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Plant-Based Bioactive Phytonutrients: From Chemical Diversity to Mechanistic Actions and Human Health: A Systematic Review

Sonam Bhutia

sonamkzbhutia@gmail.com

Government Pharmacy College Sajong https://orcid.org/0000-0001-5464-8775

Yugal Sharma

Department of Pharmaceutics, Government Pharmacy College Sajong, Government of Sikkim (GoS), Sikkim University, Rumtek, Sajong, Sikkim-India-737135 https://orcid.org/0009-0006-7581-3358

Bidhya Sharma

3Department of Pharmaceutical chemistry, Government Pharmacy College Sajong, Government of Sikkim (GoS), Sikkim University, Rumtek, Sajong, Sikkim-India-737135 https://orcid.org/0009-0000-5546-1750

Dr. Jun Moni Kalita

Department of Pharmaceutical Chemistry, School of Pharmaceutical Sciences, Girijananda Chowdhury University, Guwahati, Assam, India- 781017 https://orcid.org/0000-0002-5702-0796

Dr. Abhimanyu Nepal

Drug Testing Laboratory (AYUSH), Government of Sikkim, Gangtok-Sikkim, India-737134 https://orcid.org/0000-0003-0989-789X

Systematic Review

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Abstract

Background

Plant-based dietary patterns are increasingly associated with reduced chronic disease risk, yet the heterogeneous nature of phytonutrients, their chemical diversity, variable bioavailability, and pleiotropic mechanistic actions have hindered the translation of preclinical findings into consistent clinical recommendations.

Objective

To systematically review on chemical diversity of plant-based bioactive phytonutrients, their mechanistic actions at molecular and cellular levels, and their associations with human health outcomes, following PRISMA 2020 guidelines.

Methods

A systematic literature search was conducted in PubMed, Science direct, Web of Science, DOAJ, JSTOR, Research Gate and Google Scholar from 1990 to 2026. Studies were included if they: characterized phytonutrient classes (polyphenols, terpenoids, alkaloids, or phytosterols); reported in vitro, in vivo, or mechanistic data; and included human observational studies, or with meta-analyses examining chronic disease endpoints (cardiometabolic, neurodegenerative or oncological). Exclusion criteria were synthetic analogy, non-bioactive phytochemicals and studies lacking dose-response.

Results

Of 750 records identified, 275 studies met inclusion criteria. About 36 plant-based bioactive phytonutrients were summarised in TableNo:1 highlighting with their plant names, Phytonutrient chemical classes, mechanism of actions, therapeutic uses, dietary sources and distribution, bioavailability parameters, Polyphenols (specifically flavonoids and phenolic acids) constituted 33% of studied compounds followed by terpenoids (30%).

Conclusions

The evidence collectively supports the conclusion that a diet rich in diverse plant-based foods, providing a broad spectrum of phytonutrients, is a cornerstone of chronic disease prevention and health promotion. As scientific understanding of these bio-active phytonutrients holds increasing promise as both dietary health-promoting agents and as leads for the development of novel therapeutic interventions.

1. Introduction

The relationship between diet and human health has been a subject of scientific inquiry for centuries, yet the molecular complexity underlying this relationship has only begun to be systematically elucidated in recent decades. Plant-based bioactive compounds, collectively referred to as phytonutrients or phytochemicals, represent a chemically diverse and functionally rich category of secondary metabolites that exert profound effects on human physiology [1], [2], [3]. These compounds are not classified as essential macronutrients or micronutrients in the classical sense, yet their contributions to health maintenance, disease prevention, and therapeutic intervention are increasingly recognized as indispensable [4], [5]. Phytonutrients are defined as plant-derived bioactive compounds that positively affect human health, supporting normal physiological functioning and potentially extending lifespan [6]. They are naturally occurring in a wide variety of dietary sources including fruits, vegetables, legumes, whole grains, and herbs [7], [8]. Higher consumption of plant-based meals is inversely correlated with the incidence of chronic diseases such diabetes mellitus, obesity, cardiovascular problems, various malignancies, and neurological ailments, according to the scientific literature [9], [10]. This epidemiological evidence has catalysed intensive research into the specific molecular mechanisms by which individual phytonutrients exert their protective effects [11], [12].

The chemical diversity of phytonutrients is extraordinary. Major classes include polyphenols, flavonoids, isoflavonoids, carotenoids, terpenoids, glucosinolates, alkaloids, phytosterols, anthocyanins, limonoids, and organosulfur compounds, among others [13], [14], [15]. Each class encompasses dozens to hundreds of individual compounds, each with distinct structural features, bioavailability profiles, and mechanisms of action [16], [17]. This review synthesizes current knowledge on the chemical diversity of plant-based phytonutrients, their mechanistic actions at the cellular and molecular level, their bioavailability and bio accessibility, and their implications for human health across a spectrum of chronic diseases.

2. Methodology

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) standards-2020 were followed in the systematic review of this study, which cover identification, screening, qualification, and analysis. Systematic reviews are an efficient way for researchers to collect and screen pertinent data related to certain topics, assess and summarise the evaluations' results, and use the results in practice, policies, and future study. For the literature search, PubMed central, Science direct, Web of Science, DOAJ, JSTOR, Research Gate and Google Scholar from 1990 to 2026 were filtered using the following search terms for data from the earliest study to the retrieved date: “Phytonutrients”; “plant bio-actives”; “polyphenols”; “chronic disease”; “bioavailability”; “mechanistic pharmacology”. Studies were included if they: characterized a defined phytonutrient class (polyphenols, terpenoids, glucosinolates, alkaloids, or phytosterols); reported in vitro, in vivo, or ex vivo mechanistic data; and included human observational studies, or systematic reviews with meta-analyses

examining chronic disease endpoints (cardiovascular disease, neurodegenerative, diabetes mellitus, Cancer, obesity and metabolic syndrome or antimicrobial and antiviral, intervention duration, challenges, limitations, and future directions of the work). The search scope included titles, abstracts, and keywords, and only English-language publications were considered, including books, book chapters, PhD theses, journal articles, and conference proceedings. By offering efficient support, this structured retrieval approach satisfies the PRISMA standards' requirements and helps to guarantee the calibre and dependability of our systematic review. Exclusion criteria were such as comments, book chapters, conference papers, letters, news, patents and reports, were excluded along with synthetic analogy, non-bioactive phytochemicals, and studies lacking dose-response or mechanistic detail, non-Indexed journals and studies with insufficient data.

2.1 Chemical Classification and Diversity of Phytonutrients

2.2 Overview of Major Classes

The structural diversity of phytonutrients is a direct reflection of the complexity of plant secondary metabolism. Alkaloids, carotenoids, nitrogen-containing compounds, organosulfur compounds, phytosterols, and polyphenols are the six main families of phytochemicals [18]. Within these broad categories, dozens of specific compound classes and hundreds of individual molecules have been identified [19]. These substances, which are secondary metabolites, have important health-promoting or disease-preventing effects on humans in addition to their basic ecological roles in plants, such as defence against diseases, herbivores, and environmental stresses [20]. Polyphenols, flavonoids, carotenoids, alkaloids, glucosinolates, and terpenoids are among the most extensively studied phytochemical classes, and they are present across a wide range of plant foods including fruits, vegetables, herbs, and whole grains [21]. The biochemical structure and function of these compounds determine their classification, and their diverse chemical properties underlie their varied mechanisms of biological action [22], [23].

2.3 Polyphenols and Flavonoids

Polyphenols constitute one of the largest and most structurally diverse groups of phytonutrients. They include phenolic acids, lignans, stilbenes, and flavonoids, and are ubiquitous in plant-based foods [24], [25]. Flavonoids, a major subclass of polyphenols, are characterized by the flavan nucleus and include flavones, flavanols, flavanones, anthocyanins, isoflavones, and flavanols [26], [27]. These substances are among the most widely consumed dietary phytonutrients and can be found in fruits, vegetables, and plant-based beverages [28]. For instance, gallic acid, anthocyanin glycosides (delphinidin 3,5-diglucoside and cyanidin-3-glucoside), chlorogenic acid, catechin, epicatechin, caffeic acid, rutin, quercetin, kaempferol, ferulic acid, and resveratrol are the main polyphenolic compounds found in legumes [29]. In sorghum, phenolic compounds—particularly 3-deoxyanthocyanins and tannins—have been identified as key bioactive constituents with significant health implications [30]. Plant foods' polyphenol concentration varies greatly and is impacted by a number of variables, including post-harvest processing, growth circumstances, and genotype [31], [32]. Strong antioxidants with anti-inflammatory and anti-cancer qualities have been found in anthocyanins, a subclass of flavonoids that give many fruits and vegetables their red, blue, and purple hues [33], [34]. Resveratrol, a stilbene polyphenol found in grapes and berries, has attracted considerable attention for its cardioprotective and anti-aging properties [35]. Quercetin, a flavonol present in onions, apples, and many other plant foods, is recognized for its broad-spectrum biological activities including antioxidant, anti-inflammatory, and antidiabetic effects [36].

2.4 Carotenoids

Carotenoids are lipophilic pigments that give many fruits and vegetables their yellow, orange, and red hues. Of the more than 600 carotenoids found in nature, about 40 are found in foods that are typically consumed by humans [37]. Lycopene, β-carotene, α-carotene, lutein, zeaxanthin, and β-cryptoxanthin are the main dietary carotenoids [38], [39], [40].

Lycopene, the most studied carotenoid, is particularly abundant in tomatoes and is recognized as the most effective free radical scavenger among biological carotenoids, with singlet oxygen quenching ability approximately double that of β-carotene and ten-fold greater than α-tocopherol [41], [42]. Unlike other carotenoids, lycopene is not converted to α- or β-carotene, which may explain its predominance as a potent antioxidant with anti-proliferative and anticancer activities [43]. β-Carotene serves as a precursor to vitamin A and is an important singlet oxygen quencher [44]. Lutein and zeaxanthin are concentrated in the macula of the eye and are associated with protection against age-related macular degeneration [45]. Carotenoids exist in both trans- and cis-isomeric forms; while the trans-isomer is more thermodynamically stable, the cis-isomer exhibits higher bioactivity and bioavailability [46]. The geographical location of cultivation, variety, and processing method all significantly influence carotenoid content and bio accessibility in plant foods [47].

2.5 Terpenoids

Terpenoids represent the largest class of phytonutrients and are present in green foods, soy plants, and cereals [48]. They are characterized by the general formula (C_5H_8) and include monoterpenes, diterpenes, tetraterpenes, polyterpenes, steroid saponins, and carotenoids [49]. Citrus fruits are the primary source of limonoids, a subclass of terpenoids that have been shown to have strong anticancer, antioxidant, antibacterial, and antifungal properties. Another terpenoid-related substance whose anti-inflammatory and anticancer effects have been thoroughly investigated is curcumin [50]. Terpenoids serve anti-inflammatory, anti-infectious, and anticancer functions in humans [51]. In Capsicum peppers, the essential oil fraction contains a varied composition of organic substances, predominantly hydrocarbons with the general formula (C_5H_8), including terpenes and their derivatives, esters, phenols, carotenoids, aldehydes, and other organic compounds [52].

2.6 Glucosinolates and Organosulfur Compounds

Glucosinolates are sulphur-containing secondary metabolites found predominantly in Brassica vegetables such as broccoli, cabbage, kale, and Brussels sprouts [53], [54]. Upon hydrolysis by the enzyme myrosinase, glucosinolates yield biologically active compounds including isothiocyanates (e.g., sulforaphane) and indoles (e.g., indole-3-carbinol) [55], [56]. These metabolites have been shown to prevent organ-site carcinogenesis in mouse models and

exert chemopreventive effects in humans [57], [58]. In Brassica crops, glucosinolates are important secondary metabolites that greatly enhance their nutritional value [59]. Numerous studies have been conducted on the biosynthesis, regulation, and associated biofortification techniques of glucosinolates [60]. Along with tannins, sterols, terpenoids, flavonoids, and saponins, glucosinolates and their derivatives (isothiocyanates, glycosides) have been found to be anticarcinogenic in *Moringa oleifera* [61].

2.7 Alkaloids

Alkaloids are nitrogen-containing secondary metabolites with diverse pharmacological activities. They include compounds such as caffeine, morphine, and capsaicin [62]. Capsaicin, the principal alkaloid of Capsicum peppers, is responsible for the characteristic pungency of these plants and exerts analgesic, anti-inflammatory, and potentially anticancer effects [63]. The alkaloid content of Capsicum peppers can be used as a source of synthetic heliotrope and as a therapeutic agent, particularly as a chemoreceptor against mutagenesis or tumorigenesis [64]. Strong antioxidants, antibacterial and antifungal agents, anti-inflammatory and anti-allergic compounds, antispasmodic agents, chemopreventive agents, hepatoprotective agents, neuroprotective agents, and hypolipidemic and hypotensive agents are just a few of the pharmacological effects of alkaloids that have been demonstrated [65].

2.8 Phytosterols and Phytoestrogens

By competing with dietary cholesterol for intestinal absorption, phytosterols—plant-derived sterols structurally identical to cholesterol—lower serum cholesterol levels [66], [67]. Human research has produced conflicting findings and does not conclusively connect serum phytosterol levels with an increased risk of atherosclerosis, despite animal studies suggesting that phytosterols help lower atherosclerosis [68], [69]. Phytoestrogens, including isoflavones (e.g., genistein, daidzein) and lignans, are plant compounds that can bind to estrogen receptors and modulate estrogenic activity [70], [71]. These substances not only block oestrogen synthase but also have the ability to stop platelet aggregation, which lowers the risk of thrombosis and heart disease. They may also lessen the risk of malignancies linked to oestrogen [72], [73].

Table 1
Plant-based phytochemicals/phytonutrients:

Serial no.	Scientific name	Plant name	Phytochemicals/phytonutrients with classes	Mechanism of action	Therapeutic uses	References
1.	*Curcuma longa* L.	Turmeric	**Polyphenols-** curcuminoids (curcumin, demethoxycurcumin, bisdemethoxycurcumin)	Curcumin reduces the expression of pro-inflammatory cytokines, such as TNF-α and other interleukins, via suppressing NK-kb signalling.	Anti-inflammatory, anti-oxidant and anticancer	74,75,76
2.	*Withania somnifera* L. (Dunal)	Ashwagandha	**Steroidal lactones-** Withanolides, Withaferin A	Withanolides from *Withania somnifera* lower cortisol, supresses TNF-α/IL-1β While boosting antioxidant activity for stress protection	Adaptogenetic, neuroprotective, and anti-inflammatory	77,78,79
3.	*Camellia Sinensis* L. (Kuntze)	Tea plant	**Polyphenols-** Epigallocatechin gallate, Epigallocatechin, Epicatechin, Epicatechin gallate	*Camellia sinensis* catechins prevent lipid peroxidation and neutralise reactive oxygen species, shielding cells from oxidative damage.	Antioxidant, cardioprotective, and anticancer properties	80,81
4.	*Azadirachta indica* A.Juss	Neem	**Limonoids-** Azadirachtin, Nimbin	Azadirachtin inhibits TNF-NF-Kb driven cytokine release while nimbin exhibits antimicrobial activity via disruption of microbial enzymes and biofilms	Antimicrobial, anti-inflammatory and antimalarial effects	82,83
5.	*Zingiber officinale* Roscoe	Ginger	**Phenolic compounds/phenyl propanoids** – gingerols, shogaols	Gingerols and shogaols suppress COX and LOX activity, thereby decreasing prostaglandin and leukotriene levels while neutralizing ROS to mitigate oxidative state	Anti-inflammatory, Antiemetic and antioxidant effect	84,85,86
6.	*Andrographis Paniculata* (Burm.f.) Nees	Kalmegh	**Alkaloids-** berberine, palmatine **Glycosides-** Tinocordiside ,cordifolioside A-D	Andrographis boost macrophage activation (TLR4/NF-κB) (Toll like receptor 4) regulates Th1 and Th17 immune responses and activates Nrf2, enhancing antioxidant defence	Antidiabetic and hepatoprotective effects	87,88,89
7.	*Centella asiatica* (L.) urban	Gotu kola	**Triterpenoid saponins-** madecassoside and asiaticoside	Asiaticoside and madecassoside enhance collagen synthesis through TGF-β/S (smad signalling while mitigating oxidative stress via ROS scavenging and activating antioxidants	Wound healing, neuroprotection and anti-inflammatory	90,91
8.	*Moringa oleifera* Lam.	Drumstick tree	**Phenolic acids-** gallic acid and chlorogenic acid **Flavonoids**-quercetin	Moringa flavonoids and phenolics neutralize ROS and enhance glucose metabolism via inhibition of α-glucosidase and enhancing insulin sensitivity.	Antidiabetic, antioxidant and anti-inflammatory	92,93,94
9.	*Ginkgo biloba* L.	Ginkgo	**Terpenoids-** Ginkgolides A, B & C, Bilobalide **Flavonoids-**, kaempferol glycosides, Quercetin	*Ginkgo biloba* enhances cerebral blood flow and supresses platelet-activating factor (PAF) through ginkgolides while flavonoids and bilobalide confer antioxidant neuroprotection	Neuroprotective, cognitive-enhancing and antioxidant	95,96
10.	*Bocapo monnieri* (L.) Wettst.	Brahmi	**Triterpenoid saponins-** Bacoside A and Bacoside B	Bacoside enhance neuronal signalling via AChE inhibition, modulating neurotransmitter levels and promoting synaptic	Neuroprotective, Nootropic, memory enhancing activity	97,98,99

Serial no.	Scientific name	Plant name	Phytochemicals/phytonutrients with classes	Mechanism of action	Therapeutic uses	References
				plasticity thereby reducing oxidative stress by activating Nrf2 and scavenging ROS.		
11.	*Aloe berbendesis* (L.) Burm.f.	Aloe	**Anthraquinones-** Aloin, Aloe-emodin **Polysaccharide** Acemannan	Anthraquinones enhance gut motility through 5HT4 receptor activation and increase water secretion, Acemannan boost macrophages, collagen, fibroblasts both inhibit COX-2/PGE2 reducing inflammation	Laxative, wound healing, anti-inflammatory, antimicrobial, immunomodulatory	100,101
12.	*Allium sativum* L.	Garlic	**Organosulfur compound-** Allicin, Ajoene, Diallyl sulfides	Allicin from fresh garlic inhibits microbial thiol enzymes and HMG-CoA reductase (↓ cholesterol, ↑ ABCA1) while diallyl sulfides provide anti-oxidant protection through Nrf2/SOD activation and free radical scavenging	Anti-microbial, cardioprotective, antihyperlipidemic, antihypertensive, antioxidant	102,103
13.	*Echinacea Purpurea* (L.) Moench	Purple coneflower	**Phenolic compound-** Echinacoside, chicoric acid **Alkylamides-** Alkamides	Alkamides activates CB2 enhancing macrophage activity, chicoric acid inhibits hyaluronidase and regulates cytokines, polysaccharides activate TLR4 enhancing immunity	Immunomodulatory, antioxidant, anti-inflammatory, antimicrobial	104,105
14.	*Panax ginseng* C.A. Mey.	Ginseng	**Triterpenoid saponins-** Ginsenoside (Rb1, Rg1, Rb)	Ginsenoside modulate cortisol via GR/HPA Axis and elevate NO/ cGMP while enhancing immune cells suppressing NF-κB-mediated inflammation and activating Nrf2-driven antioxidants	Adaptogenetic effects, improves cardiovascular functions, modulates immunity and anti-inflammatory properties	106,107
15.	*Salix alba* L.	White willow	**Phenolic glycoside-**Salicin **Polyphenol**-tannins, Flavonoids	Salicin undergoes metabolic conversion to salicylic acid inhibits COX activity thereby suppressing prostaglandin synthesis	Analgesic, anti-inflammatory, antipyretic, mild anticoagulant	108,109
16.	*Matricaria chamomilla* L.	Chamomile	**Flavonoid-** Apigenin **Sesquiterpene-** Chamazulene **Sesquiterpene alcohol-** Bisabolol	Interaction with GABA receptor promotes sedation, NF- κB / COX 2 inhibition and neutralization of ROX confers anti-inflammatory and antioxidant effects	Sedative, anti-inflammatory, antioxidant	110
17.	*Calendula officinalis* L.	Marigold	**Triterpenoids-** Faradiol **Flavonoids**- Quercetin **Carotenoids-** lutein	Stimulates fibroblast proliferation, enhances collagen synthesis, and supresses inflammatory cytokines	Wound healing, anti-inflammatory, skin regenerative	111
18.	*Lavandula angustifolia* Mill.	Lavender	**Monoterpene alcohol-** linalool **Monoterpene ester-**Linalyl acetate **Monoterpene ketone-**camphor	Modulates GABAergic transmission(anxiolytic) and disrupts microbial membrane(antimicrobial)	Antifungal, antibacterial, neurologic, antimicrobial, antiparasitic, antidiabetic, and analgesic effects	112
19.	*Mentha piperita* L.	Peppermint	**Monoterpene alcohol**- Menthol **Monoterpene ketone**-menthone Flavonoids- Eriocitrin, Hesperidin	Activates TRPM8(cooling) blocks calcium channel to relax GI smooth muscles and disrupts microbial membrane	Antibacterial, antifungal	113
20.	*Valeriana officinalis* L.	Valerian	**Sesquiterpenoid-** Valere acid **Iridoid esters-** Valepotriates	Potentiates GABAergic transmission by inhibiting GABA-T (reducing GABA	Anxiety, insomnia	114

Serial no.	Scientific name	Plant name	Phytochemicals/phytonutrients with classes	Mechanism of action	Therapeutic uses	References
			Flavonoids- phenolic compounds	breakdown) and positively modulating $GABA_A$ β/γ subunits		
21.	*Silybum marianum* (L.) Gaertn.	Milk Thistle	**Flavonolignan-** silymarin, silybin, silychristin, silydianin	Stabilizes hepatocyte membrane and reduces oxidative stress through free radical scavenging and promotes liver regeneration by stimulating protein synthesis	Hepatoprotective agent, antioxidant, liver disease	115
22.	*Vaccinium macrocarpon* Aiton	Cranberry	**Tannins-** A type proanthocyanidins **Flavonoids-** Anthocyanins **Phenolic compound –** flavonoids	Inhibits *E. coli* adhesion to uroepithelial cells by blocking P- fimbrial attachment while exerting antioxidants effects via ROS scavenging	Urinary tract infections, antioxidants, adjunctive dietary use	116
23.	*Crataegus monogyna* Jacq.	Hawthorn	**Flavonoids-**Hyperoside, vitexin **Tannins-** oligomeric procyanidins	Enhances coronary perfusion via NO-mediated vasodilation, improves myocardial contractibility via phosphodiesterase inhibition and provides cardio protection against oxidative stress	Cardioprotective, chronic heart failure	117
24.	*Glycyrrhiza glabra* L.	Licorice	**Terpenoid saponin-** Glycyrrhizin **Flavonoid glycoside-** liquiritin **Polyphenolic compound-** flavonoids	Inhibits 11β-HSD1, increasing local cortisol, supresses inflammation via COX PGE2 downregulation and shows antiviral and antioxidant effects	Demulcent, expectorant, antitussive, and mild laxative	118
25.	*Taraxacum officinale* (L.) Weber ex F.H. wigg.	Dandelion	**Sesquiterpene-** Taraxacin **Terpenoids-** sesquiterpene lactones, **Phenolic compounds-** flavonoids **Polysaccharide-** insulin	Exhibits choleretic and diuretic effects (Via Renel Na^+/K^+-ATPase inhibition) and enhances antioxidant defence via Nrf2 activation	Diuretic, hepatoprotective, digestive support, antioxidant	119–120
26.	*Ocimum sanctum* L.	Tulsi (Holy Basil)	**Phenolics** (Eugenol), Flavonoids, Terpenoids.	Immunomodulatory (enhances immune response), Anti-inflammatory (inhibits COX and cytokines), Antioxidant (scavenges free radicals), Antimicrobial (inhibits bacterial and fungal growth)	Respiratory disorders (cough, asthma) Immunity booster Stress relief (adaptogenic) Antimicrobial.	121,122
27.	*Curcuma caesia* Roxb.	Black Turmeric	**Curcuminoids**, Essential oils (Camphor, Ar turmerone), Flavonoids	Antioxidant (scavenges reactive oxygen species) Anti-Inflammatory (inhibits COX and LOX pathways) Antimicrobial (disrupts microbial cell function) Analgesic activity via modulation of inflammatory mediators	Anti-inflammatory (pain, swelling) Wound healing Respiratory disorders Traditional medicine applications	123
28.	*Dioscorea alata* **L.** (or *Dioscorea* spp.)	Yam	**Steroidal saponins** (Diosgenin), Alkaloids, Phenolics	Hypoglycaemic effect (improves insulin sensitivity) Antioxidant activity (reduces oxidative stress), Anti-inflammatory (modulates inflammatory pathways)	Antidiabetic, Hormonal balance (precursor for steroid drugs) Anti-inflammatory Nutritional supplement	124

Serial no.	Scientific name	Plant name	Phytochemicals/phytonutrients with classes	Mechanism of action	Therapeutic uses	References
				Hormonal precursor activity (diosgenin as steroid precursor)		
29.	*Smallanthus sonchifolius* (Poepp.) H. Rob.	Yacon	**Fructooligosaccharides** (FOS), Phenolic compounds, Flavonoids	Prebiotic effect (stimulates beneficial gut microbiota) hypoglycaemic action (reduces glucose absorption, improves insulin sensitivity) Antioxidant activity (neutralizes free radicals)	Antidiabetic Gut health (prebiotic) Weight management Digestive health	125
30.	*Ganoderma lucidum* (Curtis) P. Karst. (Reishi mushroom)	Ganoderma	**Triterpenoids** (Ganoderic acids), Polysaccharides (β-glucans), Sterols	Immunomodulatory (activates macrophages, T-cells), Antioxidant (reduces oxidative stress). Anticancer (induces apoptosis, inhibits tumor growth), Anti-inflammatory (modulates cytokine production)	Immune booster Anticancer support Hepatoprotective Anti-aging	126
31.	*Phyllanthus emblica* **L.**	Amla (Indian Gooseberry)	**Polyphenols** (Ellagic acid, Gallic acid), Vitamin C, Tannins	Strong antioxidant that lowers oxidative stress increases the production of collagen Anti-inflammatory (inhibits inflammatory mediators) Antidiabetic (improves glucose metabolism)	Immunity booster Anti-aging Digestive health Antidiabetic	127
32.	*Tinospora cordifolia* (Willd.) Hook. f. & Thomson	Giloy	**Alkaloids** (Berberine), Diterpenoid lactones, Glycosides, Polysaccharides	Immunomodulatory (activates macrophages, enhances immune response) Anti-inflammatory (inhibits pro-inflammatory cytokines) Antioxidant (reduces oxidative stress) Antidiabetic (improves glucose metabolism)	Immunity booster Fever management Antidiabetic Anti-inflammatory	128
33.	*Cinnamomum verum* J. Presl (or *Cinnamomum zeylanicum*)	Cinnamon/Dalchini	**Polyphenols**, Cinnamaldehyde (Phenylpropanoid), Essential oil.	Improves insulin sensitivity (enhances glucose uptake), Antioxidant (free radical scavenging) Anti-inflammatory (inhibits inflammatory mediators) Antimicrobial (disrupts microbial cell membrane)	Antidiabetic Cardioprotective Antimicrobial, Digestive aid	129
34.	*Trigonella foenum-graecum* L.	Fenugreek	**Alkaloids** (Trigonelline), Steroidal saponins (Diosgenin), Flavonoids	Delays glucose absorption (high fibre content) Improves insulin sensitivity Antioxidant (reduces oxidative stress), Hypolipidemic (reduces cholesterol levels)	Antidiabetic Hypocholesterolemic Digestive aid Lactation support	130

Serial no.	Scientific name	Plant name	Phytochemicals/phytonutrients with classes	Mechanism of action	Therapeutic uses	References
35.	*Piper nigrum* L.	Black Pepper	**Alkaloid** (Piperine), Volatile oils, Phenolic compounds	Enhances bioavailability (inhibits drug-metabolizing enzymes like CYP450), Antioxidant activity, Anti-inflammatory (inhibits cytokines), Digestive stimulant (increases enzyme secretion)	Bioavailability enhancer, Digestive aid Anti-inflammatory Antimicrobial	131
36.	*Terminalia chebula* Retz.	Haritaki	**Tannins** (Chebulagic acid, Chebulinic acid), Polyphenols, Flavonoids	Antioxidant (free radical scavenging) Mild laxative (enhances intestinal motility) Antimicrobial activity Anti-inflammatory (reduces inflammatory mediators)	Digestive health (constipation) Detoxification Antimicrobial Traditional Ayurvedic formulations (e.g., Triphala)	132

3. Dietary Sources and Distribution

3.1 Fruits and Vegetables

The main food sources of phytonutrients are fruits and vegetables. To maintain health and lower the risk of chronic diseases, the World Health Organization advises consuming at least 400 g of fruits and vegetables each day [133]. The beneficial effects of fruits and vegetables on human health are mainly attributed to the interaction between bioactive compounds and other nutrients in whole foods [134]. Tomatoes (*Solanum lycopersicum*) are among the most extensively studied plant foods for their phytonutrient content. They are rich in lycopene, phenolic acids (including chlorogenic acid and caffeic acid), flavonoids (including quercetin and kaempferol), and carotenoids (including β-carotene and lutein) [135], [136]. Lycopene, the most researched carotenoid, is one of the phytonutrients that contribute significantly to tomatoes' unique nutritional value [137]. Tomato also contains folate, potassium, vitamins C and E, flavonoids, chlorophyll, and β-carotene [138]. Broccoli, cabbage, kale, Brussels sprouts, cauliflower, and other Brassica vegetables are high in glucosinolates, carotenoids, phenols, vitamins (particularly vitamin C, folate, tocopherol, and phylloquinone), and minerals [139]. Polyphenols, glucosinolates, and vitamins are some of the main phytochemical components found in cabbage, which is used for food and traditional medicine all over the world [140]. Citrus fruits are rich sources of limonoids, flavonoids (including hesperidin, naringin, naringenin, and rutin), and carotenoids (including β-carotene, lutein, and β-cryptoxanthin) [141]. Oranges account for approximately 75% of cultivated citrus fruits and contain a particularly rich array of bioactive phytonutrients [142]. Natural pharmacological bioactive substances found in capsicum peppers include essential oils, capsaicin, and a variety of organic micronutrients [143]. They are a good source of lycopene, flavonoids, trace metals, and vitamins K, C, B, and carotene (pro-vitamin A) [144].

3.2 Legumes

Legumes are important sources of phytonutrients including phenolic acids, carotenoids, tocopherols, isoflavones, and polyphenols [145]. Low-density lipoprotein cholesterol (LDL-C) may be shielded from free radical oxidation by the substantial amounts of bioactive phytochemicals found in pulses, such as phenolic acids, carotenoids, and tocopherols [146]. While lipophilic phytonutrients like carotenoids and tocopherols may prevent cardiovascular diseases and some eye pathologies, hydrophilic phytochemicals like ascorbic acid, phenolic acids, and polyphenols have been linked to improved immune system function and decreased cancer risk [147].

3.3 Medicinal and Functional Plants

The drumstick tree, or *Moringa oleifera*, is well known for its leaves, which are rich in essential nutrients and bioactive compounds like vitamins, minerals, antioxidants, and anti-inflammatory chemicals [148], [149]. Astragalin, isoquercetin, and crypto-chlorogenic acid are the primary phytochemicals present in moringa leaves and are well-known for their anti-inflammatory, antihypertensive, and antioxidant qualities [150]. Additionally, flavonoids, phenolic acids, carotenoids, saponins, tannins, and glucosinolates are found in moringa leaves [151]. Sorghum's genetic diversity, hardiness, and high phytonutrient content make it a crucial crop for world food security [152]. Phenolic chemicals, particularly 3-deoxyanthocyanins and tannins, are more abundant in coloured sorghum cultivars, especially those with red, brown, and black pericarps [153].

4. Mechanisms of Biological Action

4.1 Antioxidant Activity and Oxidative Stress Mitigation

Antioxidant activity is one of the most well-researched ways that phytonutrients promote health. Many chronic diseases are linked to oxidative stress, which is caused by an imbalance between the body's antioxidant defences and the formation of reactive oxygen species (ROS) and reactive nitrogen species (RNS) [154], [155]. By scavenging free radicals, chelating transition metal catalysts, activating antioxidant enzymes, decreasing α-tocopherol radicals, and inhibiting oxidases, phytonutrients such as polyphenols, flavonoids, carotenoids, and vitamin C function as powerful antioxidants [156], [157].

Among biological carotenoids, lycopene is the most efficient at quenching singlet oxygen; it can do so twice as well as β-carotene and 10 times more effectively than α-tocopherol [158], [159]. Flavonoids have antioxidant capacity and can inhibit cellular oxidative stress [160]. Vitamin C is an efficient electron donor and a good reducing agent [161]. The high phenolic and flavonoid content of Moringa oleifera leaves is primarily responsible for their potent antioxidant qualities [162]. Antioxidant activity also reduces structural damage and apoptosis on the endothelium of capillaries and arteries by quenching free radicals through bioactive components such as superoxide dismutase (SOD), minerals (zinc, selenium), vitamins (A, B, C, E), and secondary metabolites (flavonoids, phenolics, polysaccharides, polyphenols, and saponins) [163]. Scavenging free radicals that cause oxidative stress prevents the onset of chronic diseases that can impair the cardiovascular system [164].

4.2 Anti-inflammatory Mechanisms

Chronic inflammation is a central pathological mechanism in the development of cardiovascular disease, diabetes, cancer, and neurodegenerative disorders [165], [166]. Phytonutrients modulate inflammatory pathways through multiple mechanisms. Polyphenols and flavonoids have been shown to suppress inflammation markers and decrease lipid accumulation [167]. In addition to reducing the phosphorylation of extracellular signal-regulated kinases (ERK), p38, and c-Jun N-terminal kinases (JNK), sorghum extracts also efficiently suppress MAPK signalling pathways, insulin signalling, and glucose uptake, which may help regulate adipocyte development [168]. Phenolics, flavonoids, tannins, terpenoids, carotenoids, and anthocyanins, characterized by antioxidant and anti-inflammatory properties, have been shown to reduce atherosclerosis formation and the risk of developing cardiovascular disease, and to decrease inflammatory biomarker levels [169]. Tomato phytochemicals, such as lycopene and phenolic compounds, are essential for reducing inflammation and oxidative stress, which helps treat a variety of illnesses [170], [171].

4.3 Anticancer Mechanisms

Through a variety of complimentary methods, including as induction of apoptosis, suppression of cell proliferation, control of cell cycle progression, prevention of angiogenesis, and modulation of carcinogen-metabolizing enzymes, phytonutrients have anticancer effects [172], [173], [174]. Numerous proteins involved in cell division and signalling pathways have their expression altered by carotenoids [175]. Lycopene can boost the production of numerous differentiation-related proteins, including cell surface antigen (CD14), oxygen burst oxidase, and chemotactic peptide receptors, and is linked to a decrease in cyclin D1 protein, a recognised oncogene overexpressed in many primary tumours [176]. Additionally, lycopene scavenges peroxyl radicals and promotes cell-to-cell communication through gap junctions [177]. Richer in phenolic compounds, coloured sorghum increased cell cycle arrest and apoptosis while inhibiting ROS activity, tumour development, and cancer cell proliferation [178]. Sorghum extracts affected essential angiogenesis drivers like VEGF and VEGF-R2, downregulated important cell cycle regulators including cyclin D, cyclin E, and pRb, and modified Jak/STAT pathways, successfully stopping the progression of STAT5b/IGF-1R and STAT3/VEGF signalling channels [179]. At every stage of carcinogenesis, flavonoids alter signal transduction pathways. Following absorption, they are carried to target organs where they have anticarcinogenic effects [180]. In mice models, it has been demonstrated that glucosinolate metabolites, especially indole-3-carbinol, suppress organ-site carcinogenesis [181], [182]. *Moringa oleifera* is known to include anticarcinogenic substances such as glucosinolates, isothiocyanates, glycosides, and glycerol-1-9-octadecanoate [183].

4.4 Cardioprotective Mechanisms

Phytonutrients exert cardioprotective effects through multiple pathways including reduction of LDL oxidation, inhibition of platelet aggregation, modulation of lipid metabolism, reduction of blood pressure, and anti-inflammatory effects [184], [185], [186]. For cardiovascular health, sorghum enhanced HO1 and eNOS expression, altered platelet microparticles, and reduced platelet aggregation [187In addition to blocking oestrogen synthase, phytoestrogens may also stop platelets from aggregating, which lowers the risk of thrombosis and heart disease [188], [189]. Many plant chemicals have been shown to have antihyperlipidemic, antihypercholesterolemic, and antiatherosclerosis characteristics by inhibiting lipid peroxidation and reducing calcium and cholesterol deposits on blood vessel inner walls [190]. The antioxidant potential of pulses is attributed to polyphenols, tocopherols, and carotenoids; in vitro free radical scavenging activity has been shown for a number of bean, lentil, chickpea, and pea varieties [191].

4.5 Antidiabetic Mechanisms

Phytonutrients modulate glucose metabolism and insulin signaling through multiple mechanisms. Flavonoids, particularly those from citrus fruits, have been shown to exert antidiabetic effects through in vivo and in vitro studies on the molecular mechanisms of antidiabetic action [192]. Vegetable sprouts include bioactive peptides and phytochemicals that lower postprandial glucose levels by inhibiting digestive enzymes such α-amylase, β-glucosidase, and dipeptidyl peptidase IV (DPP-IV) [193]. Sorghum extracts influence glucose absorption and efficiently suppress insulin and MAPK signalling pathways [194]. Depending on the vegetables chosen and the quantity of phytonutrients, minerals, vitamins, and dietary fibres taken, eating veggies may help avoid diabetes [195].

4.6 Neuroprotective Mechanisms

Neurodegenerative illnesses are largely caused by oxidative stress, and the neuroprotective potential of phytonutrients with antioxidant qualities is becoming more widely acknowledged [196]. The pathophysiology of neurodegenerative illnesses is caused by oxidative stress, which arises from an imbalance between pro- and antioxidant levels in favour of pro-oxidants [197]. It has been discovered that fruits and fruit juices have a significant nutritional effect in preventing physiological illnesses and neurodegenerative diseases [198]. Alkaloids have been found to be neuroprotective [199]. γ-Chinese cabbage and other Brassica vegetables include a novel functional nutrient called aminobutyric acid (GABA), which has been linked to neurological and psychiatric diseases and is crucial for brain plasticity [200].

4.7 Antimicrobial and Antiviral Mechanisms

Phytonutrients exhibit broad-spectrum antimicrobial and antiviral activities. Phytoconstituents including vitamins (A, B, C, D, E), minerals (selenium, zinc, copper), alkaloids, glycosides, kaempferols, quercetin, gallic acid, caffeic acid, and other compounds have been shown to exhibit antimicrobial, immunomodulatory, anti-inflammatory, antioxidant, and antiviral properties [201]. These phytoconstituents prevent viruses from entering and replicating in

host cells by binding to viral and host cell receptor proteins, and also modulate the immune system to produce adequate antibodies (CD4 + T-cells) necessary to fight against viral infections [202].

Mangiferin has been shown to antagonize the in vitro cytopathic effect of HIV on MT-2 cells and prevent cell death, while flavonoids (quercetin, catechin, and epicatechin) inhibit various stages of the replication cycle of target viruses [203]. Selenium strengthens the immune system and reduces the risk of cancer, while copper can destroy viruses including SARS-CoV-2 [204]. The synergistic effects of phytonutrients in Capsicum peppers are thought to make them potentially effective antimicrobial, anti-inflammatory, anticancer, anti-tumour, and anti-mutagenic agents [205].

4.8 Immunomodulatory Mechanisms

Through a variety of mechanisms, phytonutrients influence immune function. A phytonutrient found in kale, melatonin (5-methoxy-N-acetyltryptamine) provides beneficial physiological effects such as immunological and body mass regulation, enhanced cardiovascular and reproductive health, bone formation and protection, antioxidant activities, and detoxification of free radicals [206]. Phytoconstituents also modulate the immune system to produce adequate antibodies necessary to fight against viral infections [207].

5. Bioavailability and Bio accessibility

5.1 Definitions and Importance

The bioavailability of phytonutrients is a major factor in the nutritional efficacy of plant-based diets [208]. Bioavailability is a more general phrase that encompasses bio-accessibility, which is the percentage of nutrients that are eventually accessible at the site of action [209]. Unlike bioavailability, which quantifies the quantity of chemicals absorbed and metabolised, bio-accessibility refers to the quantity of polyphenols released for absorption from food material in the digestive tract [210]. Because of the intense metabolism that occurs during absorption, metabolites that reach the blood system may differ from the original compounds found in food, so determining the bioactive compound content directly from food is insufficient for predicting potential in vivo effects [211]. Phytochemicals are viewed by the human body as xenobiotics substances outside of normal physiological function and if they are not adequately broken down and removed, homeostasis may be upset [212]. Phytonutrients must be made accessible before they may exert their bioactivity, and even before taking dose- and host-related parameters into account, significant variations may result from their matrix release, alterations during digestion, absorption, metabolism, and biodistribution [213].

5.2 Factors Affecting Bioavailability

Multiple factors influence the bioavailability of phytonutrients. The physical or chemical form in which a nutrient exists, whether processed and cooked, the dose ingested, its catabolism, and the metabolic state of an individual all play important roles [214]. Even when a phytonutrient in pure form is shown to have a strong antioxidant property in vitro, its positive effects on an individual's health may be limited in vivo [215]. The physical makeup of the meal as well as internal factors like the microbiome and digestive enzymes influence the bioavailability of polyphenols [216]. Simple carbohydrates, dietary fats (particularly advantageous for hydrophobic polyphenols like curcumin), and additional antioxidants may improve the accessibility of polyphenols for absorption and further metabolism, while components like dietary fibre (such as hemicellulose), divalent minerals, and foods high in protein and viscosity can hinder polyphenol bio-accessibility [217], [218]. Before passively diffusing across intestinal boundaries, flavonoid glycosides typically undergo de-glycosylation at the small intestine. The esterase in the gut microbiota then breaks down the released bioactive compounds to produce further metabolites [219]. Before intestinal absorption, the gut microbiota can alter the native form of polymeric or glycosylated phenolic compounds [220]. Ascorbic acid helps stabilise folates during digestion and absorption, increasing folate bioavailability [221]. Long-chain triglycerides enhance β-carotene bio-accessibility in comparison to medium-chain triglycerides, and monounsaturated fatty acids encourage greater carotenoid bioavailability than polyunsaturated fatty acids [222].

6. Phytonutrients and Specific Chronic Diseases

6.1 Cardiovascular disease

Phytonutrients exert cardioprotective effects through multiple complementary mechanisms. Epidemiological studies have suggested that consumption or tissue concentration of polyphenols and carotenoids is associated with reduced risk of developing cardiovascular diseases [223]. Dietary proanthocyanidins have been shown to have a favourable role in reducing gastric cancer risk in epidemiological studies [224]. Phytosterols can reduce atherosclerosis in animal studies, though human studies have yielded mixed results [225], [226]. The cardioprotective effect of dietary pulses is partially explained by the high content of viscous soluble fibres in these foods, alongside the valuable contribution of bioactive compounds including fibres, isoflavonoids, phenolic acids, polyphenols, folate, and vitamin B6 [227]. Sorghum decreased platelet aggregation, changed platelet microparticles, and increased HO1 and eNOS expression for cardiovascular health [228].

6.2 Diabetes Mellitus

Phytonutrients modulate glucose metabolism and insulin sensitivity through multiple mechanisms. Flavonoids, particularly those from citrus fruits, have been shown to exert antidiabetic effects [229]. Vegetable sprouts include bioactive peptides and phytochemicals that lower postprandial glucose levels by inhibiting digestive enzymes such α-amylase, β-glucosidase, and DPP-IV [230]. Consuming pulses like beans has been linked in studies to lower rates of diabetes, glycaemic control, and cardiovascular disease [231].

6.3 Cancer

Phytonutrients exert anticancer effects through multiple mechanisms as described in Section 4.3. Epidemiological evidence consistently demonstrates an inverse relationship between consumption of plant-based foods rich in phytonutrients and cancer risk [232, [233], [234]. Lycopene is associated with reduction of cyclin D1 protein, a known oncogene overexpressed in many primary tumors [235]. It has been demonstrated that glucosinolate metabolites, especially indole-3-carbinol, suppress organ-site carcinogenesis [236], [237]. Coloured sorghum induced cell cycle arrest and death while inhibiting the growth, proliferation, and ROS activity of cancer cells [238].

6.4 Neurodegenerative Diseases

Neurodegenerative illnesses are largely caused by oxidative stress, and the neuroprotective potential of phytonutrients with antioxidant qualities is becoming more widely acknowledged [239]. It has been discovered that fruits and fruit juices have a significant dietary effect in avoiding many physiological illnesses and neurodegenerative diseases [240]. Alkaloids have been found to have neuroprotective properties [241]. Recently found in Brassica vegetables, GABA is a unique functional nutrient that is associated to neurological and psychiatric diseases and is crucial for brain plasticity [242].

6.5 Obesity and Metabolic Syndrome

Through a variety of processes, phytonutrients influence energy balance, lipid metabolism, and adipogenesis. Extracts from sorghum bran reduce ERK, p38, and JNK phosphorylation, which may help regulate adipocyte development [243]. The low calorific value of moringa leaves can help reduce obesity, while the fiber-rich pods can help prevent and treat colon cancer [244]. Potential treatments for metabolic syndrome problems include vegetable sprouts [245].

7. Analytical Methods and Research Approaches

7.1 In Vitro and In Vivo Models

Research on phytonutrient bioactivity employs a range of experimental models from cell-based assays to animal studies and human clinical trials. In vitro models using human-based cell model systems have been designed to study properties of drugs and phytochemicals [246]. Novel cell lines and culture strategies have helped in overcoming the scarcity of human liver material and problems in maintaining the expression and function of metabolizing enzymes [247]. With its tissue and organ systems, the nematode Caenorhabditis elegans is being used more and more as an in vivo model to investigate the metabolism of methylated catechin derivatives and their biological effects on resistance to oxidative and thermal stress [248]. Despite the promising effects of phytonutrient extracts on health metabolism, drawing definitive conclusions based solely on cell studies to evaluate the health effects of polyphenols has inherent limitations, as lab extract experiments do not accurately represent metabolism and actual dietary concentrations [249]. Polyphenols' metabolic changes within cell models can alter their structure, influencing the observed bioactivity [250].

7.2 Mass Spectrometry and Biomarker Analysis

Mass spectrometry has emerged as a crucial method for evaluating the health benefits of dietary ingredients and for identifying exposure biomarkers (bioavailability and bioefficacy) [251]. Understanding the relationship between dietary patterns, specific foods or food components, and the physiological impacts at the cellular, tissue, and whole-body levels following acute and chronic absorption is the main goal of current nutrition research [252]. Understanding how food affects certain health outcomes requires knowledge of dose-effect relationships and the bioavailability of bioactive dietary ingredients [253]. Mass spectrometric techniques have been used to review the bioavailability of glucosinolates and related chemicals, including factors that influence absorption, distribution, metabolism, and excretion [254]. Mass spectrometry has been used to describe the metabolic changes of flavonoids, which are mostly found in plants and the majority of food products in their glucosylated form [255].

7.3 Bio-accessibility Assessment Methods

Research comparing in vitro and in vivo methods for assessing bioavailability and bio accessibility is ongoing, with each experimental method having unique benefits and drawback [256]. It has been shown that there is a strong correlation between in vitro carotenoid bio-accessibility, in vivo observations, and outcomes from bioavailability trials involving human subjects. This suggests that in vitro models could be a less time-consuming and expensive substitute for in vivo studies when evaluating carotenoid bio-accessibility [257].

8. Challenges, Limitations, and Future Directions

8.1 Discrepancies Between *In Vitro* and *In Vivo* Studies

When comparing observational and intervention studies, there are differences in the potential effects of phytonutrients, particularly when employing pure substances [258]. Variations in consumption amounts and their bioavailability may contribute to these disparities [259]. Beta-carotene supplements have been shown to have negative effects on people with cardiovascular disease, and some studies have showed that supplementing with beta-carotene with vitamin C and E has no positive impact on cardiovascular illness. This emphasises how crucial it is to research phytonutrients as entire foods rather than as separate substances [260]. Clinical trials are advised to evaluate the effectiveness and safety of phytoconstituents in people because the majority of research on phytonutrient bioactivity is based on in vitro and animal-based in vivo investigations [261], [262]. Only in vitro and animal-based in vivo research can ensure the safety and effectiveness of phytoconstituents for human ingestion [263].

9.2 Bioavailability Gaps

The effects of food processing, changes during digestion, the role of cellular transporters in influx/efflux through the gastrointestinal epithelium, changes during colonic fermentation, and phase I and phase II metabolism after absorption are just a few of the many aspects of secondary plant metabolite

bioavailability that we still don't fully understand [264]. For the majority of polyphenols and their metabolites, pharmacodynamics and tissue distribution are still poorly understood [265].

9.3 Standardization and Quality Control

Herbal products must go through rigorous testing to ascertain their safety and effectiveness, quality control, and trustworthy clinical trials [266], [267]. To improve public health care, traditional herbal medicine systems must be carefully and scientifically integrated into evidence-based clinical illness management [268], [269].

9.4 Future Research Directions

To fully grasp the potential of phytochemicals in functional meals, future research should concentrate on multidisciplinary study, personalised nutrition, and artificial intelligence-driven food invention [270]. Despite the enormous promise of phytonutrients, issues with bioavailability, regulatory acceptability, and consumer acceptance continue [271]. Polyphenol metabolite health benefits may be tested utilising in vitro models for preclinical research employing stem cells and patient-specific induced pluripotent stem cells [272]. Microengineered physiological systems, also referred to as "organs-on-chips," have the potential to be used in phytonutrient research since they can replicate physiologically significant aspects of human tissues and their interactions [273]. The accessibility, bioavailability, and biological efficacy of crop nutrients or supplementary antioxidants determine their actual potential for improving human health [274]. Only now are studies on the absorption, metabolism, and in vivo potency of phytonutrients starting to yield some results. When combined with contemporary biotechnology, understanding the transcriptome-proteome-metabolome of new transgenics should provide new insights to allay worries and open markets for genetically modified horticultural crops [275].

10. Conclusion

The evidence collectively supports the conclusion that a diet rich in diverse plant-based foods, providing a broad spectrum of phytonutrients, is a cornerstone of chronic disease prevention and health promotion. As scientific understanding of phytonutrient chemistry, mechanisms, and bioavailability continues to advance, these compounds hold increasing promise as both dietary health-promoting agents and as leads for the development of novel therapeutic interventions for Nrf2 activation and gut microbiota.

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Figures

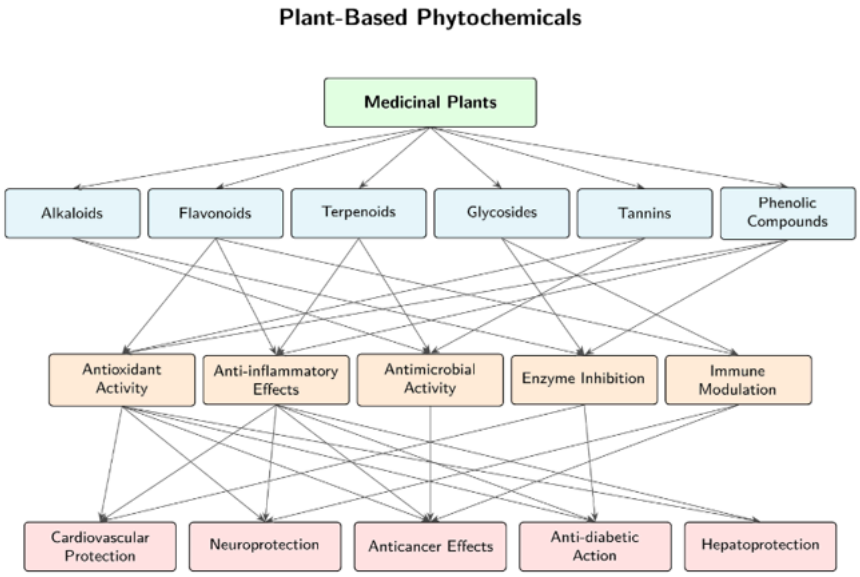


Figure 1

Plant-based phytonutrients and their therapeutic activities

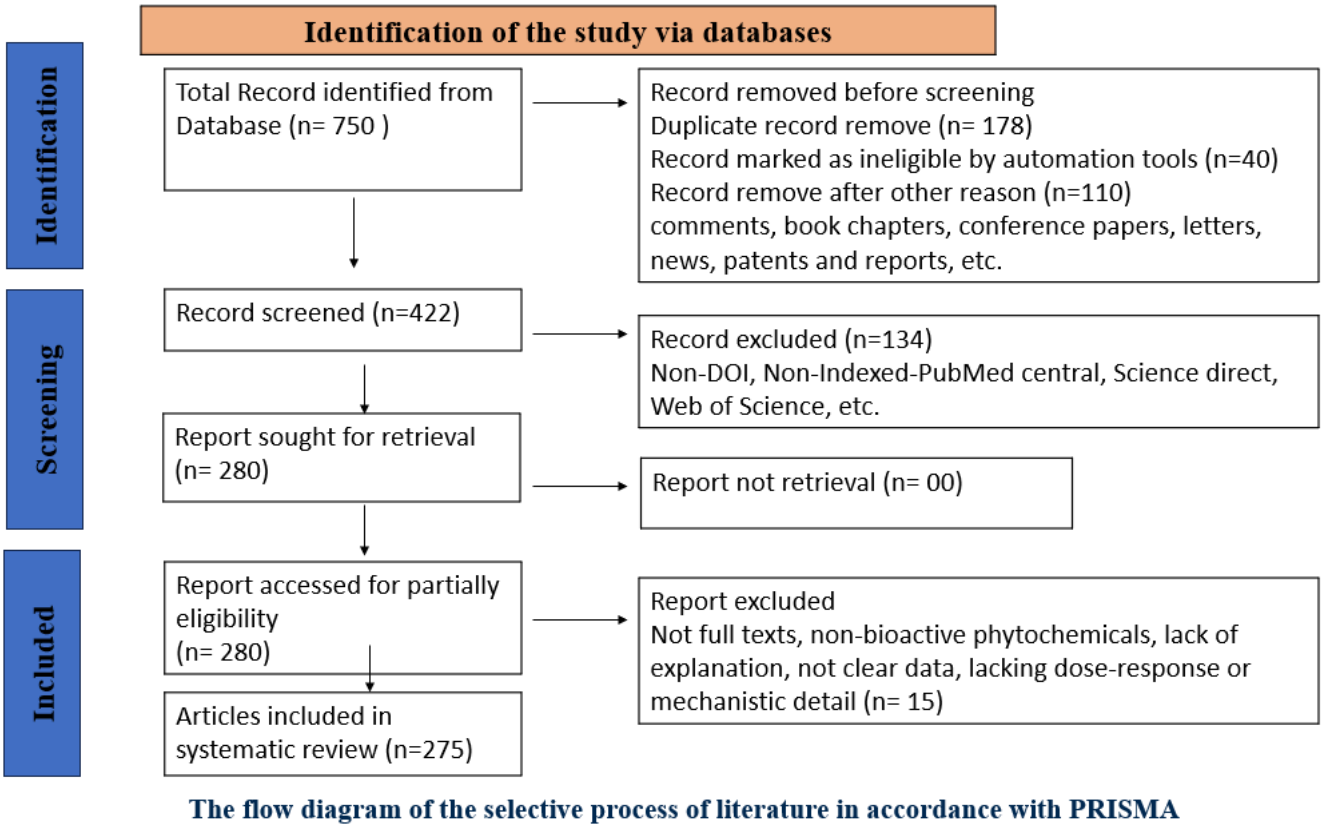


Figure 2

Follow diagram of PRISMA 2020 guideline

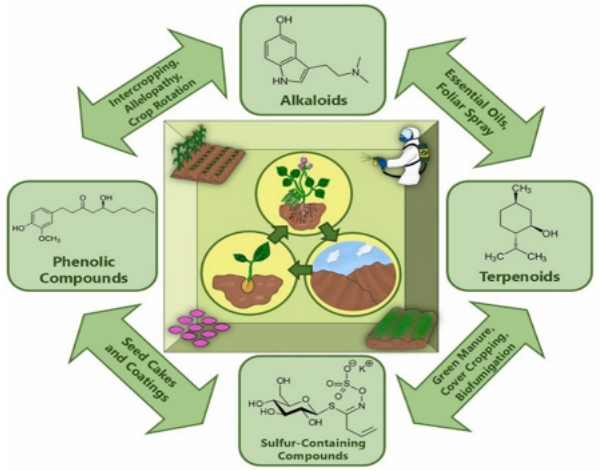


Figure 3

Phytochemicals diversity

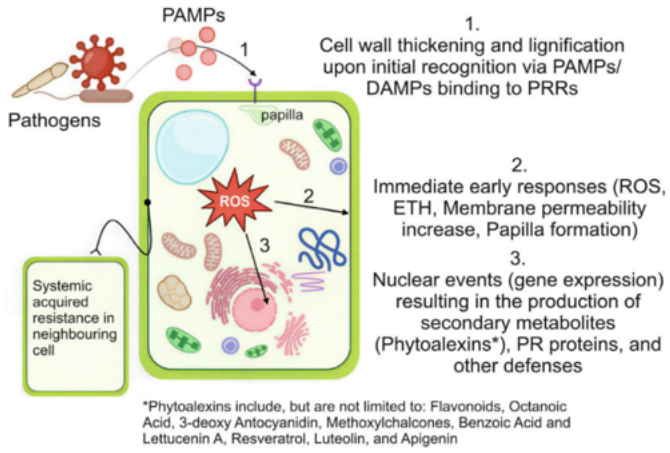


Figure 4

Mechanistic Actions in Human Health

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