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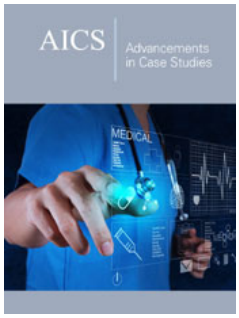
Plant-Derived Medicinal Compounds: Pharmacological Activities and Therapeutic Potential-A Mini Review

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Abstract

Plants produce a remarkable diversity of secondary metabolites that have served as a principal source of therapeutic agents throughout human history and that continue to inspire modern drug discovery. These plant-derived medicinal compounds-broadly classified as polyphenols and flavonoids, alkaloids, terpenoids, saponins and sulfur-containing metabolites-display antioxidant, anti-inflammatory, antimicrobial, anticancer, antidiabetic and immunomodulatory activities through the modulation of multiple molecular targets and signaling pathways. Representative molecules such as quercetin, curcumin, resveratrol, berberine, artemisinin, *paclitaxel*, *ginsenosides*, *cucurbitacins*, *sulforaphane* and *epigallocatechin gallate* illustrate the structural and mechanistic breadth of this chemical space, and several have become established drugs. Nevertheless, the clinical translation of most phytochemicals remains limited by poor aqueous solubility, low oral bioavailability, rapid metabolism and the variable standardization of plant extracts. This mini review summarizes the principal classes of plant-derived medicinal compounds, their pharmacological activities and mechanisms of action, and the key challenges that must be addressed to advance these molecules towards clinical application.

Keywords: Phytochemicals; Medicinal plants; Polyphenols; Alkaloids; Terpenoids; Drug discovery

Introduction

Natural products have historically been one of the most productive sources of new medicines, and a systematic analysis of the origin of small-molecule drugs approved between 1981 and 2019 confirmed that natural products, their derivatives and compounds inspired by natural pharmacophores together account for a very large proportion of all approved agents [1]. Plants, in particular, constitute a vast and chemically diverse reservoir of secondary metabolites that have evolved primarily as chemical defenses against herbivores, pathogens and abiotic stress [2,3]. Although industrial interest in natural-product screening declined during the 1990s, advances in genome mining, metabolomics, synthetic biology and computational target prediction have revitalized the search for plant-derived leads [1,2]. Ethnopharmacological knowledge-encompassing Ayurveda, Traditional Chinese Medicine, Unani medicine and other systems-continues to guide the identification of pharmacologically active plants and their constituents, and many modern drugs can be traced to traditional use [3]. The aim of this mini review is to provide a concise overview of the major classes of plant-derived medicinal compounds, their pharmacological activities and mechanisms of action, and the principal challenges that limit their clinical translation.

Major Classes of Plant-Derived Medicinal Compounds

The bioactive constituents of medicinal plants are conventionally grouped according to their biosynthetic origin and chemical structure. The principal classes are the

phenolic compounds (derived largely from the shikimate and phenylpropanoid pathways), the alkaloids (nitrogen-containing compounds derived mainly from amino acids), the terpenoids (built from isoprene units), and a heterogeneous group of sulfur- and nitrogen-containing metabolites, including glucosinolates and their isothiocyanate derivatives [3]. Saponins, which are glycosylated triterpenoid or steroidal aglycones, form an important sub-group of the terpenoid family [3]. Each class encompasses hundreds to thousands of individual structures, and a single plant frequently accumulates a complex mixture of compounds that act in a synergistic or additive manner [3]. This structural diversity underpins the broad, pleiotropic pharmacological profiles of plant extracts and distinguishes them from single-target synthetic drugs.

Phenolic Compounds and Flavonoids

Phenolic compounds are the most abundant and widely distributed class of plant secondary metabolites, ranging from simple phenolic acids to complex polymers such as tannins. Flavonoids-comprising flavanols, flavones, flavanones, flavan-3-ols, isoflavones and anthocyanidins-are the largest sub-group and share a common diphenyl propane skeleton; Their biological properties depend on the number and position of hydroxyl, methoxyl and glycosyl substituents [3]. Quercetin, a ubiquitous flavanol, displays antioxidant, anti-inflammatory, antiviral, antihypertensive and anti-diabetic activities and has been examined in a wide range of chronic and age-related diseases, supporting its consideration as a therapeutic product [4]. However, the clinical exploitation of flavonoids is constrained by extensive phase II metabolism and generally low systemic bioavailability [5].

Curcumin and Resveratrol: Representative Polyphenols

Curcumin, the yellow pigment of turmeric (*Curcuma longa*), exhibits potent anti-inflammatory, antioxidant and anticancer activities and interferes with numerous molecular targets, including the transcription factors NF-κB and STAT3 and multiple kinases and growth-factor receptors [6]. The therapeutic potential of curcumin is, however, severely limited by its low aqueous solubility, poor intestinal absorption and rapid metabolism and elimination [7]. Resveratrol, a stilbene found in grapes, red wine and several berries, has attracted attention for its cardioprotective, anti-inflammatory, antioxidant and anticancer effects and for its ability to modulate sirtuins and other longevity-associated pathways, with in vivo evidence supporting beneficial effects on cardiovascular and metabolic parameters [8]. Together, curcumin and resveratrol exemplify a recurring theme in this field: Remarkable preclinical activity coupled with formidable pharmacokinetic barriers.

Alkaloids

Alkaloids are a structurally diverse group of nitrogen-containing compounds with pronounced pharmacological activity. Their basic nitrogen atom readily forms hydrogen bonds and ionic interactions with biological targets, and many alkaloids act on enzymes, ion channels and neurotransmitter receptors; Consequently, alkaloids have furnished some of the most important plant-derived medicines [3]. The isoquinoline alkaloid berberine, obtained from Berberis and *Coptis* species, provides a well-studied example: It improves glucose and lipid homeostasis, exerts broad anti-inflammatory effects, and many of its metabolic benefits appear to be mediated through modulation of the gut microbiota and its metabolites [9]. Berberine therefore illustrates how a single biosynthetic class can yield compounds with activities spanning metabolic, inflammatory and gastrointestinal systems.

Terpenoids

Terpenoids (isoprenoids) constitute the largest and most diverse family of plant natural products, with more than 40,000 known structures, and include several clinically important drugs [3]. *Artemisinin*, a *sesquiterpene lactone* isolated from *Artemisia annua*, is the paradigmatic example: Its discovery, grounded in Traditional Chinese Medicine, provided the basis for *artemisinin*-based combination therapies, the first-line treatment for *Plasmodium falciparum* malaria, and earned the 2015 Nobel Prize in Physiology or Medicine [10]. *Paclitaxel* (Taxol), a complex diterpenoid originally isolated from the bark of the Pacific yew (*Taxus brevifolia*), stabilizes microtubules and blocks mitotic division, and remains one of the most important anticancer drugs in clinical use for breast, ovarian and lung tumors [11]. Ginsenosides, the triterpenoid saponins of *Panax ginseng*, display a wide spectrum of pharmacological activities; Ginsenoside Rg3, in particular, inhibits tumor growth, angiogenesis and metastasis, and its mechanisms and delivery strategies have been comprehensively reviewed [12]. *Cucurbitacins*, highly oxygenated tetracyclic triterpenoids characteristic of the *Cucurbitaceae* family, are potent cytotoxic compounds that inhibit the JAK/STAT and Wnt pathways and induce apoptosis and cell-cycle arrest, and they are regarded as promising anticancer leads [13]. These examples demonstrate the ability of individual terpenoids to engage diverse oncogenic and metabolic pathways.

Sulforaphane and Tea Catechins

Two further groups of compounds deserve mention for their strong association with dietary chemoprevention. Sulforaphane, an isothiocyanate derived from glucoraphanin in broccoli and other cruciferous vegetables, exerts chemo preventive and cytoprotective effects largely through activation of the Keap1-Nrf2-ARE pathway, induction of phase II detoxifying enzymes and inhibition of histone deacetylases [14]. Epigallocatechin Gallate (EGCG), the most abundant catechin in green tea (*Camellia sinensis*), displays antioxidant, anti-inflammatory and anticancer activities and targets multiple cancer hallmarks through the modulation of diverse signaling pathways [15]. Both compounds illustrate how common dietary plants can yield molecules with defined pharmacological mechanisms.

Mechanisms of Action

Despite their structural heterogeneity, plant bioactive compounds converge on a limited set of conserved mechanisms. The

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most frequently reported are antioxidant and anti-inflammatory actions: Polyphenols counteract oxidative stress both by directly scavenging reactive species and by upregulating endogenous antioxidant defenses, while simultaneously suppressing pro-inflammatory signaling cascades such as NF-κB and the NLRP3 inflammasome [3]. In addition, many phytochemicals modulate cell-death, metabolic and microbiota-related pathways, and a growing body of evidence indicates that the gut microbiota mediates part of the systemic effects of dietary phytochemicals [9]. The pleiotropic and often synergistic nature of these mechanisms helps to explain why plant extracts frequently produce effects that cannot be attributed to a single constituent or target [3].

Bioavailability and Translational Challenges

Notwithstanding their striking preclinical activities, the clinical translation of most plant-derived compounds remains limited by unfavorable pharmacokinetics. *Curcumin* is the classic example: It is poorly soluble in water, poorly absorbed, and rapidly conjugated and eliminated, resulting in extremely low systemic exposure after oral administration, and strategies such as absorption enhancers, lipid-based formulations and nanoparticle delivery systems are being developed to overcome this barrier [7]. Flavonoids and other polyphenols similarly undergo extensive phase II metabolism (glucuronidation, sulfation and methylation) in the intestine and liver, so that circulating concentrations of the parent compounds are typically far below those used *in vitro* [5]. The chemical standardization of herbal materials introduces an additional layer of complexity, because the content of bioactive constituents varies with plant genotype, geographical origin and processing, demanding rigorous quality control to ensure reproducible efficacy and safety [5]. Addressing these obstacles requires improved formulation and delivery technologies, mechanistic and pharmacokinetic characterization of active metabolites, and rigorous, well-controlled clinical trials. Encouragingly, several plant-derived compounds-among them artemisinin, paclitaxel, berberine and saponin-based adjuvants-have already achieved clinical use, demonstrating that these barriers can be surmounted when pharmacology, formulation science and clinical development are pursued systematically.

Conclusion

Plant secondary metabolites constitute an exceptionally rich and structurally diverse source of pharmacologically active compounds and continue to provide both essential medicines and valuable leads for drug discovery. The major classes-polyphenols and flavonoids, alkaloids, terpenoids and sulfur-containing isothiocyanates-exhibit antioxidant, anti-inflammatory, anticancer, antidiabetic and immunomodulatory activities mediated through a limited set of conserved molecular mechanisms, including direct antioxidant and anti-inflammatory actions and the modulation of the gut microbiota. Compounds such as quercetin, curcumin, resveratrol, berberine, artemisinin, paclitaxel, ginsenosides, cucurbitacins, sulforaphane and EGCG illustrate the breadth of this chemical space and the recurring challenge of poor bioavailability. Future progress will depend on the integration of advanced analytical and biosynthetic technologies, rational formulation and delivery strategies, and rigorous clinical evaluation, in order to convert the remarkable chemical diversity of plants into effective and reproducible therapies.

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