges to public health systems worldwide. According to the global burden of disease (GBD) study, more than 70% of global deaths are attributed to non-communicable diseases, many of which stem from poor dietary patterns and lifestyle factors. The common pathological features of these disorders include oxidative stress, inflammation, mitochondrial dysfunction and metabolic dysregulation. Scientific investigations increasingly demonstrate that regular consumption of vegetables rich in antioxidants and phytochemicals can counteract these detrimental processes. They act through mechanisms such as reactive oxygen species neutralization, inhibition of inflammatory mediators, enhancement of insulin sensitivity, regulation of lipid metabolism and protection

of neural and cardiovascular tissues. Consequently, the inclusion of vegetables as nutraceutical components of the daily diet offers a practical, safe and cost-effective approach to improving human health and managing chronic diseases (Dama *et al.*, 2024).

Given these considerations, the present review aims to consolidate current knowledge on the nutraceutical potential of vegetables, emphasizing their bioactive composition, mechanisms of action and relevance in preventing chronic diseases. Although, individual studies have explored the biological effects of specific vegetables or isolated compounds, comprehensive integration of phytochemical diversity, mechanistic understanding and disease-specific outcomes remains limited. Therefore, the objectives of this review are threefold: (i) to outline the major phytochemical constituents responsible for the nutraceutical value of vegetables; (ii) to elucidate the underlying biochemical and molecular pathways through which these compounds exert health-promoting effects; and (iii) to discuss emerging insights, challenges and future opportunities in harnessing vegetables as functional nutraceuticals. Through this synthesis, the review seeks to establish a holistic understanding of how vegetable-derived bioactives can serve as natural therapeutic agents, bridging the gap between nutrition and molecular medicine in the pursuit of better health and chronic disease management.

## 2. Phytochemical and nutraceutical composition of vegetables

Vegetables represent one of the most diverse groups of plant-based foods, offering a broad spectrum of nutrients and phytochemicals that collectively contribute to human health and disease prevention. Their nutritional and bioactive composition varies across species, cultivars and growing conditions, yet they uniformly provide essential macronutrients, micronutrients and an array of secondary metabolites with significant nutraceutical value (Table 1). Understanding the nutritional and phytochemical make-up of vegetables is fundamental to appreciating their therapeutic potential and functional role in human diets.

**Table 1: Major phytochemicals in vegetables and their nutraceutical functions (Chan *et al.*, 2023)**

Phytochemical class	Representative compounds	Major vegetable sources	Primary mechanisms/health benefits
<b>Flavonoids</b>	Quercetin, Kaempferol, Luteolin	Onion, Broccoli, Kale, Spinach	Potent antioxidant; inhibits NF- $\kappa$ B and COX-2; reduces inflammation and cancer risk
<b>Phenolic acids</b>	Chlorogenic acid, Ferulic acid, Caffeic acid	Tomato, Carrot, Eggplant	Scavenges ROS; prevents lipid peroxidation; improves glucose metabolism
<b>Carotenoids</b>	$\beta$ -Carotene, Lycopene, Lutein, Zeaxanthin	Carrot, Tomato, Pumpkin, Spinach	Enhances vision; protects cardiovascular system; prevents cancer
<b>Glucosinolates/ Isothiocyanates</b>	Sulforaphane, Indole-3-carbinol	Broccoli, Cabbage, Kale	Induces detoxification enzymes; promotes apoptosis; anti-carcinogenic
<b>Saponins</b>	Diosgenin, Spinacoside	Spinach, Legumes	Lowers cholesterol; supports immune function
<b>Alkaloids</b>	Solanine, Trigonelline	Eggplant, Tomato, Fenugreek	Exhibits hypoglycemic, antimicrobial and neuroprotective effects
<b>Terpenoids and tannins</b>	Limonene, Catechins	Leafy greens, Herbs	Antioxidant, hepatoprotective and anti-inflammatory activity
<b>Flavonoids</b>	Quercetin, Kaempferol, Luteolin	Onion, Broccoli, Kale, Spinach	Potent antioxidant; inhibits NF- $\kappa$ B and COX-2; reduces inflammation and cancer risk

## 2.1 Macronutrients and micronutrients

Vegetables are inherently low in calories and fats but are rich in essential nutrients required for metabolic functions and physiological homeostasis. Macronutrients such as carbohydrates, proteins and dietary fiber constitute the primary nutritional base of most vegetables. Carbohydrates, largely present as complex polysaccharides and non-starch polysaccharides, serve as major energy sources while simultaneously contributing to gut health by promoting beneficial microbial activity. The dietary fiber component, particularly soluble fiber like pectin and insoluble cellulose, aids digestion, regulates blood glucose levels, lowers serum cholesterol and enhances satiety attributes that make vegetables integral to preventive nutrition strategies against obesity and cardiovascular disorders (Alblooshi *et al.*, 2024). The micronutrient composition of vegetables is equally remarkable, encompassing a wide variety of vitamins and minerals essential for enzymatic functions, antioxidant defense and cellular integrity. Leafy vegetables such as spinach, amaranth and kale are excellent sources of provitamin A ( $\beta$ -carotene), vitamin C (ascorbic acid), vitamin E (tocopherol) and folate, all of which play critical roles in maintaining immune function and preventing oxidative stress. Minerals like potassium, magnesium, iron, calcium and zinc are abundantly supplied through root and leafy vegetables, supporting vital processes such as muscle contraction, oxygen transport and enzyme activation. The synergy between these macro and micronutrients enhances the overall functional and nutraceutical value of vegetables, establishing them as essential components of a balanced diet.

## 2.2 Major bioactive compounds

Beyond basic nutrition, vegetables are exceptional sources of bioactive phytochemicals, secondary metabolites that exert health-promoting effects at cellular and molecular levels. These compounds possess antioxidant, anti-inflammatory, antimicrobial, anticancer and immunomodulatory properties, making them key contributors to the nutraceutical potential of vegetables.

### 2.2.1 Flavonoids

Flavonoids are a large class of polyphenolic compounds widely distributed in vegetables such as onions, broccoli, kale and spinach. Among the most studied flavonoids are quercetin, kaempferol and luteolin, known for their potent antioxidant and anti-inflammatory activities. Quercetin, abundant in onions and leafy greens, scavenges reactive oxygen species (ROS), modulates nitric oxide production and inhibits pro-inflammatory enzymes such as cyclooxygenase (COX) and lipoxygenase (LOX). Kaempferol, present in cruciferous vegetables like kale and broccoli, exhibits anticancer and cardioprotective actions by influencing apoptosis and mitochondrial pathways. Luteolin, found in celery and peppers, demonstrates neuroprotective and anti-allergic properties through the suppression of NF- $\kappa$ B and MAPK signaling pathways (Hossain *et al.*, 2025).

### 2.2.2 Phenolic acids

Phenolic acids form another important class of vegetable-derived antioxidants, predominantly represented by chlorogenic acid, ferulic acid and caffeic acid. These compounds are abundant in tomatoes, carrots and spinach and play a major role in neutralizing free radicals, inhibiting lipid peroxidation and modulating glucose metabolism. Chlorogenic acid, notably present in eggplants and potatoes, exhibits hypoglycemic activity by reducing glucose absorption and enhancing

insulin sensitivity (Gao *et al.*, 2022). Ferulic acid contributes to vascular health by improving endothelial function and reducing oxidative stress, while caffeic acid has demonstrated strong antimicrobial and anticancer effects through its ability to modulate apoptosis and cellular redox balance.

### 2.2.3 Carotenoids

Carotenoids are lipid-soluble pigments responsible for the vibrant yellow, orange and red hues of many vegetables. The most significant among them include  $\beta$ -carotene, lycopene and lutein.  $\beta$ -carotene, abundant in carrots and pumpkins, functions as a provitamin A compound essential for vision, immune function and epithelial integrity. Lycopene, primarily found in tomatoes and red peppers, is one of the most efficient singlet oxygen quenchers known and is linked to reduced risks of prostate and cardiovascular diseases (Aruoma *et al.*, 2012). Lutein, concentrated in dark leafy vegetables such as kale and spinach, protects against age-related macular degeneration and oxidative damage to retinal cells. Together, these carotenoids contribute substantially to the antioxidant defense system and cellular protection mechanisms.

### 2.2.4 Glucosinolates and isothiocyanates

Vegetables belonging to the Brassicaceae family, including broccoli, cabbage, cauliflower and kale, are rich in glucosinolates sulfur-containing compounds that, upon enzymatic hydrolysis, yield isothiocyanates such as sulforaphane and indole-3-carbinol. These breakdown products exhibit potent chemopreventive effects by modulating detoxification enzymes, suppressing carcinogen activation and inducing apoptosis in cancerous cells. Sulforaphane, for instance, activates the Nrf2 pathway, thereby enhancing the expression of antioxidant and phase II detoxifying enzymes. Indole-3-carbinol influences estrogen metabolism, reducing the risk of hormone-related cancers such as breast and prostate malignancies. Thus, glucosinolates and their derivatives contribute uniquely to the nutraceutical and disease-preventive potential of cruciferous vegetables (Hassan and Sarfraz, 2018).

### 2.2.5 Saponins, alkaloids, tannins and terpenoids

Apart from polyphenols and carotenoids, vegetables also contain diverse classes of non-phenolic phytochemicals that contribute to their biological activity. Saponins, found in spinach and legumes, possess cholesterol-lowering and immune-stimulating effects. Alkaloids, though sometimes toxic in high concentrations, demonstrate strong antimicrobial and anti-inflammatory properties at physiological levels, as seen in solanaceous vegetables like eggplants and peppers (Sarker and Oba, 2020). Tannins function as natural antioxidants and metal chelators, while terpenoids, including monoterpenes and diterpenes found in herbs and leafy vegetables, exhibit anti-inflammatory, anticarcinogenic and hepatoprotective activities. The synergistic action of these compounds enhances the functional efficacy of vegetables, establishing them as complex yet potent nutraceutical matrices.

## 2.3 Factors affecting phytochemical profiles

The concentration and composition of phytochemicals in vegetables are influenced by multiple intrinsic and extrinsic factors. Genotype plays a crucial role in determining phytochemical abundance, as genetic variability leads to differences in enzyme activities associated with secondary metabolism. The maturity stage of the vegetable at

harvest also significantly affects nutrient density young leaves or immature pods often contain higher levels of phenolic compounds and vitamins compared to their mature counterparts. Environmental conditions such as temperature, light intensity, soil fertility and water availability impact phytochemical biosynthesis. For example, stress conditions like drought or UV exposure can enhance the accumulation of flavonoids and phenolics as protective metabolites. Postharvest handling and processing methods-such as boiling, steaming, drying, or freezing can either degrade or enhance phytochemical availability. While high temperatures may lead to carotenoid degradation, moderate heat processing can improve the bioavailability of lycopene in tomatoes by breaking cell wall matrices (Arya *et al.*, 2019). Hence, optimal cultivation and processing practices are essential for maintaining the nutraceutical quality of vegetables.

#### 2.4 Comparative analysis of nutraceutical richness across vegetable groups

Different vegetable groups display varying profiles of nutrients and phytochemicals, reflecting their evolutionary adaptations and metabolic pathways. Leafy vegetables such as spinach, kale and amaranth are particularly rich in iron, folate, chlorophyll and antioxidant vitamins, making them potent protectors against anemia and oxidative stress. Solanaceous vegetables like tomatoes, peppers and eggplants provide carotenoids, alkaloids and phenolic acids that exhibit strong antioxidant and anticancer potential. Cruciferous vegetables including broccoli, cabbage and cauliflower are distinguished by their glucosinolate and isothiocyanate content, recognized for detoxifying and anticancer properties. Root and tuber vegetables, such as carrots, beets and sweet potatoes, are excellent sources of  $\beta$ -carotene, anthocyanins and minerals that support eye health and energy metabolism. Together, these groups represent a vast reservoir of nutraceutical compounds capable of targeting different physiological systems and disease pathways (Saiwal *et al.*, 2019). The diversity in phytochemical and nutritional composition across vegetable types highlights the importance of dietary variety. A balanced intake of different vegetables ensures a comprehensive supply of bioactive compounds, thereby maximizing the synergistic benefits essential for disease prevention and overall health maintenance.

### 3. Mechanisms of nutraceutical action

The health-promoting effects of vegetables stem primarily from the complex interactions of their bioactive compounds within cellular and molecular systems. These phytochemicals modulate a wide range of biological pathways responsible for oxidative balance, inflammation, apoptosis, metabolism and neural function. The mechanisms through which vegetable-derived nutraceuticals act are multifaceted, often overlapping across several disease pathways, thereby providing broad-spectrum protection. Understanding these mechanisms is fundamental to appreciating how regular consumption of vegetables can contribute to the prevention and management of chronic diseases.

#### 3.1 Antioxidant mechanisms

Oxidative stress plays a central role in the pathogenesis of numerous chronic disorders, including cardiovascular disease, diabetes, cancer and neurodegeneration. It arises from an imbalance between the production of reactive oxygen species (ROS) and the body's antioxidant defense systems. Vegetable-derived antioxidants counteract these deleterious processes through multiple mechanisms such as ROS

scavenging, metal chelation, inhibition of lipid peroxidation and activation of endogenous antioxidant pathways. Compounds like flavonoids, phenolic acids, carotenoids and vitamins (particularly vitamin C and E) directly neutralize reactive radicals such as superoxide anions, hydroxyl radicals and hydrogen peroxide. Their polyhydroxyl structures enable the donation of hydrogen atoms or electrons, thereby stabilizing free radicals and interrupting chain reactions in lipid peroxidation. For instance, quercetin and kaempferol in leafy vegetables donate electrons to neutralize free radicals, while  $\beta$ -carotene and lycopene in carotenoid-rich vegetables quench singlet oxygen effectively. Phenolic acids such as ferulic and caffeic acids chelate transition metals like iron and copper, preventing Fenton reactions that generate hydroxyl radicals (Ayeti *et al.*, 2018).

In addition to direct scavenging, vegetable phytochemicals also activate the endogenous antioxidant defense system through modulation of the Nrf2/ARE (nuclear factor erythroid 2-related factor 2/ antioxidant response element) pathway. Under oxidative stress, compounds such as sulforaphane (from crucifers) and curcumin-like phenolics facilitate the dissociation of Nrf2 from its repressor Keap1, allowing its translocation to the nucleus where it binds to the ARE sequence. This process upregulates the transcription of antioxidant and detoxifying enzymes such as heme oxygenase-1 (HO-1), superoxide dismutase (SOD), catalase and glutathione peroxidase (GPx). The overall outcome is a reinforced cellular antioxidant capacity that protects DNA, lipids and proteins from oxidative damage. Thus, the antioxidant actions of vegetables are both direct and indirect, forming a critical line of defense against oxidative-stress-induced diseases.

#### 3.2 Anti-inflammatory mechanisms

Inflammation is a physiological defense mechanism, but when persistent, it contributes to the progression of chronic illnesses such as arthritis, cancer, diabetes and cardiovascular disorders. Vegetable-derived bioactive compounds exhibit strong anti-inflammatory properties by modulating key signaling pathways, suppressing pro-inflammatory mediators and inhibiting enzymes involved in eicosanoid synthesis. Flavonoids such as quercetin and luteolin inhibit the activation of nuclear factor kappa-light-chain-enhancer of activated B cells (NF- $\kappa$ B), a master regulator of inflammation. Under stress or infection, NF- $\kappa$ B translocates to the nucleus to stimulate the transcription of pro-inflammatory genes such as cyclooxygenase-2 (COX-2), inducible nitric oxide synthase (iNOS), tumor necrosis factor-alpha (TNF- $\alpha$ ) and interleukins (IL-1 $\beta$ , IL-6). By preventing NF- $\kappa$ B activation, vegetable polyphenols reduce cytokine production and restore immune homeostasis. Similarly, carotenoids like lycopene and  $\beta$ -carotene inhibit COX-2 and LOX enzyme activities, reducing the synthesis of prostaglandins and leukotrienes, which are potent mediators of inflammation.

Furthermore, isothiocyanates derived from cruciferous vegetables, such as sulforaphane, suppress the MAPK (mitogen-activated protein kinase) signaling cascade and reduce oxidative stress-induced inflammatory responses. Phenolic acids and saponins also contribute by modulating the release of histamines and bradykinins and downregulating adhesion molecules that facilitate leukocyte migration to inflamed tissues (Sharma *et al.*, 2019). Collectively, these mechanisms demonstrate that vegetable-derived nutraceuticals exert anti-inflammatory effects through a delicate balance of gene regulation, enzyme inhibition and cytokine modulation, thereby offering protection against chronic inflammatory disorders.

### 3.3 Anticancer mechanisms

The anticancer potential of vegetables has been widely acknowledged in both epidemiological and experimental studies. Their chemopreventive effects are mediated through multiple pathways, including induction of apoptosis, regulation of the cell cycle, autophagy activation and epigenetic modulation. Unlike conventional chemotherapy, vegetable-derived phytochemicals act gently on cellular systems, targeting early stages of carcinogenesis without harming normal tissues. Flavonoids and polyphenols trigger programmed cell death (apoptosis) by activating intrinsic mitochondrial pathways involving caspase-3 and caspase-9, increasing the Bax/Bcl-2 ratio and promoting cytochrome c release. For example, quercetin induces apoptosis in colon and breast cancer cells by modulating p53 and PI3K/Akt pathways. Similarly, sulforaphane from broccoli induces apoptosis and cell cycle arrest at the G2/M phase through upregulation of p21 and p27, two key cyclin-dependent kinase inhibitors. Autophagy, another important mechanism of cellular homeostasis, is stimulated by certain vegetable-derived compounds such as luteolin and resveratrol, which remove damaged cellular organelles and limit tumor progression. Additionally, vegetables modulate epigenetic processes DNA methylation, histone acetylation and micro RNA expression that control gene activation and silencing. Sulforaphane, for example, acts as a histone deacetylase (HDAC) inhibitor, restoring the expression of tumor suppressor genes. Lycopene, abundant in tomatoes, interferes with insulin-like growth factor (IGF) signaling and downregulates oncogene expression. Polyphenols such as ferulic acid and catechins reduce oxidative DNA damage and inhibit angiogenesis by regulating vascular endothelial growth factor (VEGF) pathways. Collectively, these mechanisms illustrate the multi-targeted anticancer actions of vegetable nutraceuticals, making them valuable candidates for cancer prevention and adjunctive therapy (Nicolescu *et al.*, 2023).

### 3.4 Antidiabetic and hypoglycemic mechanisms

The global prevalence of diabetes mellitus has increased dramatically, driven by lifestyle changes and poor dietary patterns. Vegetable-based nutraceuticals help regulate glucose metabolism through several complementary mechanisms, including enhancement of insulin sensitivity, stimulation of glucose uptake and inhibition of carbohydrate-digesting enzymes. Polyphenols, saponins and alkaloids present in vegetables activate AMP-activated protein kinase (AMPK), a key energy sensor that enhances glucose uptake in muscle cells and increases fatty acid oxidation. Bitter melon, okra and fenugreek contain compounds that mimic insulin activity by promoting the translocation of GLUT4 (glucose transporter type 4) to the plasma membrane, thus facilitating cellular glucose entry. In addition, vegetables rich in dietary fiber slow the absorption of glucose in the intestine, reducing postprandial glycemic spikes (Zhu *et al.*, 2018).

Many vegetable phytochemicals also inhibit  $\alpha$ -glucosidase and  $\alpha$ -amylase, two key enzymes responsible for breaking down complex carbohydrates into glucose. By delaying carbohydrate digestion, these compounds help maintain lower blood glucose levels and reduce insulin demand. Phenolic acids such as chlorogenic acid and caffeic acid enhance hepatic glycogen storage and reduce gluconeogenesis, thereby improving glucose homeostasis. Furthermore, the antioxidant components of vegetables alleviate oxidative stress in pancreatic  $\beta$ -cells, protecting them from glucotoxicity and preserving insulin secretion. Collectively, these mechanisms underline the role of

vegetables as natural agents for glycemic control and diabetes management.

### 3.5 Cardioprotective mechanisms

Cardiovascular diseases (CVDs) remain one of the leading causes of death globally. Vegetable-derived nutraceuticals contribute significantly to cardiovascular health by reducing oxidative stress, modulating lipid metabolism and improving endothelial function. Phenolic compounds, carotenoids and organosulfur molecules reduce low-density lipoprotein (LDL) oxidation, a key step in atherogenesis. Lycopene, in particular, inhibits lipid peroxidation in arterial walls, thereby lowering the risk of plaque formation. Quercetin and ferulic acid improve lipid profiles by decreasing total cholesterol and triglycerides while increasing high-density lipoprotein (HDL) levels. Saponins contribute to cholesterol reduction by binding bile acids in the intestine and promoting their excretion.

At the vascular level, vegetable phytochemicals stimulate the production of endothelial nitric oxide synthase (eNOS), enhancing nitric oxide (NO) bioavailability. This leads to vasodilation, improved blood flow and reduced blood pressure. Polyphenols also suppress platelet aggregation, reducing the likelihood of thrombosis (Wink, 2022). Moreover, the potassium and magnesium content in vegetables helps regulate electrolyte balance and cardiac rhythm. By combining antioxidant, lipid-regulatory and vasodilatory effects, vegetable-based nutraceuticals provide comprehensive cardioprotection and help maintain vascular integrity.

### 3.6 Neuroprotective mechanisms

Neurodegenerative disorders such as Alzheimer's, Parkinson's and dementia are increasingly prevalent, largely due to aging populations and oxidative neuronal damage. Vegetable-derived bioactives exhibit potent neuroprotective effects by modulating neurotransmitter systems, preventing protein aggregation and reducing oxidative and inflammatory insults in neural tissues. Compounds such as lutein, quercetin and anthocyanins cross the blood-brain barrier and protect neurons from oxidative damage by scavenging ROS and upregulating antioxidant enzymes. Lutein, commonly found in spinach and kale, accumulates in neural membranes, where it stabilizes lipid bilayers and protects against photo-oxidative injury. Certain polyphenols and isothiocyanates also inhibit acetylcholinesterase (AChE), thereby maintaining higher levels of acetylcholine and improving synaptic transmission, which is crucial for memory and cognition (Aruoma *et al.*, 2012).

Vegetable compounds further modulate dopaminergic and cholinergic pathways that are impaired in Parkinson's and Alzheimer's diseases. Lycopene and sulforaphane reduce neuroinflammation by inhibiting microglial activation and downregulating pro-inflammatory cytokines such as IL-1 $\beta$  and TNF- $\alpha$ . Additionally, these compounds prevent the aggregation of amyloid- $\beta$  peptides, which are implicated in Alzheimer's pathology. Through these concerted actions, vegetable-based nutraceuticals preserve neuronal integrity, enhance cognitive function and slow neurodegenerative progression.

## 4. Role of vegetable-derived nutraceuticals in chronic disease prevention

The rising prevalence of chronic diseases such as cardiovascular disorders, diabetes, cancer, neurodegenerative conditions and obesity has become a pressing global health challenge. Modern dietary habits

characterized by high-fat, high-sugar and processed foods have accelerated these disorders, leading to metabolic imbalance, oxidative stress and chronic inflammation. In contrast, a diet rich in vegetables has consistently been associated with a lower risk of such diseases (Tripathy *et al.*, 2021). The bioactive compounds found in vegetables polyphenols, flavonoids, carotenoids, alkaloids, glucosinolates and

organosulfur compounds intervene at multiple biological targets, exerting antioxidant, anti-inflammatory and metabolic regulatory effects. This section discusses how vegetable-derived nutraceuticals contribute to the prevention and management of major chronic diseases through well-defined molecular and physiological mechanisms.

**Table 2: Role of vegetable-derived nutraceuticals in chronic disease prevention (Saiwal *et al.*, 2019)**

Disease category	Key vegetables/bioactive compounds	Mechanisms/physiological effects
Cardiovascular diseases	Tomato (Lycopene), Garlic (Allicin)	Reduces LDL oxidation, enhances eNOS activity, regulates lipid profile, lowers blood pressure
Diabetes mellitus	Bitter gourd (Charantin), Fenugreek (Trigonelline), Okra (Mucilage, Polyphenols)	Improves insulin sensitivity, inhibits $\alpha$ -amylase and $\alpha$ -glucosidase, lowers blood glucose
Cancer	Broccoli (Sulforaphane), Spinach (Lutein), Carrot ( $\beta$ -Carotene)	Induces apoptosis, suppresses cell proliferation, regulates detoxification enzymes
Neurodegenerative disorders	Spinach, Kale (Lutein, Zeaxanthin, Polyphenols)	Inhibits AChE activity, prevents amyloid aggregation, reduces oxidative stress
Obesity/ Metabolic syndrome	Leafy greens, Cruciferous vegetables	Regulates lipid metabolism <i>via</i> AMPK activation, enhances gut microbiota composition
Liver and gastrointestinal health	Beetroot, Cabbage, Moringa	Enhances detoxification, supports bile secretion, protects hepatocytes from oxidative injury

#### 4.1 Cardiovascular diseases

Cardiovascular diseases (CVDs) remain the leading cause of global mortality, accounting for over 17 million deaths annually. The pathogenesis of CVDs is primarily linked to oxidative stress, inflammation, lipid peroxidation and endothelial dysfunction. Several vegetables possess cardioprotective properties due to their rich reservoir of antioxidants, carotenoids, organosulfur compounds and dietary fiber, which collectively regulate lipid metabolism and vascular function. Tomatoes, rich in the carotenoid lycopene, play a crucial role in cardiovascular protection. Lycopene scavenges free radicals, inhibits the oxidation of low-density lipoprotein (LDL) and enhances endothelial nitric oxide synthesis, improving vascular relaxation and reducing arterial stiffness. Clinical studies have demonstrated that regular tomato or tomato product consumption leads to significant reductions in serum cholesterol, triglycerides and systolic blood pressure. Garlic, another potent cardioprotective vegetable, contains allicin and other sulfur-containing compounds that lower serum lipids and inhibit platelet aggregation. Allicin also suppresses the enzyme HMG-CoA reductase, the key regulatory enzyme in cholesterol biosynthesis, thereby exerting a natural statin-like effect (Parulekar *et al.*, 2019). Furthermore, cruciferous vegetables such as broccoli and cabbage contribute to vascular protection through glucosinolate-derived isothiocyanates, which induce phase II detoxifying enzymes and reduce inflammatory markers like CRP (C-reactive protein). Epidemiological data consistently show an inverse association between vegetable intake and the incidence of coronary heart disease and stroke. A 2020 meta-analysis revealed that consuming at least 400 g of vegetables per day was associated with a 20-25% lower risk of cardiovascular events. This evidence underscores that regular inclusion of vegetables, particularly those rich in carotenoids and organosulfur compounds, can effectively modulate oxidative and lipid-mediated pathways that lead to cardiovascular complications.

#### 4.2 Diabetes mellitus

Diabetes mellitus, characterized by hyperglycemia resulting from impaired insulin secretion or action, is one of the most prevalent

metabolic disorders worldwide. Vegetable-based nutraceuticals exert hypoglycemic and insulin-sensitizing effects through mechanisms involving the modulation of carbohydrate-digesting enzymes, glucose uptake and oxidative stress. Bitter gourd is among the most well-studied antidiabetic vegetables. It contains charantin, vicine and polypeptide- bioactive compounds that mimic insulin action and stimulate glucose uptake in peripheral tissues. These compounds activate the AMP-activated protein kinase (AMPK) pathway, enhancing glucose utilization while suppressing hepatic gluconeogenesis. Fenugreek, another traditional antidiabetic vegetable, is rich in soluble fiber and saponins that delay glucose absorption and improve insulin sensitivity. Its alkaloid component, trigonelline, has been shown to stimulate  $\beta$ -cell regeneration and enhance insulin release. Okra polysaccharides act as natural inhibitors of  $\alpha$ -amylase and  $\alpha$ -glucosidase, reducing postprandial glucose spikes by slowing carbohydrate digestion. Phenolic compounds in okra also protect pancreatic cells from oxidative damage. Clinical trials have shown that individuals consuming bitter gourd or fenugreek supplements experience notable improvements in fasting blood glucose and HbA1c levels (Arcusa *et al.*, 2021). Epidemiological studies further confirm that diets high in vegetable fiber and polyphenols are associated with lower diabetes prevalence and improved glycemic control. Thus, vegetable-derived nutraceuticals contribute to diabetes prevention by targeting both the biochemical and molecular aspects of glucose homeostasis enhancing insulin activity, improving oxidative balance and regulating carbohydrate metabolism.

#### 4.3 Cancer

Cancer represents a multifactorial disease involving uncontrolled cellular proliferation, genomic instability and evasion of apoptosis. Numerous studies have demonstrated that regular consumption of vegetables can reduce the risk of various cancers, including those of the lung, breast, colon and prostate. The protective role of vegetables is primarily attributed to their rich composition of isothiocyanates, polyphenols, carotenoids and folate, which modulate cellular

signaling, detoxification and apoptosis pathways. Broccoli and other cruciferous vegetables contain glucosinolates that are hydrolyzed to form sulforaphane and indole-3-carbinol, compounds known for their chemopreventive properties. Sulforaphane activates the Nrf2 signaling pathway, enhancing the expression of phase II detoxifying enzymes like glutathione S-transferase (GST) and NAD(P) H:quinone oxidoreductase, which neutralize carcinogens and prevent DNA damage. Indole-3-carbinol influences estrogen metabolism, reducing the formation of carcinogenic estrogen derivatives that contribute to hormone-dependent cancers such as breast and prostate cancer (Sachdeva *et al.*, 2020). Spinach and carrots are abundant in carotenoids such as  $\beta$ -carotene and lutein, which quench singlet oxygen and prevent oxidative DNA damage. Phenolic compounds from these vegetables, including ferulic and caffeic acids, modulate the expression of apoptosis-related genes such as p53 and Bax, promoting the elimination of damaged or precancerous cells. Epidemiological evidence supports these findings; populations consuming higher amounts of cruciferous and leafy vegetables exhibit significantly lower rates of gastrointestinal and pulmonary cancers. A 2019 meta-analysis reported that individuals with high cruciferous vegetable intake had a 15-25% lower cancer risk compared to those with low intake (Arya *et al.*, 2019). These findings confirm that the bioactive matrix of vegetables interferes with multiple stages of carcinogenesis, from initiation to progression, offering both preventive and therapeutic potential.

#### 4.4 Neurodegenerative disorders

Neurodegenerative diseases such as Alzheimer's and Parkinson's are primarily linked to oxidative stress, inflammation and the accumulation of misfolded proteins like amyloid- $\beta$  and  $\alpha$ -synuclein. Vegetable-derived nutraceuticals provide neuroprotection by modulating redox balance, neurotransmitter function and protein aggregation processes. Spinach and kale are particularly rich in lutein, zeaxanthin and flavonoids, which are known to cross the blood-brain barrier and accumulate in neuronal membranes. These compounds neutralize reactive oxygen species, inhibit lipid peroxidation and preserve membrane integrity. Lutein enhances mitochondrial efficiency and protects neuronal cells from glutamate-induced cytotoxicity. Similarly, phenolic compounds from leafy vegetables inhibit acetylcholinesterase (AChE) activity, thereby maintaining higher acetylcholine levels and improving cognitive function mechanisms particularly relevant in Alzheimer's disease (Behera and Singh, 2019). Moreover, cruciferous vegetable components such as sulforaphane modulate neuroinflammation by inhibiting microglial activation and suppressing pro-inflammatory cytokines (IL-1 $\beta$ , TNF- $\alpha$ ). Sulforaphane also induces the expression of neuroprotective enzymes through Nrf2 signaling. Human cohort studies have reported that higher dietary intake of green leafy vegetables is associated with slower cognitive decline and a significantly lower risk of developing dementia. A longitudinal study from the Rush Memory and Ageing Project found that individuals consuming one or more servings of green leafy vegetables daily had cognitive abilities equivalent to those of individuals 11 years younger. These findings underscore the capacity of vegetable-derived phytochemicals to delay neurodegeneration and preserve cognitive function through antioxidant, anti-inflammatory and neurotransmitter-regulating mechanisms.

#### 4.5 Obesity and metabolic syndrome

Obesity and metabolic syndrome, characterized by central adiposity, dyslipidemia and insulin resistance, are major precursors to cardiovascular disease and diabetes. Vegetables contribute to weight management and metabolic regulation through mechanisms involving appetite control, lipid metabolism and oxidative stress reduction. Leafy greens such as spinach, lettuce and amaranth are low in energy density but high in fiber and water content, which promote satiety and reduce total caloric intake. Polyphenols from leafy and cruciferous vegetables enhance fat oxidation by activating AMPK and downregulating lipogenic enzymes such as fatty acid synthase (FAS). Cruciferous vegetables, in particular, modulate adipogenesis and lipid accumulation through isothiocyanates that regulate peroxisome proliferator-activated receptors (PPARs) (Arcusa *et al.*, 2021). Vegetable consumption also influences the gut microbiome, increasing the abundance of beneficial bacteria such as *Bifidobacterium* and *Lactobacillus*, which improve metabolic efficiency and reduce systemic inflammation. Clinical trials have shown that increased consumption of high-fiber vegetables significantly reduces body weight, waist circumference and plasma triglyceride levels. Meta-analyses indicate that adherence to vegetable-rich diets lowers the risk of metabolic syndrome by approximately 30%, primarily due to their combined antioxidant and metabolic regulatory effects (Corzo *et al.*, 2020). Thus, vegetables act as metabolic modulators, promoting energy balance and protecting against obesity-related complications.

#### 4.6 Integration of epidemiological and clinical evidence

A vast body of epidemiological data reinforces the association between high vegetable consumption and reduced risk of chronic diseases. The European Prospective Investigation into Cancer and Nutrition (EPIC) study, involving more than half a million participants, demonstrated that individuals with the highest vegetable intake exhibited significantly lower all-cause mortality and reduced incidence of CVD, cancer and diabetes. Similarly, the Nurses' Health Study and Health Professionals Follow-Up Study from Harvard University consistently reported that each additional daily serving of vegetables reduces the risk of coronary heart disease by 4-6%. Clinical trials further validate these observations. Controlled interventions using tomato lycopene extracts, garlic supplements and cruciferous vegetable concentrates have shown measurable improvements in lipid profiles, inflammatory biomarkers and oxidative stress markers (Attanzio *et al.*, 2018). Meta-analyses reveal that diets rich in green leafy vegetables are strongly associated with lower risks of type 2 diabetes, cognitive decline and certain cancers. The convergence of experimental, clinical and population-based evidence strongly supports the inclusion of diverse vegetables in daily diets as an effective, natural strategy for disease prevention and long-term health maintenance.

### 5. Emerging research and omics-based insights

Recent advances in high-throughput technologies and molecular biology have greatly expanded our understanding of how vegetable-derived nutraceuticals interact with human physiology. The integration of multi-omics platforms—metabolomics, nutrigenomics, transcriptomics, proteomics and metagenomics—has enabled researchers to unravel the complex relationships between diet, genes and health outcomes. These tools provide insights into how specific phytochemicals influence metabolic pathways, regulate gene

expression and modulate cellular responses. Additionally, emerging studies on gut microbiota and nanotechnology-based delivery systems have opened new avenues for enhancing the bioavailability and functional efficacy of vegetable-derived bioactives (Tavares *et al.*, 2022).

### 5.1 Metabolomics and nutrigenomics

Metabolomics is the comprehensive profiling of small metabolites within biological systems, which has become a crucial approach for understanding the biochemical impact of vegetable consumption on human metabolism. Through advanced analytical techniques such as LC-MS (liquid chromatography-mass spectrometry) and NMR spectroscopy, researchers can identify and quantify the metabolites derived from vegetable phytochemicals and track their transformation within the body. For instance, the metabolism of phenolic compounds such as quercetin or chlorogenic acid leads to the formation of conjugated derivatives (glucuronides and sulfates) that retain significant antioxidant potential. These metabolic fingerprints not only help in characterizing bioactive components but also serve as biomarkers for dietary intake and physiological response. Nutrigenomics, which explores gene-nutrient interactions, has provided valuable insights into how vegetable-derived compounds modulate gene expression and influence disease susceptibility. Studies indicate that phytochemicals from vegetables can activate or suppress specific genes related to oxidative stress, inflammation and energy metabolism. For example, sulforaphane from cruciferous vegetables activates the Nrf2 (nuclear factor erythroid 2-related factor 2) pathway, promoting the transcription of detoxifying and antioxidant enzymes such as glutathione S-transferase and heme oxygenase-1. Similarly, polyphenols like quercetin and resveratrol interact with SIRT1 (sirtuin 1), a longevity-associated gene that regulates mitochondrial function and lipid metabolism. These gene-nutrient interactions explain how regular vegetable consumption contributes to improved cellular resilience and reduced disease risk at the molecular level (Milton-Laskibar *et al.*, 2022). Nutrigenomic studies have also highlighted interindividual variability in response to vegetable-based nutraceuticals, suggesting that genetic polymorphisms influence how people metabolize and respond to phytochemicals. This emerging concept of personalized nutrition proposes that tailored vegetable-based diets can optimize health outcomes by aligning with individual genetic profiles. Thus, metabolomics and nutrigenomics together offer a molecular foundation for understanding the nutraceutical efficacy of vegetables in precision health management (Meléndez-Martínez *et al.*, 2021).

### 5.2 Transcriptomic and proteomic insights

Transcriptomics and proteomics have become indispensable tools for investigating how vegetable phytochemicals regulate gene and protein expression in cellular and tissue systems. Transcriptomic analyses using microarrays and RNA-sequencing reveal global changes in mRNA expression induced by dietary bioactives, while proteomics provides complementary information about protein abundance, modification and signaling activity. Research has shown that vegetable-derived compounds can influence multiple signaling cascades, including oxidative stress, apoptosis and metabolic regulation pathways. For instance, treatment with sulforaphane-rich broccoli extract upregulates genes associated with antioxidant defense (e.g., HO-1, GCLC) and downregulates pro-inflammatory genes such as IL-6 and TNF- $\alpha$ . Carotenoids like lycopene from tomatoes have been found

to suppress transcripts linked to lipid peroxidation and cell proliferation, contributing to their cardioprotective and anticancer effects (Bacil *et al.*, 2022). Proteomic studies further demonstrate that vegetable polyphenols can modulate the activity of critical proteins involved in energy metabolism and cellular protection. For example, quercetin enhances mitochondrial biogenesis by upregulating PGC-1  $\alpha$  and activating AMPK, improving oxidative phosphorylation efficiency. Similarly, SIRT1 activation by vegetable polyphenols enhances stress tolerance and delays cellular ageing. Studies on cruciferous vegetables reveal that isothiocyanates induce the expression of phase II detoxification enzymes, which are key components of cellular defense against xenobiotics (Arshad *et al.*, 2025). Collectively, transcriptomic and proteomic evidence reinforces the idea that vegetable bioactives act through coordinated modulation of multiple genes and proteins rather than a single target, producing systemic and sustained protective effects.

### 5.3 Bioavailability, biotransformation and gut microbiota interactions

One of the persistent challenges in nutraceutical research is the bioavailability of vegetable-derived compounds. Despite their abundance in raw vegetables, many phytochemicals exhibit low absorption and rapid metabolism within the gastrointestinal tract, limiting their biological impact. However, recent findings indicate that their biotransformation by gut microbiota plays a decisive role in enhancing bioactivity. The human gut microbiome functions as a metabolic interface between diet and host physiology. When vegetable compounds such as polyphenols, flavonoids and glucosinolates reach the colon, they are metabolized by gut bacteria into smaller, more bioavailable metabolites (Ajeeshkumar *et al.*, 2021). For instance, quercetin is converted into phenylacetic acid derivatives, while isothiocyanates from crucifers are produced through microbial hydrolysis of glucosinolates. These metabolites often exhibit greater antioxidant and anti-inflammatory potency than their precursors. Moreover, vegetable fiber acts as a prebiotic, promoting the growth of beneficial microbial genera such as *Bifidobacterium* and *Lactobacillus*. This, in turn, enhances short-chain fatty acid (SCFA) production, which supports intestinal integrity, reduces inflammation and improves lipid and glucose metabolism (Marino *et al.*, 2023). Metagenomic analyses reveal that regular vegetable intake promotes a diverse and stable gut microbiota composition, which is associated with reduced risks of obesity, metabolic syndrome and inflammatory bowel disease. In essence, the gut microbiome serves as a biological amplifier for vegetable-derived nutraceuticals, transforming, activating and extending their physiological benefits through microbial metabolism and host-microbe signaling.

### 5.4 Nanoencapsulation and delivery systems

Despite the proven efficacy of vegetable-derived phytochemicals, their practical use in nutraceutical formulations is often constrained by poor solubility, instability and low bioavailability. To overcome these challenges, researchers have increasingly turned to nanoencapsulation and delivery technologies, which protect bioactives from degradation, improve intestinal absorption and enable targeted release at specific sites of action. Nanoencapsulation involves entrapping phytochemicals such as carotenoids, polyphenols and flavonoids within nanoscale carriers made of lipids, proteins, or polysaccharides. These nanocarriers enhance the stability of sensitive

compounds like lycopene and  $\beta$ -carotene, which are otherwise prone to oxidation and light degradation. Lipid-based systems such as nanoemulsions and liposomes improve solubility and intestinal permeability, while polymer-based nanoparticles enable controlled release, maintaining steady plasma concentrations of bioactives over time (Neagu *et al.*, 2023).

For instance, encapsulated lycopene has demonstrated improved antioxidant efficacy in protecting LDL from oxidation compared to its unencapsulated form. Similarly, nanoencapsulation of sulforaphane enhances its chemical stability and bioavailability, leading to greater induction of detoxifying enzymes in experimental models. Advances in nanotechnology also allow the combination of multiple phytochemicals into a single delivery platform, thereby exploiting synergistic effects among different vegetable compounds. Moreover, bioengineered nanoparticles using plant-derived polymers offer a biocompatible and eco-friendly alternative to synthetic carriers. These systems align well with the principles of green chemistry and sustainable nutraceutical development. The integration of nanotechnology into vegetable-based nutraceutical research represents a frontier that promises to bridge the gap between laboratory findings and clinical applicability by ensuring optimal delivery, absorption and efficacy of plant bioactives (Wang *et al.*, 2025).

## 6. Nutraceutical applications and functional food development

The growing awareness of the link between diet and health has stimulated global interest in vegetables not only as essential foods but also as sources of nutraceutical and functional products. The concept of functional foods has evolved from traditional dietary practices to scientifically formulated products designed to deliver specific physiological benefits. Vegetable-derived nutraceuticals, enriched with bioactive phytochemicals, antioxidants and essential micronutrients, are now being incorporated into diverse formulations such as capsules, powders, beverages and fortified products. The development of these value-added forms bridges the gap between conventional nutrition and preventive medicine, offering consumers accessible options for maintaining health and managing chronic diseases (Kainat *et al.*, 2022).

### 6.1 Vegetable-based nutraceutical products

The increasing commercialization of vegetable-derived nutraceuticals reflects a paradigm shift from raw consumption to processed, concentrated and standardized formulations. These products are developed in various forms: capsules, tablets, powders and juices to enhance convenience, shelf-life and therapeutic efficacy. Capsule-based products containing dehydrated vegetable extracts or purified phytochemicals have gained substantial popularity. For instance, lycopene capsules derived from tomato extract are widely marketed for cardiovascular and prostate health, owing to lycopene's strong antioxidant and lipid-lowering properties. Similarly, garlic-based capsules standardized for allicin content are used for cholesterol reduction and immune support. Broccoli sprout extract supplements, rich in sulforaphane, have shown promise in cancer chemoprevention and detoxification therapy. Vegetable powders and dehydrated blends represent another growing segment in the nutraceutical market. They serve as convenient dietary supplements that retain most of the nutritional and bioactive integrity of fresh produce. Spinach, beetroot,

moringa and kale powders are incorporated into smoothies and energy mixes to enhance antioxidant and micronutrient intake. Functional juices derived from carrot, amla and tomato are fortified with vitamins and polyphenols to provide targeted health benefits such as improved vision, skin protection and cardiovascular support (Seneviratne *et al.*, 2020). In addition, novel formulations such as vegetable-based gummies, bars and effervescent tablets have emerged to appeal to younger consumers and those seeking convenience. These innovative delivery systems ensure higher compliance and allow manufacturers to combine multiple bioactives for synergistic effects. The growing popularity of such products underscores the transition of vegetables from mere dietary components to scientifically validated therapeutic resources.

### 6.2 Fortification and value addition in vegetable processing

Fortification and value addition play critical roles in enhancing the nutraceutical quality and consumer appeal of vegetable-based products. Fortification involves enriching foods with essential micronutrients or bioactive compounds to address nutritional deficiencies or specific health needs. Vegetable-derived ingredients are frequently incorporated into staple foods, beverages and snacks to boost their antioxidant and phytochemical content. For example, incorporation of spinach or carrot powders into bakery products increases  $\beta$ -carotene and iron content, while fortifying pasta or noodles with dehydrated leafy vegetable extracts enhances fiber and mineral levels. Similarly, beverages fortified with beetroot or kale extracts have been shown to improve vascular function due to elevated nitrate and polyphenol levels. The development of such value-added products not only promotes vegetable utilization but also provides a practical strategy to integrate bioactive compounds into everyday diets (Sonowal *et al.*, 2025). Processing technologies such as freeze-drying, spray drying and microencapsulation are increasingly employed to preserve phytochemicals during product development. These approaches maintain nutrient stability and bioavailability while extending shelf life. Moreover, the use of low-temperature drying and nonthermal processing methods (*e.g.*, high-pressure processing, pulsed electric fields) minimizes nutrient degradation and color loss, thereby enhancing both aesthetic and functional qualities. An emerging area of value addition involves fermented vegetable products, where microbial fermentation enhances bioactive content and digestibility. For instance, fermentation of cabbage into kimchi or sauerkraut increases phenolic concentration and probiotic content, improving gut health and immune response. Thus, fortification and advanced processing represent key strategies to retain and even enhance the nutraceutical potential of vegetables in modern food systems (Kumar *et al.*, 2018).

### 6.3 Integrating vegetables into functional and preventive nutrition strategies

Vegetables form the cornerstone of preventive nutrition, which emphasizes disease prevention through regular intake of nutrient-dense and bioactive-rich foods. Integrating vegetables into functional food design involves developing dietary formulations that target specific physiological benefits, such as cardiovascular protection, glycemic control, cognitive enhancement and immune modulation. The inclusion of vegetable-based nutraceuticals in personalized dietary interventions is gaining momentum, particularly with insights from nutrigenomics and metabolomics. For instance, tailored diets incorporating cruciferous vegetables may be recommended for

individuals with higher oxidative stress susceptibility, while carotenoid-rich foods can be advised for those with elevated cardiovascular risk profiles. Functional food industries are increasingly utilizing vegetable bioactives as natural alternatives to synthetic additives and supplements. Carotenoids, anthocyanins and chlorophylls are used as natural colorants with added antioxidant properties, while polyphenols serve as preservatives that extend shelf-life without compromising health. Additionally, vegetable-derived fibers are incorporated into low-glycemic and cholesterol-lowering foods (Qi *et al.*, 2023). From a public health perspective, integrating vegetable nutraceuticals into preventive nutrition frameworks can significantly reduce the burden of non-communicable diseases. Programs promoting vegetable-rich diets, community nutrition awareness and school-based interventions have demonstrated tangible improvements in dietary behavior and health outcomes. Hence, combining scientific formulation with public health education ensures that vegetable-based functional nutrition becomes a sustainable and impactful health strategy.

#### 6.4 Consumer acceptance, safety and regulatory perspectives

The successful adoption of vegetable-based nutraceuticals depends not only on their efficacy but also on consumer perception, safety assurance and regulatory compliance. Consumer acceptance is strongly influenced by factors such as taste, convenience, cost and perceived naturalness of the product. Surveys reveal that modern consumers increasingly prefer plant-based nutraceuticals over synthetic alternatives due to their perceived safety, environmental sustainability and holistic health benefits. However, maintaining the natural sensory characteristics of vegetables while developing concentrated or fortified products remains a significant challenge. Safety assessment of nutraceutical products is critical to ensure they are free from contaminants, pesticide residues and heavy metals. Standardization of bioactive concentrations is also necessary to guarantee consistent therapeutic efficacy. Over consumption of certain bioactives, such as oxalates or alkaloids, can pose health risks; hence, dose optimization and clinical validation are essential before commercialization. From a regulatory standpoint, nutraceuticals occupy a unique position between foods and pharmaceuticals, leading to variations in legislation across regions. In India, the food safety and standards authority of India (FSSAI) regulate nutraceutical products under the Food Safety and Standards Regulations (2016), requiring evidence-based safety and labeling compliance. Similarly, in the European Union, nutraceuticals are governed under the European Food Safety Authority (EFSA) guidelines, while in the United States, the Food and Drug Administration (FDA) monitors them as dietary supplements (Sharma *et al.*, 2024). The establishment of clear global regulatory frameworks is vital for harmonizing quality standards and ensuring consumer trust. As the global nutraceutical market continues to expand, research-driven innovation combined with regulatory transparency will determine the success of vegetable-derived products. Consumer education, scientific validation and sustainable production practices must advance hand in hand to make vegetable nutraceuticals a mainstream component of preventive healthcare systems (Morabito *et al.*, 2025).

### 7. Challenges, gaps and future perspectives

Despite the remarkable progress in understanding the nutraceutical potential of vegetables, several challenges continue to limit their optimal utilization in human health management. Although, the

biological benefits of vegetable-derived bioactives have been widely documented through *in vitro* and *in vivo* studies, the translation of these findings into clinical relevance remains a significant hurdle. Issues such as variability in bioactive content, lack of standardization, limited clinical evidence and regulatory ambiguity must be addressed to ensure that vegetable-based nutraceuticals fulfill their promise as reliable and sustainable health interventions. Furthermore, integrating nutrigenomic insights, ensuring environmental sustainability and establishing coherent policy frameworks are essential to advancing this field toward global public health impact.

#### 7.1 Limited clinical validation and standardization of nutraceutical claims

One of the major limitations in the current nutraceutical landscape is the scarcity of well-designed clinical trials that substantiate the efficacy of vegetable-derived compounds in disease prevention and therapy. Although, numerous laboratory studies demonstrate antioxidant, anti-inflammatory and metabolic benefits, these outcomes are not always reproducible in human populations due to differences in bioavailability, dosage and dietary context. Most available data are based on observational or short-term intervention studies, which may not adequately capture long-term physiological effects. Furthermore, the lack of standardization in nutraceutical formulations poses a serious challenge to scientific validation. Variations in extraction techniques, dosage forms and storage conditions can alter the concentration and activity of bioactive compounds. Without standardized reference materials or biomarkers of efficacy, comparing data across studies becomes difficult. Therefore, rigorous clinical research using standardized formulations, controlled dosages and defined endpoints is urgently needed to translate the promising laboratory evidence of vegetable nutraceuticals into reproducible, evidence-based health recommendations.

#### 7.2 Variability in bioactive content due to cultivar and environment

The nutritional and phytochemical profiles of vegetables are highly influenced by genetic, agronomic and environmental factors. Variability in cultivar type, soil fertility, irrigation, temperature and postharvest handling can lead to significant differences in the concentration of vitamins, phenolics, carotenoids and glucosinolates. For instance, carotenoid levels in tomatoes and leafy vegetables fluctuate with sunlight exposure, while glucosinolate content in crucifers is affected by sulfur availability and growing season. Such variability complicates the consistency of nutraceutical products derived from vegetables. The absence of reliable cultivation standards makes it challenging to guarantee uniform bioactive concentrations across production batches. To mitigate this issue, good agricultural practices (GAPs), standardized processing protocols and analytical quality control must be implemented to ensure reproducibility and product efficacy. The development of biofortified cultivars through traditional breeding or biotechnological approaches also presents a promising avenue to enhance the stability and uniformity of nutraceutical content in vegetables.

#### 7.3 Need for integrative nutrigenomics and personalized nutrition

The growing field of nutrigenomics provides an opportunity to bridge the gap between population-based nutrition and personalized dietary recommendations. However, its integration into vegetable-based

nutraceutical research remains limited. Individual variations in genetic makeup, metabolic rate, gut microbiota composition and nutrient absorption can influence how vegetable phytochemicals exert their effects. Consequently, the “one-size-fits-all” dietary approach may not yield uniform health outcomes. Emerging research emphasizes the importance of personalized nutrition tailoring dietary interventions to individual genetic and metabolic profiles. For instance, polymorphisms in genes related to antioxidant enzymes (such as GST or NQO1) may alter individual responses to compounds like sulforaphane or quercetin. Integrating nutrigenomic and metabolomic data can help identify responsive subpopulations, optimize bioactive dosages and enhance clinical efficacy. Future research should therefore adopt multi-omics strategies to understand gene-nutrient interactions more comprehensively and develop precision-based nutraceutical formulations that align with personalized health goals.

#### 7.4 Sustainable production of nutraceutical-rich vegetables

Sustainability is another critical dimension in the future of vegetable-based nutraceutical development. The increasing global demand for nutraceutical-rich vegetables must be balanced with environmental responsibility and resource efficiency. Intensive cultivation practices, excessive chemical inputs and postharvest losses can compromise both nutritional quality and ecological integrity. Adopting sustainable agricultural practices including organic farming, integrated nutrient management and protected cultivation can enhance the natural biosynthesis of bioactive compounds while preserving soil and ecosystem health. Controlled environment agriculture (*e.g.*, hydroponics and vertical farming) allows for the production of high-value vegetables with consistent phytochemical profiles under optimized conditions. Furthermore, the utilization of agricultural by-products and waste streams (such as peels, stems and leaves) for nutraceutical extraction can promote a circular bioeconomy and reduce environmental impact. Emphasis on climate-resilient varieties is also vital, as rising global temperatures and unpredictable rainfall patterns affect secondary metabolite synthesis. Future strategies should thus focus on breeding or engineering vegetables that maintain high nutraceutical potential under climate stress, ensuring both nutritional security and ecological sustainability.

#### 7.5 Policy frameworks and nutraceutical labeling standards

The global nutraceutical market is expanding rapidly, yet policy frameworks and labeling regulations remain inconsistent across regions. The lack of harmonized definitions and guidelines for nutraceutical products often leads to confusion among manufacturers, consumers and regulatory authorities. In many countries, vegetable-based nutraceuticals are classified ambiguously as either foods, supplements, or medicines resulting in varied safety and efficacy standards. In India, the Food Safety and Standards Authority of India (FSSAI) has taken steps to define regulatory categories and labeling requirements for nutraceuticals under the Food Safety and Standards Regulations (2016). However, enforcement challenges and gaps in clinical substantiation persist. Similarly, the European Food Safety Authority (EFSA) and U.S. Food and Drug Administration (FDA) have established safety and labeling criteria for dietary supplements, but these frameworks differ in evidence thresholds and permitted health claims. To build consumer trust and ensure product credibility, global harmonization of nutraceutical labeling and quality standards is essential. Products should disclose bioactive concentrations, source materials and clinical validation data transparently. Establishing

internationally recognized certification systems similar to organic or fair-trade standards could further enhance market integrity. Collaboration among policymakers, researchers and industry stakeholders will be crucial for developing cohesive regulations that encourage innovation while ensuring safety and efficacy.

#### 7.6 Future perspectives

The future of vegetable-derived nutraceuticals lies in the integration of multidisciplinary innovations spanning molecular nutrition, sustainable agriculture, biotechnology and personalized health science. Continued advances in omics technologies will refine our understanding of how vegetable phytochemicals interact with genes, proteins and metabolic pathways. This knowledge can drive the development of customized dietary interventions that address specific health conditions. Simultaneously, leveraging green extraction technologies and nanoencapsulation systems will enhance the stability, absorption and targeted delivery of vegetable bioactives, improving their clinical relevance. Digital health tools and artificial intelligence may further enable real-time dietary monitoring and predictive nutrition modeling based on individual genetic and metabolic data. Ultimately, achieving the full potential of vegetable nutraceuticals requires a transdisciplinary approach linking scientific research with policy support, consumer education and sustainable production systems. When aligned with public health goals and environmental stewardship, vegetable-based nutraceuticals can redefine the global paradigm of preventive healthcare and functional nutrition in the decades to come.

### 8. Conclusion

Vegetables constitute an indispensable component of the human diet and represent one of the most potent natural sources of nutraceuticals for promoting health and longevity. Their rich composition of vitamins, minerals and diverse bioactive phytochemicals including flavonoids, carotenoids, phenolic acids, glucosinolates, alkaloids and saponins confers them with extraordinary potential to combat oxidative stress, chronic inflammation and metabolic dysregulation. Unlike synthetic pharmaceuticals, vegetable-derived compounds act through multiple molecular pathways simultaneously, targeting the root causes of chronic diseases rather than merely alleviating symptoms. This multifactorial mode of action underscores their value as integral agents in preventive and functional nutrition. The nutraceutical mechanisms of vegetables operate through intricate biochemical interactions at cellular and molecular levels. By scavenging reactive oxygen species, activating the Nrf2 antioxidant response pathway and modulating pro-inflammatory transcription factors such as NF- $\kappa$ B, these phytochemicals maintain redox balance and immune homeostasis. Their capacity to regulate apoptosis, glucose metabolism, lipid homeostasis and neurotransmitter activity enables them to offer comprehensive protection against major non-communicable diseases including cardiovascular disorders, diabetes, cancer and neurodegenerative conditions. Such broad-spectrum efficacy positions vegetables not only as nutritional essentials but also as functional therapeutics with significant implications for public health. However, realizing the full potential of vegetables as nutraceuticals requires overcoming existing challenges such as limited clinical validation, variability in bioactive content and regulatory inconsistencies. Future progress will depend on the integration of molecular nutrition, omics technologies and personalized dietary strategies to elucidate gene-nutrient interactions and optimize health

outcomes. Advances in nanoencapsulation, biofortification and green processing technologies can further enhance the stability, bioavailability and targeted delivery of vegetable bioactives, ensuring consistent efficacy. Equally important is the adoption of sustainable agricultural practices to maintain ecological balance while producing nutraceutical-rich vegetables. Linking molecular nutrition research with environmentally responsible cultivation and equitable food systems can transform vegetables into the foundation of preventive therapeutics. As the global burden of chronic diseases continues to rise, harnessing the nutraceutical wealth of vegetables offers a sustainable, accessible and scientifically grounded approach to improving human health and achieving long-term nutritional security.

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## Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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