Phytochemical Profiling and Biological Activities of Medicinal Plant Extracts: A Comprehensive Review

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Abstract—Medicinal plants represent an immense reservoir of bioactive compounds with diverse pharmacological activities. This review provides a comprehensive examination of the phytochemical profiles and biological activities of selected medicinal plant extracts, with emphasis on modern extraction technologies, analytical profiling methods, and the molecular mechanisms underlying their therapeutic effects. The major classes of plant secondary metabolites reviewed include alkaloids, flavonoids, terpenoids, phenolic acids, and tannins, with detailed discussion of their biosynthetic pathways, chemical structures, and pharmacological targets. Modern extraction techniques covered include supercritical fluid extraction (SFE), ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), pressurized liquid extraction (PLE), and enzyme-assisted extraction (EAE). Phytochemical profiling of Moringa oleifera, Camellia sinensis (green tea), and Rosmarinus officinalis (rosemary) is presented using HPLC-MS, GC-MS, and NMR data. The antimicrobial activities of plant extracts, including synergistic interactions with conventional antibiotics, are examined alongside their antioxidant, anti-inflammatory, and anticancer properties. Quality control approaches, including chromatographic fingerprinting, marker compound quantification, and DNA barcoding for botanical authentication, are also discussed. This review highlights the potential of integrating traditional botanical knowledge with modern analytical and pharmacological methods for drug discovery and development.

Keywords—Phytochemistry, plant extracts, secondary metabolites, flavonoids, terpenoids, alkaloids, antimicrobial, anticancer, extraction techniques, quality control

I. INTRODUCTION

Medicinal plants have served as the foundation of traditional healing systems across all cultures throughout human history. The World Health Organization estimates that 25% of modern pharmaceutical drugs are derived directly or indirectly from plant sources, and approximately 11% of the 252 drugs considered essential by the WHO are exclusively of plant origin [1]. The scientific discipline of phytochemistry, which investigates the chemical constituents of plants and their biological activities, has become increasingly sophisticated with the advent of modern analytical techniques including high-performance liquid chromatography (HPLC), gas chromatography-mass

spectrometry (GC-MS), nuclear magnetic resonance (NMR) spectroscopy, and liquid chromatography-tandem mass spectrometry (LC-MS/MS) [2].

Plant secondary metabolites, including alkaloids, flavonoids, terpenoids, phenolic acids, tannins, saponins, and essential oils, are the primary bioactive compounds responsible for the therapeutic effects of medicinal plants. These compounds are produced by plants as part of their defense mechanisms against herbivores, pathogens, and environmental stressors, but they interact with numerous molecular targets in the human body, producing pharmacological effects that range from antimicrobial and anti-inflammatory to anticancer and neuroprotective activities [3, 4]. This review provides a comprehensive examination of the phytochemical profiles and biological activities of selected medicinal plant extracts, with emphasis on modern extraction techniques, analytical methods, and the relationship between chemical composition and pharmacological activity.

II. MODERN EXTRACTION TECHNIQUES FOR PLANT BIOACTIVE COMPOUNDS

A. Conventional Extraction Methods

Traditional extraction methods include maceration, percolation, Soxhlet extraction, and hydrodistillation. Maceration involves soaking the plant material in a solvent (typically ethanol, methanol, or water) for an extended period with occasional agitation, allowing passive diffusion of soluble compounds from the plant matrix into the solvent [5]. Soxhlet extraction provides continuous solvent recycling and is particularly effective for exhaustive extraction of lipophilic compounds. Hydrodistillation and steam distillation remain the standard methods for extracting volatile essential oils from aromatic plants. While these methods are well-established and inexpensive, they often require large volumes of organic solvents, prolonged extraction times, and may cause thermal degradation of heat-sensitive bioactive compounds [6].

B. Advanced Green Extraction Technologies

Supercritical fluid extraction (SFE) using carbon dioxide (CO2) as the primary solvent has emerged as a preferred green technology for extracting plant bioactive compounds. Supercritical CO2 (above 31.1 degrees Celsius and 73.8 bar) possesses liquid-like density and gas-like diffusivity, enabling rapid and efficient extraction of non-polar to moderately polar compounds without leaving toxic solvent residues [7]. Ultrasound-assisted extraction (UAE) uses acoustic cavitation to disrupt plant cell walls, enhancing mass transfer and reducing extraction time by 50-90% compared to conventional methods. Microwave-assisted extraction (MAE) employs microwave energy to heat the solvent and plant matrix simultaneously, accelerating the extraction process while improving yields of thermally stable compounds [8].

Pressurized liquid extraction (PLE), also known as accelerated solvent extraction (ASE), uses elevated temperatures (50-200 degrees Celsius) and pressures (100-150 bar) to maintain the solvent in a liquid state above its normal boiling point, significantly enhancing extraction efficiency. Enzyme-assisted extraction (EAE) employs cell wall-degrading enzymes (cellulase, pectinase, hemicellulase) to break down the plant cell wall matrix, facilitating the release of intracellular bioactive compounds and improving extraction yields by 30-60% [6, 9].

III. PHYTOCHEMICAL CLASSES AND THEIR BIOLOGICAL ACTIVITIES

C. *Alkaloids*

Alkaloids are nitrogen-containing heterocyclic compounds found in approximately 20% of plant species. Major classes include isoquinoline alkaloids (berberine, morphine), indole alkaloids (vinblastine, vincristine), tropane alkaloids (atropine, scopolamine), and purine alkaloids (caffeine, theophylline) [10]. Berberine, isolated from Berberis and Coptis species, has demonstrated significant biological activities including antimicrobial effects against Helicobacter pylori through inhibition of bacterial FtsZ protein assembly, anti-inflammatory activity through suppression of the NF-kB and MAPK pathways, hypoglycemic effects through activation of AMP-activated protein kinase (AMPK), and hypolipidemic effects through upregulation of LDL receptor expression [11, 12].

D. *Flavonoids*

Flavonoids constitute the largest group of plant polyphenols, with over 10,000 identified structures classified into flavones (apigenin, luteolin), flavonols (quercetin, kaempferol), flavanones (naringenin, hesperidin), flavan-3-ols (catechin, epicatechin), isoflavones (genistein, daidzein), and anthocyanins (cyanidin, delphinidin) [13]. The biological activities of flavonoids are attributed to their ability to scavenge reactive oxygen species (ROS), chelate transition metals, modulate enzyme activity, and regulate cell signaling pathways. Quercetin, found abundantly in onions, apples, and tea, inhibits COX-2 and 5-LOX, downregulates NF-kB activation, induces apoptosis in cancer cells through mitochondrial pathway activation, and enhances intestinal barrier function by upregulating tight junction protein expression (claudin-1, occludin, and ZO-1) [14, 15].

E. *Terpenoids*

Terpenoids (isoprenoids) represent the largest class of plant secondary metabolites, with over 55,000 identified compounds. They are classified by the number of isoprene units: monoterpenoids (C10: menthol, thymol, carvacrol), sesquiterpenoids (C15: artemisinin, bisabolol), diterpenoids (C20: taxol, forskolin), triterpenoids (C30: ursolic acid, oleanolic acid), and tetraterpenoids (C40: beta-carotene, lycopene) [16]. Thymol and carvacrol, the major monoterpenoids in thyme (Thymus vulgaris) and oregano (Origanum vulgare), exhibit broad-spectrum antimicrobial activity through disruption of bacterial cell membrane integrity, inhibition of efflux pumps, and interference with quorum sensing. These compounds have demonstrated efficacy against multidrug-resistant bacteria including methicillin-resistant Staphylococcus aureus (MRSA) and extended-spectrum beta-lactamase (ESBL)-producing Enterobacteriaceae [17, 18].

F. *Phenolic Acids and Tannins*

Phenolic acids are divided into hydroxybenzoic acids (gallic acid, ellagic acid, vanillic acid) and hydroxycinnamic acids (caffeic acid, ferulic acid, chlorogenic acid, rosmarinic acid). These compounds exhibit potent antioxidant activity through hydrogen atom transfer and single electron transfer mechanisms [19]. Tannins, high-molecular-weight polyphenols classified as hydrolyzable tannins (gallotannins, ellagitannins) and condensed tannins (proanthocyanidins), exhibit astringent, antimicrobial, and wound-healing properties. Ellagitannins from pomegranate (Punica granatum) are converted by gut microbiota to urolithins, which possess potent anti-inflammatory and anticancer activities and are considered postbiotics [20, 21].

IV. PHYTOCHEMICAL PROFILING OF SELECTED MEDICINAL PLANTS

G. Moringa oleifera (Drumstick Tree)

Moringa oleifera leaves contain a remarkably diverse phytochemical profile including isothiocyanates (moringin, the most abundant), flavonoids (quercetin-3-glucoside, kaempferol-3-glucoside), phenolic acids (chlorogenic acid, gallic acid), carotenoids (beta-carotene, lutein), vitamins (A, C, E), and minerals (calcium, iron, potassium). GC-MS and LC-MS/MS profiling has identified over 90 bioactive compounds in the leaf extract [22]. The isothiocyanate moringin has demonstrated potent anti-inflammatory activity through inhibition of iNOS, COX-2, and pro-inflammatory cytokine production, as well as anticancer effects through induction of apoptosis via the intrinsic mitochondrial pathway and inhibition of NF-kB-mediated cell survival signaling [23].

H. Camellia sinensis (Green Tea)

Green tea polyphenols, collectively known as catechins, constitute 30-42% of the dry leaf weight. The major catechins include epigallocatechin-3-gallate (EGCG, 50-80% of total catechins), epigallocatechin (EGC), epicatechin-3-gallate (ECG), and epicatechin (EC) [24]. EGCG is one of the most extensively studied plant polyphenols, with documented anticancer, cardioprotective, neuroprotective, anti-obesity, and antimicrobial properties. In cancer research, EGCG inhibits multiple signaling pathways including EGFR, PI3K/Akt/mTOR, Wnt/beta-catenin, and VEGF-mediated angiogenesis, while activating tumor suppressor pathways including p53 and AMPK [25, 26].

I. Rosmarinus officinalis (Rosemary)

Rosemary contains the phenolic diterpenes carnosic acid and carnosol (which account for over 90% of its antioxidant activity), rosmarinic acid (a hydroxycinnamic acid ester), and volatile monoterpenoids (1,8-cineole, alpha-pinene, camphor). HPLC-DAD-ESI-MS analysis has identified over 60 polyphenolic compounds in rosemary extracts [27]. Carnosic acid is a potent activator of the Nrf2-Keap1-ARE pathway, the master regulator of cellular antioxidant defense, leading to upregulation of phase II detoxification enzymes (glutathione S-transferase, NAD(P)H:quinone oxidoreductase 1) and heme oxygenase-1 (HO-1). This mechanism underlies the hepatoprotective, neuroprotective, and chemopreventive properties of rosemary extract [28, 29].

V. ANTIMICROBIAL ACTIVITIES OF PLANT EXTRACTS

The antimicrobial potential of plant extracts has gained renewed importance in the era of rising antibiotic resistance. Plant-derived antimicrobials act through multiple mechanisms that differ fundamentally from conventional antibiotics, making the development of bacterial resistance more difficult. These mechanisms include disruption of membrane integrity (thymol, carvacrol, eugenol), inhibition of nucleic acid synthesis (berberine, sanguinarine), inhibition of energy metabolism (plumbagin, juglone), inhibition of biofilm formation (catechins, curcumin), and potentiation of conventional antibiotics through efflux pump inhibition (piperine, reserpine) [30, 31].

Synergistic interactions between plant extracts and conventional antibiotics have been extensively documented. The combination of EGCG with beta-lactam antibiotics restores the susceptibility of MRSA by interfering with penicillin-binding protein 2a (PBP2a). Berberine combined with ciprofloxacin demonstrates synergistic activity against multidrug-resistant Pseudomonas aeruginosa through dual inhibition of DNA gyrase and the NorA efflux pump [32, 33]. These findings support the development of combination therapies incorporating plant-derived compounds as antibiotic adjuvants.

VI. ANTIOXIDANT AND ANTI-INFLAMMATORY ACTIVITIES

The antioxidant capacity of plant extracts is assessed through a battery of in vitro assays including DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging, ABTS (2,2-azino-bis-3-ethylbenzothiazoline-6-sulfonic acid) radical decolorization, FRAP (ferric reducing antioxidant power), ORAC (oxygen radical absorbance capacity), and CUPRAC (cupric reducing antioxidant capacity) assays. However, it is increasingly recognized that in vitro antioxidant assays do not necessarily predict in vivo efficacy, as bioavailability, metabolism, and tissue distribution significantly modulate the biological activity of dietary antioxidants [34].

The anti-inflammatory mechanisms of plant polyphenols operate at multiple levels of the inflammatory cascade. At the transcriptional level, compounds such as curcumin, resveratrol, and EGCG inhibit NF-kB nuclear translocation, suppress AP-1 activation, and activate the anti-inflammatory Nrf2 pathway. At the enzymatic level, flavonoids inhibit COX-1/2, 5-LOX, and phospholipase A2 (PLA2). At the cytokine level, plant polyphenols suppress the production of pro-inflammatory mediators (TNF-alpha, IL-1beta, IL-6, MCP-1) while enhancing the production of anti-inflammatory cytokines (IL-10, TGF-beta) [35, 36].

VII.ANTICANCER ACTIVITIES OF PLANT EXTRACTS

Plant-derived compounds represent a significant source of anticancer drugs, with vincristine, vinblastine (from Catharanthus roseus), paclitaxel (from Taxus brevifolia), camptothecin (from Camptotheca acuminata), and podophyllotoxin derivatives (from Podophyllum peltatum) being among the most successful anticancer agents in clinical use [37]. Current research focuses on the multi-targeted anticancer effects of plant polyphenols, which simultaneously modulate cell proliferation, apoptosis, autophagy, angiogenesis, metastasis, and drug resistance through epigenetic mechanisms including DNA methylation, histone modification, and microRNA regulation [38].

Curcumin, resveratrol, EGCG, and quercetin have demonstrated the ability to reverse epigenetic alterations in cancer cells by inhibiting DNA methyltransferases (DNMTs), modulating histone acetyltransferases (HATs) and histone deacetylases (HDACs), and regulating the expression of tumor-suppressive microRNAs (miR-34a, miR-21, miR-200 family). These epigenetic mechanisms provide a molecular basis for the chemopreventive properties of dietary polyphenols and support their potential role as adjuncts to conventional chemotherapy [39, 40].

VIII. QUALITY CONTROL AND STANDARDIZATION

Standardization of plant extracts is essential for ensuring reproducible therapeutic effects and is a critical requirement for regulatory approval. Modern quality control approaches employ chromatographic fingerprinting using HPLC-DAD, HPLC-ELSD, or UHPLC-QTOF-MS to generate characteristic chemical profiles that serve as identity markers for specific plant extracts [41]. Quantitative determination of marker compounds (active ingredients or characteristic constituents) is performed using validated analytical methods following International Conference on Harmonisation (ICH) guidelines for specificity, linearity, accuracy, precision, and robustness [42].

DNA barcoding has emerged as a complementary authentication tool for verifying the botanical identity of plant materials, particularly when morphological identification is difficult due to processing (powdering, extraction). The internal transcribed spacer (ITS) region of ribosomal DNA

and the maturase K (matK) and ribulose-1,5-bisphosphate carboxylase (rbcL) chloroplast genes are commonly used barcode markers for medicinal plant authentication [43].

IX. CONCLUSION

The phytochemical investigation of medicinal plants continues to yield valuable insights into the chemical diversity of nature and its potential for drug discovery and development. Modern analytical techniques have enabled comprehensive profiling of plant secondary metabolites, revealing the complex chemical architecture underlying the biological activities of traditional herbal remedies. The antimicrobial, antioxidant, anti-inflammatory, and anticancer properties of plant extracts are mediated through well-characterized molecular mechanisms that often involve multi-target activity, providing advantages over single-target synthetic drugs. However, challenges related to bioavailability, standardization, quality control, and clinical validation must be addressed to fully realize the therapeutic potential of medicinal plant extracts. The integration of traditional botanical knowledge with modern phytochemical, pharmacological, and biotechnological approaches holds great promise for the development of novel plant-derived therapeutics and nutraceuticals.

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