CHAPTER N0.

15

Phytochemicals and Their Mechanism of Action

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Summary: Phytochemicals are bioactive substances that are naturally occurring plant metabolites with critical roles in plant defense and have significant contributions to human health. The compounds are flavonoids, alkaloids, terpenoids, tannins, phenolics, carotenoids and numerous others, which have various pharmacological activities like antioxidant, anti-inflammatory, antimicrobial, anticancer, antiviral, enzyme-modulating, hormonal, immunomodulating, and epigenetic. Their levels differ according to plant species, conditions, and distribution by the anatomy. Maceration, Soxhlet extraction, ultrasound-assisted extraction, and supercritical fluid extraction are the traditional and modern methods that allow the extraction of these compounds using improved yield and selectivity. Phytochemicals help in the prevention and treatment of chronic illnesses, such as cancer, heart disease, diabetes, neurodegenerative illnesses, and intestinal malfunctions. Clinical translation is hampered by their poor solubility and stability as well as bioavailability despite their therapeutic capability. Nanotechnology-based systems of delivery such as nano-encapsulation, liposomes and phytosomes, have potential solutions to improve absorption and targeted delivery. The discovery, characterization and application of phytochemicals is being transformed by emerging methods of using artificial intelligence, machine learning, personalized nutrition and sustainable bioprocessing. Further studies that aim at enhancing isolation, clinical trials, elucidation of the molecular mechanisms, and sustainable use of resources are necessary to ensure that the therapeutic and nutraceutical potential of phytochemicals can be fully realized.
Keywords: Medicinal plants, Ethnomedicine, Biological activity, Alternative Medicine, Herbal drugs

INTRODUCTION

Phytochemicals are chemical substances generated in plants as part of the regular metabolic process. Phytochemicals are physiologically active, organic substances found in plants that offer beneficial effects to humans as nutrients and therapeutic components (Hasler & Blumberg, 1999). They protect plants from destruction while also enhancing the plant's hue, scent, and taste. Typically, the chemical compounds produced by plants that defend against environmental threats like stress, disease, UV rays, drought, and pollution and are referred to as phytochemicals (Gibson et al., 1998).

They have recently been proven to have functions in protection of human health when taken in large quantities. Over four hundred and fifty phytochemicals have been so far identified and classified based on the protective mechanism, as well as the physical and chemical characteristics; of these, about three hundred and fifty phytochemicals have been extensively studied. Many phytochemicals, particularly pigment compounds like flavonoids and anthocyanin are often present in greater amounts in the outer parts of various parts of plants such as in fruits and leaves of vegetables. However, the concentration of these phytochemicals varies among plants depending on their variety and the climatic conditions of their growth. These agents possess biological properties such as antioxidant properties, antimicrobial properties, anticancer properties, amplifying immune response of the body, hormonal metabolism modulation, platelet aggregation and enzyme detoxification (Koche et al., 2016).

Phytochemicals use higher plants as storage for their products, which are significant in the pharmaceutical business. Some valuable medicinal characteristics are related with the various portions of plants, which occurs from the interplay of secondary metabolic products. Numerous kinds of phytochemicals exist in various plant species. Every one of these possesses distinct characteristics and purposes as well. These functions include nutritional advantages, physiological functions, anti-nutritional qualities, anti-oxidants, anti-cancer, pain relieving, phytotoxicity, anti-inflammatory, pro-oxidants and other pharmacological actions (Ganzera et al., 2005).

Antimicrobial agents prevent the growth of or eliminate microbes to manage their harmful effects, such as odor, discoloration, and degradation. Antibiotics, also referred to as antibacterial agents, combat bacteria, while antifungal agents target fungi. They can likewise be categorized based on their functions (Cowan, 1999). Alkaloids, carotenoids, flavonoids, ketones, phenolic compounds sesquiterpenes, steroids, tannins and triterpenoids are present in the pharmacological plants have been suggested to be link in antimicrobial activities (Sathianarayanan et al., 2010). Mahua, pomegranate, eucalyptus, and other plants have a wide range of therapeutic characteristics (Bains et al., 2020).

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MECHANISM OF ACTION

Antioxidant

Antioxidants are compounds that safeguard an organism's cells from harm caused by the harmful effects of reactive species. They function by inhibiting the oxidation of crucial macromolecules through various mechanisms like scavenging or chelating harmful radicals. Antioxidants can be categorized into enzymatic antioxidants such as GPX (glutathione peroxidase), superoxide, CAT (catalase), and dismutase and non-enzymatic antioxidants including mineral, glutathione (GSH), uric acid, vitamins C, E, ubiquinones, carotenoids, lycopene, polyphenols, and β-carotene antioxidants like Zn, Cu and Se. Antioxidants can be categorized based on their defense mechanisms. The primary defense consists of CAT, SOD, and GSH, whereas the secondary defense includes vitamins A, C, D, and E. The third defense line comprises coenzyme Q10, bioflavonoids, and carotenoids. Polyphenols are the key phytoconstituents with antioxidant ability. Phenolic compounds are thought to have antioxidant activity due to their high redox potential which allows them to be hydrogen donors, singlet oxygen quenchers and reducing agents. Polyphenols are major primary plant compounds that have antioxidant effects. They are considered to have high redox potential that makes them acting as reducing agents, hydrogen donors, and singlet oxygen quenchers, making them antioxidants. The antioxidant activity of the phenolic compounds strongly relies on the structure, particularly the electron delocalization of an aromatic core. The interaction of these compounds with the free radicals causes the electron of the phenolic antioxidant to be delocalized and the resonance effect of the aromatic nucleus stabilizes it, thereby preventing the free radical chain reaction. The presence of hydroxyl groups in position 3'-, 4'- and 5' of B-ring of phenolic compounds improves antioxidant activity in comparison to the presence of hydroxyl groups in a single phenol. Moreover, the presence of a hydroxyl group at 3 position and a conjugated, 2, 3, and 4-oxo group seems to contribute to the antioxidant properties (Hotta et al., 2010).

Almost all flavonoids can operate as antioxidants. The mechanisms and sequence of mechanisms through which free radicals can disrupt cellular function are not fully understood, but one of the most crucial seems to be lipid peroxidation, leading to damage of cellular membranes. This cellular harm causes a change in the overall charge of the cell, influencing the osmotic pressure, leading to swelling and ultimately cell death (Panche et al., 2016).

Anti-Inflammatory Agent

Inflammation represents the immune system's initial biological reaction to infection, harm, or irritation. Research indicates that the anti-inflammatory effect is achieved through the modulation of several inflammatory cytokines, including interferon gamma-γ, interleukins, nitric oxide, tumor necrosis factor alpha-α, along with the non-cytokine mediator, prostaglandin E2. Vegetables, Fruits and legumes are rich in phytochemicals that exhibit anti-inflammatory properties, yet their mechanisms of action remain not fully understood (Zhu et al., 2018). A diverse array of phytoconstituents contributed to anti-inflammatory properties, such as alkaloids, terpenoids and phenolics. Nonetheless, research has concentrated on a category of compounds to clarify the action mechanisms of herbs, define, and confirm their potential effectiveness as medicinal agents for treating inflammatory diseases. Multiple mode of actions has been suggested to clarify the anti-inflammatory effects of phytoconstituents, which generally involve;

- Activities related to antioxidation and scavenging of radicals
- Regulation of the cellular functions of inflammation-associated cells (macrophages, lymphocytes, neutrophils, and mast cells)
- Regulation of proinflammatory enzyme functions such as phospholipase A2, cyclooxygenase, and lipoxygenase, along with the nitric oxide, synthesizing enzyme, NOS (nitric oxide synthase)
- Regulation of the generation of additional proinflammatory substances
- Regulation of inflammation-promoting gene activity

Viruses, substances, and reactive oxygen/nitrogen species can all trigger the inflammatory process, increasing the production and secretion of proinflammatory cytokines. Unregulated stimulation of NF-κB/AP-1 and TNF-α signaling has shown that these factors play a crucial role in the connection between inflammation and chronic illnesses. Phytochemicals have been demonstrated to influence a variety of inflammatory processes. These modulations act as control points where the elevation of processes of inflammation can be unplugged, hence reducing the danger of following disorders (Bellik et al., 2013).

Modulators of Enzymes

There are metabolic enzyme inhibitions, which are competitive, non-competitive, and mechanism-based. The exposure of the phytochemicals to the detoxification systems in the body, such as phase I-oxidation, phase II-conjugation and phase III- transportation, can be experienced by the phytochemicals. In these processes, the phytochemicals may act as a competitive or non-competitive inhibitor of enzyme interaction with the substrates co-ingested with the phytochemicals such as carcinogens and medicines. The reaction between the phytochemicals and the enzymes of the metabolism may result in the formation of the reactive intermediates, some of which may result in the enzyme deactivation. This is referred to as mechanism based inhibition. The most widely reported instances of herbal constituents that restrain the activities of metabolic enzymes are those of sulfur and phenolic -containing compounds (Mandlekar et al., 2006). It was also found that flavonoids interact with transporter proteins (primarily plasma membrane ATP-binding cassette transporters) including P-glycoprotein. P-gp is composed of a membrane-bound localization area of ligand-specific binding and a cytosolic area of polynucleotide binding and hydrolysis (Di Pietro et al., 2002).

The application of a rational in vitro screening of the whole flavonoid family revealed that polyphenols prenylated selectively bind to P-glycoprotein and are effective in preventing drug interactions and nucleotide hydrolysis. NMR analysis revealed that flavonoids prevented the action of the mouse multidrug resistance transporter protein (MDR) by binding to the ATP-binding site of this protein (Nissler et al., 2004). Capsaicin (chili peppers), curcumin (turmeric), resveratrol (red wine or grapes) and sulforaphane (broccoli) have been shown to inhibit P-gp function and amplify the accumulation of the chemotherapeutic agent Daunorubicin in human multi-drug-resistant cancer cells (Nabekura et al., 2005).

Hormonal Activity

The transcription factors known as estrogen receptors (ERs) come in two varieties: Estrogen receptor alpha and Estrogen receptor beta. These ERs regulate common illnesses like lung cancer, breast cancer, osteoporosis, neurological conditions, and liver injuries. A variety of phytochemicals derived from different vegetables and fruits have been shown to have estrogen-like properties, and they are known as phytoestrogens. As ER modulators, estrogen-like compounds can be involved in the avoidance and management of numerous diseases as supplementary or alternative medicinal agents (Li et al., 2023).

Symptoms associated with menopause are the most well-documented of all phytoestrogen-related health effects in humans. There was no evidence in interventional trials on the possible effects of resorcylic acid lactones and coumestrol on hormonal symptoms in peri-menopausal and menopausal women, as these substances are toxic. Preparations containing alfalfa, clover, hops, kudzu, linseed, and soy are currently available on the food supplement market. Other plants, such as black sage, chaste raspberry, and sweet yam, are used to treat menopausal symptoms; however, their mechanisms of action are not exclusively estrogenic. Although results have been observed and validated by reviews, the effects of estrogen-related compounds on menopausal symptoms remain controversial (Canivenc-Lavier & Bennetau-Pelissero, 2023).

Immune System Modulator

Phytoimmunomodulators have shown to be important modulators of immune responses and serve as a helpful herbal remedy for individuals requiring herbal medicines to mitigate the side effects of synthetic drugs. They maintain our immune system in a vigilant state and are crucial for boosting cells that participate in both innate and adaptive immunological responses. The primary way they safeguard our body cells from oxidative harm and increase our immunity is by scavenging free radicals (Maheshwari et al., 2022). From a clinical viewpoint, immunomodulators can be grouped into three main types: immunoadjuvants, immunostimulants, and immunosuppressants.

Phytochemicals cause immunostimulation by boosting lymphocyte and antibody synthesis, T cell growth and maturation, proliferation of NK cells, monocytes proliferation, maturation and stimulation, releasing interleukin IL, enhancing DTH (delayed type hypersensitivity) feedback and macrophage activity. The immunosuppressive activity happens due to reduction of cytokine production, leukocyte suppression, blockage of antibody production, reduction of macrophage activity, and restriction of synthesis of iNOS (inducible nitric oxide synthase) (Jayaraman & Variyar, 2020).

The immunoadjuvant action is produced by activating the macrophage-monocyte system, strengthening the function of helper T cells, encouraging the increase of lymphocyte number, activating CD4+ and cytotoxic T cell responses, boosting antibody generation, stimulating DTH and by adjusting receptor expression (Banstola et al., 2020; Gorbet & Ranjan, 2020; Zhou et al., 2021).

Epigenetic Modulator

Epigenetic mechanisms control gene expression via genomic DNA methylation, chromatin remodeling, the expression of non-coding RNAs (such as microRNAs and long non-coding RNAs), and post-translational modifications of histones.

These mechanisms are regulated by particular classes of proteins that attach, eliminate or preserve specific chemical groups forming epigenetic marks that determine the suppression or activation of gene transcription (Pop et al., 2019). Unusual epigenetic alterations can disrupt essential cellular functions, such as the regulation of the cell cycle, cell communication, DNA repair mechanisms, apoptosis, inflammation, and stress response (Khan et al., 2024). Epigenetic modifications are dysregulated with serious health implications on humans, including metabolic syndrome, cancer, and neurodegenerative disorders, including Huntington's disease, Alzheimer's disease, and amyotrophic lateral sclerosis (Smith & Ryckman, 2015; Berson et al., 2018). However, those changes are reversible, which is a clear way of therapeutic treatment. Fruits, grains, spices, vegetables and medicinal herbs are some sources of plant secondary metabolites, which include terpenoids, phenolics, terpenes and sulfur containing compounds. Compounds derived in plants have been observed to demonstrate encouraging efficacy in targeting these abnormal epigenetic changes, including lycopene (epi-miRs), apigenin (histone acetylation), quercetin (DNA methylation and epi-miRs), berberine (DNA methylation), curcumin (histone acetylation and epi-miRs), genistein (histone acetylation and DNA methylation), etc (Khan et al., 2024).

Antiviral Agent

Numerous active phytochemicals, such as saponins, terpenoids, flavonoids, limonoids, polyphenolics, lignans, furyl compounds, sulphides, organosulfur compounds, coumarins, and alkaloids, etc. have demonstrated therapeutic uses against various functionally and genetically varied viruses. The antiviral action of these substances can be understood through their scavenging abilities, antioxidant properties, preventing viral entry, blocking DNA and RNA synthesis, or hindering viral replication, among others (Naithani et al., 2008).

Alkaloids prevent virus attachment, restrict the virus proliferation and lessen viral titers in pulmonary tissues (HIV, HSV). Lectins block viral penetration (HIV), reverse transcriptase and N-glycohydrolases. Terpenes (Saponin) suppress the virus reproduction (HSV, Influenza). Polyphenols prevent the viral cell access by altering the viral surface structure and impact the expression of viral proteins on the cell surface. Flavonoids have a suppressive influence on reverse transcriptase, inhibiting RNA synthesis (Kapoor et al., 2017).

Antibacterial Agent

Herbal remedies contain a variety of compounds, including alkaloids, tannins, coumarins, terpenoids, steroids, and antimicrobial peptides, that may serve as substitute or adjuncts to conventional antibiotics (Salarbashi et al., 2014; El Kolli et al., 2016; AlSheikh et al., 2020; Bazzaz et al., 2021). These compounds demonstrate their antimicrobial actions by many ways, which include (i) disrupting the structure of the bacterial cell, leading to increased permeability and leakage of cellular components, (ii) changes in the cell wall and cell membrane of bacteria, (iii) depletion of ATP, (iv) blocking protein synthesis, (v) causing intracytoplasmic damage, disturbances in pH, and DNA damage, and (vi) hindering quorum sensing in bacteria (Cheesman et al., 2017; Bazzaz et al., 2018; Gemeda et al., 2018; Fatemi et al., 2020).

SOURCES

Phytochemicals are bioactive substances that are highly distributed in fruits, vegetables, seeds, roots, and other parts of plants. An example is carotenoids ßß-carotene, which is found in high amounts in carrots, spinach, red peppers, and peaches, and is also found in fruit in berries, apples, and grapes, and vegetables in broccoli and cabbage (Kumar et al., 2023). Phenolics and carotenoids tend to be higher in roots and peels of vegetables; e.g., underground vegetable peels, including those of Beta vulgaris, Daucus carota, and Solanum tuberosum, have a higher level of phenolic (ranging between 930.0 and 1658.2 mg/100 g) and carotenoids (44.0 to 188.3 mg/100 g). Another significant group of phytochemicals is flavonoids, which are abundantly found in citrus fruits, tea leaves, and some herbs and have structural variation that leads to diverse biological activities (Dias et al., 2021).

METHODS OF EXTRACTION AND PURIFICATION

The isolation and extraction of phytochemicals should be selective in terms of high yield and bioactivity. Traditional methods, including maceration, percolation, infusion, decoction, and Soxhlet extraction, are quite popular, and novel methods include ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), supercritical fluid extraction (SFE), and enzyme-assisted extraction (EAE), which are more effective and selective (Altemimi et al., 2017). Such extraction parameters as the type of solvent, their polarity, temperature, duration, particle size and repetitions are essential factors in the determination of phytochemical yield. As an example, cold-water extraction may produce larger quantities of some phenolics than either hot-water extraction or sequential solvent organization (Moomin et al., 2023). After extraction, purification and isolation techniques like liquid-liquid partitioning, column chromatography and preparative HPLC are commonly used with identification being done by HPLC, GC-MS, or NMR.

HEALTH BENEFITS AND DISEASE PREVENTION

There are many health related benefits of phytochemicals as their pharmacological and therapeutic efficacy helps fight against many diseases like diabetes, cardiovascular diseases, cancer prevention, neurodegenerative disorders, gut problems and many more.

Cancer Prevention

Phytochemicals have been extensively investigated for their potential to combat cancer (Tabolacci et al., 2019). Numerous studies indicated the use of dietary phytochemicals has reduced the occurrence of cancer through safeguards that improve DNA repair, shield by strengthening our antioxidant enzymes, and numerous other measures (Wagh et al., 2020). Dietary elements including capsaicin, cucurbitacin B, catechins, isoflavones, lycopenes, piperlongumine, phenethyl isothiocyanate, and benzyl isothiocyanate have shown suppressive effects on cancer cells, suggesting they could act as chemopreventive agents (Ranjan et al., 2019). In a research, Zu et al. (2014) showed that increased consumption of lycopene correlated with reduced rates of prostate cancer. BITC (benzyl isothiocyanate) enhances the sensitivity of tumors towards chemotherapy and demonstrates considerable anticancer activity against many human cancers, including leukemia (Xu & Thornalley, 2000), hepatocellular carcinoma (Zhu et al., 2017), prostate cancer (Cho et al., 2016), breast cancer, lung cancer (Wu et al., 2010), colon cancer (Lai et al., 2010), and pancreatic cancer (Sahu & Srivastava, 2009). Soy-derived isoflavones, like genistein, have been proven to exert considerable anti-cancer properties against breast, leukemia, gastric, lymphoma, prostate, and non-small cell lung cancer (Sarkar & Li, 2002).

Cardiovascular Health

Various bioactive compounds typically sourced from terrestrial plants, including isoflavones, quercetin, diosgenin, catechin, sulforaphane, resveratrol, carotenoids, and tocotrienols have been found to lower the CVDs risk and contribute to cardioprotection (Vasanthi et al., 2012). Certain alkaloids decrease the risk of cardiovascular diseases and hypertension by acting as antioxidants, vasodilators, and anti-arrhythmic agents (Pagliaro et al., 2015; Pham et al., 2020). Reserpine is used for the treatment of hypertension and ajmaline is used to treat arrhythmias. Polyphenols consisting stilbenes, flavonoids, lignans and phenolic acid fight against inflammation, oxidative stress, and endothelial dysfunction in atherosclerosis and other CVDs (Bakoyiannis et al., 2019; Islam et al., 2021).

Tea, chocolate, berries, and citrus fruits are stuffed with flavonoids that boost nitric oxide bioavailability and improve endothelial function, leading to lowered BP (Khan et al., 2012; Darawsha et al., 2021). Plant sterols, also referred to as phytosterols, have a similar structure to cholesterol. Their

primary cardioprotective effect is to decrease the LDL cholesterol in serum by diminishing the intestinal uptake of dietary cholesterol (Cicero & Colletti, 2016; Haines et al., 2024).

Diabetes Management

Hyperglycemia represents one of the dominant circumstances that lead to different complications related to diabetes. The primary complications involve diabetic nephropathy, retinopathy, neuropathy, slow wound healing, heart attack, peripheral vascular issues and diabetic ketoacidosis (Teoh & Das, 2018). Various phytoactive substances like flavonoids, and phenols have been identified as agents that help address the issues arising from diabetes (Bacanli et al., 2019). Resveratrol is a polyphenol present in red wine, grapes, and certain other berries has potential effects on improving insulin sensitivity and in lowering the likelihood of these metabolic disorders. In addition, resveratrol enhances insulin signaling and promotes the absorption of glucose by adipose and muscle tissues, along with the enhancement of their mitochondrial activity. In this manner, insulin sensitivity and glucose metabolism improve (Offor et al., 2015). Flavonoids such as kaempferol, quercetin, and luteolin have shown effectiveness in protecting β-cells from damage induced by malfunction and programmed cell death (Aba & Asuzu, 2018).

Berberine, an alkaloid, suppresses inflammation, enhances glucose absorption in skeletal muscles, and also reduces the composition of the gut microbiota, elements that allow it to enhance insulin sensitivity to its peak level. Sulfur-rich sulforaphane is present in beneficial plants of the Brassica family, such as broccoli, cabbage, and Brussels sprouts. It is verified to generate antioxidative enzymes along with phase II detoxification enzymes which subsequently may shield the pancreatic β-cells from destruction caused by free radicals/inflammation. It also enhances insulin sensitivity and reduces blood sugar levels (Chukwuemeka et al., 2013).

Neuroprotection

Neurodegenerative diseases, namely Parkinson's disease (PD) and Alzheimer's disease (AD) are typically identified as conditions defined by the degeneration of neurons. Numerous studies have been performed to confirm the role of phytochemicals in treating these diseases (Velmurugan et al., 2018). Phytochemicals occur naturally and are demonstrated to provide protective effects against oxidative stress and neuroinflammation, key features of neurodegenerative diseases (Kim et al., 2010). The polyphenol most commonly present in tea leaves is epigallocatechin-3-gallate (EGCG), and over the last few decades, it has attracted significant attention for its ability to slow down neuron degeneration (Pervin et al., 2018).

Numerous investigations in neurodegenerative models indicate that berberine provides neuroprotective effects by modulating neurotrophin levels (Ji & Shen, 2011; Durairajan et al., 2012). Berberine has also been reported to inhibit the function of several enzymes associated with the advancement of Alzheimer's disease (Hsu et al., 2013). Curcumin is a polyphenol with inflammatory and antioxidant characteristics and is frequently utilized as a food additive to create neuroprotective benefits by regulating oxidative and inflammatory processes in the development of PD and AD (Frautschy et al., 2001; Lim et al., 2001; Wang et al., 2010).

Gut Health Maintenance

Phytochemicals positively impact humans and animals by modifying intestinal microflora through the selective stimulation of specific populations of bacteria in the gut, called "probiotics" (Peng et al., 2020). These consist of endosymbionts such as yeast, bacilli, and lactic acid bacteria that take part in the GI metabolism of humans and animals (Adjei-Fremah et al., 2018). Saponins, capsaicin, and polyphenols (quercetin, flavonoids, and catechins) show potential as phytochemicals for managing gut microbiota. These substances influence the chemical makeup of microorganisms, reducing harmful pathogens while boosting useful bacteria such as Bifidobacterium and Lactobacillus. Moreover, they encourage the production of bioactive compounds that possess antibacterial and anti-inflammatory effects. This focused approach, tailored to specific microbial profiles, could improve gut health, avert conditions such as diabetes and obesity, and optimize treatment outcomes (Singh et al., 2025). The alkaloids generated in tea and coffee plants function by inhibiting harmful bacteria, thus enhancing gut health (Clarke et al., 2019). Saponins, because of their detergent-like structure, influence the gut microbiota by altering cell membrane permeability and the adhesion of microbes to surfaces (Gamage et al., 2017).

FUTURE PERSPECTIVES

For numerous natural products, including phytochemicals, conducting extensive and meticulously regulated clinical trials is crucial to verify and substantiate their anticancer properties, side effects, and safety before they are utilized as anticancer medications/adjuvants. Additionally, comprehensive standardization grounded in contemporary methods should be conducted by assessing their effectiveness, ingredients, dosage schedule, quality, safety, bioavailability, production practices, as well as regulatory and approval processes, on the promising natural products to fulfill the quality and standards of international benchmarks. Despite the limited clinical applications of natural compounds arising from their low aqueous solubility, fast metabolism, specificity in targeting, decreased absorption, and decreased bioavailability, nanotechnology-based formulations are employed to address these challenges. Furthermore, there is insufficient understanding of the molecular interactions between natural compounds and different signaling molecules during the preclinical phase (Naeem et al., 2022).

MACHINE LEARNING IN PHYTOCHEMICAL DISCOVERY

The range of plant metabolites is huge-it has been approximated that there are millions of different compounds. The adoption of AI and machine-learning solutions is being welcomed to assist in analyzing large so-called omics datasets (metabolomics, genomics) to discover new phytochemical

structures, predict bioactivities and streamline extraction and formulation procedures (Varghese et al., 2025). This trend indicates that future research will make use of more and more computational tools to speed up the process of phytochemical screening and structure-activity prediction

NANOTECHNOLOGY AND ADVANCED DELIVERY SYSTEMS

The major limitation towards the translation of numerous phytochemicals to the clinical or nutraceutical market is poor bioavailability. It is mentioned that the use of Nano-encapsulation, phytosomes, liposomes, and other delivery systems will be used in future work in relation to the improvement of absorption, stability, and targeted delivery. Indicatively, reviews on functional-food applications observe that nano-encapsulation has the potential of increasing the efficacy of phytochemicals in human nutrition (Ahmed et al., 2025). Therefore, a way forward is to devote more effort into formulation science of phytochemicals, the area that may connect the gap between encouraging in vitro activity and practical application to people.

INDIVIDUALIZED NUTRITION AND LASER-GUIDED PHYTOCHEMICAL TREATMENT

Phytochemicals shall have a more part to play, as the science of nutrition shifts towards personalised or precision science. According to one of the recent editorials, the recommended intake of phytochemicals, the variability of responses (because of genetics, gut microbiota, etc.) and the functional response to phytochemicals have not been thoroughly investigated, despite the fact that phytochemical dietary intake is receiving growing attention. Thus, future studies can study the interaction of personal genetic and metabolic and microbiome profiles with phytochemicals and design specific dietary or therapeutic phytochemical regimens. Literature has highlighted that phytochemical studies are being synergized with sustainable food production, waste-valorization (e.g., use of agricultural/food industry by-products to extract bioactives), and use of plant resources to enable circular food economies.

CONCLUSION

To conclude, phytochemicals represent a diverse group of bioactive compounds, which play a crucial role in maintaining human health and preventing illness through complicated biochemical mechanisms. These are metabolites that are found in plants, such as alkaloids, flavonoids, terpenoids, phenolics, and saponins and they exert their therapeutic action by modulating cellular signaling pathways, gene expression, enzyme activity, and oxidative balance. Many phytochemicals interact with specific molecular targets, including receptors, transcription factors, and kinases, and influence such processes as apoptosis, angiogenesis, and immune modulation. The bioefficacy and therapeutic effects of different phytochemicals in the plant structures are enhanced by the overall action of different phytochemicals. Despite this fact that a lot has been done in terms of understanding their mechanisms, there are still problems associated with bioavailability, metabolism, and standardization of formulations containing phytochemicals. It is important to conduct continued interdisciplinary research that integrates phytochemistry, molecular biology and pharmacology so as to fully exploit their clinical uses. Overall, phytochemicals present an optimistic and scientifically proven foundation on the development of new preventive and therapeutic agents of nature.

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