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Research Article

Plant Extracts in Modern Medicine: Review of Prospects and Challenges

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Abstract

Plant extracts and their bioactive constituents have long served as important sources of therapeutic agents and continue to contribute significantly to modern drug discovery and development. Their vast chemical diversity, multi-target pharmacological activities, and widespread use in traditional medicine make them valuable candidates for addressing current healthcare challenges. However, despite their therapeutic potential, the translation of plant-based products into evidence-based medicines remains constrained by issues such as chemical variability, lack of standardization, inconsistent clinical evidence, safety concerns, herb-drug interactions, contamination, regulatory fragmentation, and sustainability challenges. This review aims to examine the current prospects and challenges associated with the development and utilization of plant extracts in modern therapeutics. A narrative review approach was employed, drawing on peer-reviewed review articles, methodological papers, World Health Organization (WHO) guidance documents, and recent primary studies published between 2014 and 2025. Literature was retrieved from major databases, including PubMed, Scopus, ScienceDirect, and WHO publications, using relevant keywords related to phytomedicine, standardization, metabolomics, network pharmacology, herbal clinical trials, and regulatory frameworks. The review highlights several emerging opportunities that could enhance the clinical and commercial value of plant extracts. At the same time, significant barriers persist, including variability in chemical composition, limited high-quality clinical evidence, safety and toxicity concerns, contamination and adulteration risks, fragmented regulatory requirements, and supply-chain sustainability issues. Plant extracts remain promising sources of future therapeutics, but their successful integration into modern medicine requires coordinated efforts in standardization, safety assessment, clinical validation, regulatory harmonization, and sustainable production. Advances in analytical and biotechnological tools provide practical pathways for overcoming existing limitations and accelerating the development of safe, effective, and scientifically validated plant-based medicines.

Keywords

Plant Extracts, Phytochemistry, Metabolomics, Standardization, Prospects, Natural Products

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1. Introduction

Human use of medicinal plants dates back thousands of years, across diverse cultures. Contemporary pharmacology continues to rely heavily on plant-derived compounds: many clinically used drugs (or their prototypes) trace back to botanical origins [1]. As the chemical diversity of plants is vast and often exceeds what can be synthetically reproduced, systematic scientific exploration of plant extracts remains invaluable. Modern techniques chromatography, mass spectrometry, bioassays, molecular biology have enhanced the capacity to isolate, characterize, and test bioactive plant constituents [2]. However, translating traditional botanical knowledge into evidence-based therapies requires rigorous standardization, mechanistic elucidation, and clinical validation. Plants have been sources of medicinal agents for millennia; numerous cornerstone drugs (e.g., aspirin, paclitaxel, artemisinin) were derived from botanical sources or inspired by them. Interest in plant-derived therapeutics persists because of unmatched chemical diversity, multi-target pharmacology, and the social/cultural prevalence of traditional medicines [2]. At the same time, modern drug development demands rigorous standardization, safety evaluation, and clinical evidence areas where botanical products face major obstacles. In this review we examine both the prospects that create new opportunities for plant extracts in contemporary therapeutics and the challenges that require systematic solutions [2].

2. Search Approach

This narrative review synthesizes findings from peer-reviewed reviews, methodological papers, WHO guidance, and recent primary studies (2014-2025). Searches were performed across PubMed, Scopus, ScienceDirect, and WHO publications using keywords such as “plant extracts”, “phytomedicine”, “standardization”, “metabolomics”, “network pharmacology”, “herbal clinical trials”, “regulation herbal medicines”, and “antimicrobial plant extracts” [3]. Priority was given to recent high-quality reviews, WHO technical documents, and methodological guidance papers (e.g., on metabolomics and herbal clinical trials).

3. Prospects

There are a lot of scientific and technological opportunities in the arena of plant medicines. The most important ones are shown in the following Table:

Table 1. *Selected Prospects and their practical impact.*

Prospect	Practical impact / Example
Metabolomics fingerprints	Batch to batch comparability, detect adulteration (Salem et al., 2020)
Network pharmacology	Map multi-target effects; prioritize candidates (Chaachouay et al., 2024)
Synthetic biology	Scalable production of scarce metabolites (Chaachouay et al., 2024)
Nanotechnology	Improve bioavailability, targeted delivery (Latif et al., 2025)
Combo therapies for AMR	Potentiation of antibiotics, efflux pump inhibition (Vaou et al., 2021)

3.1. Metabolomics-Driven Standardization And Quality Control

Problem: botanical extracts are complex mixtures whose composition varies by genotype, environment, harvest time and extraction method.

Prospect: untargeted and targeted metabolomics (LC-MS, GC-MS, NMR) allow comprehensive chemical fingerprinting and quantitation of marker profiles, enabling robust batch-to-batch comparability and standardization [4]. Metabolomics can (a) define chemical fingerprints for identity and potency, (b) identify bioactive markers for potency assays, and (c) detect adulterants/contaminants supporting reproducible preclinical and clinical studies [4].

Evidence: methodological reviews and application papers show metabolomics workflows successfully standardize extracts and correlate chemical features with biological activity [5].

3.2. Systems and Network Pharmacology for Multi-Component Therapeutics

Plant extracts often produce polypharmacological effects (many constituents acting on many targets). Network pharmacology and systems biology frameworks help map compound target-pathway networks to (a) rationalize traditional multi-component uses, (b) prioritize candidate constituents, and (c predict off-target effects and synergistic interactions [5, 6]. Integrating metabolomics with network analysis accelerates the transition from empirical herbal use to mechanistic, evidence-

based therapies.

3.3. Synthetic Biology, Semi-Synthesis and SustainableSupply

High value plant metabolites (e.g., paclitaxel precursors, artemisinin) historically strained wild resources. Advances in synthetic biology and semi-synthesis allow microbial or plant-cell production of complex natural products, reducing ecological pressure and stabilizing supply [6]. This enables scalable manufacturing of lead compounds and analogues for optimization.

3.4. Advanced Formulation and Targeted Delivery (Nanotechnology)

Many plant compounds suffer poor solubility, instability, or low bioavailability. Nanoparticle-based delivery systems, lipid carriers, and prodrug strategies can improve pharmacokinetics, target delivery, and therapeutic windows, enabling previously unusable extracts or compounds to become clinically viable [6].

3.5. Combination Therapy and Antibiotic Resistance Mitigation

Plant extracts may contain constituents that inhibit bacterial efflux pumps, disrupt biofilms, or potentiate antibiotic activity; combining extracts with existing antibiotics could help counter antimicrobial resistance (AMR). Evidence shows plant compounds can act synergistically with conventional antimicrobials, offering an adjunctive strategy in AMR management [7].

3.6. Improved Clinical Trial Design and Evidence Synthesis

Recent methodological reviews call for larger, better-powered RCTs with chemically characterized extracts, pre-registered protocols, and standardized endpoints improvements that would substantially increase confidence in botanical therapies [7]. Embedding pharmacokinetic/pharmacodynamic (PK/PD) and biomarker studies in trials helps link chemistry to clinical effect.

4. Challenges Scientific, Regulatory, Safety, and Supply Chain Barriers

Plant-based medicines continue to show strong therapeutic potential, but several interconnected challenges limit their transition from traditional use to fully validated, globally accepted modern therapeutics [8]. These challenges fall into six major domains: Chemical variability, Poor clinical evidence, safety, regulatory, andSustainability. Each is explained below in Table 2 below and the details are itemized.

Table 2. Major challenges and recommended mitigations.

Challenge	Mitigation
Chemical variability	Metabolomics fingerprinting, multi-marker standards, GACP
Poor clinical evidence	Standardized extracts, larger randomized trials with PK/PD
Safety & interactions	Preclinical ADME/Tox, active pharmacovigilance, label warnings
Contamination/adulteration	testing, GMP, supplier audits
Regulatory fragmentation	International harmonization, WHO guidance adoption
Sustainability	Cultivation programs, synthetic biology, fair benefit sharing

4.1. Chemical Variability and Standardization Difficulties

Challenge: Natural variability (genotype, environment, phenology, processing) yields inconsistent chemical profiles. Traditional standardization (single marker compounds) can be insufficient; multi-marker or fingerprint approaches are needed but require investment in analytics and agreed standards [8]. Without standardization, reproducibility of pharmacology and clinical trials is poor.

4.2. Heterogeneity and Quality of Clinical Evidence

Many clinical trials of herbal extracts are small, open-label, or use poorly characterized preparations, producing inconclusive evidence [8]. This undermines regulatory approval and clinician confidence. Systematic reviews frequently call for multi-center, standardized, randomized, blinded trials with meaningful clinical endpoints.

4.3. Safety, Toxicity, and Herb-Drug Interactions

Plants produce potent bioactive molecules and may cause direct toxicity (e.g., hepatotoxicity, cardiotoxicity), or interact pharmacokinetically (CYP induction/inhibition) or pharmacodynamically with conventional drugs [8]. Limited post-marketing pharmacovigilance for herbal products in many regions exacerbates risk [8]. Careful toxicity testing, ADME profiling, and surveillance systems are essential.

4.4. Contamination, Adulteration and Poor Manufacturing Practice

Herbal products have been documented with heavy metals, pesticides, microbial contamination, and pharmaceutical adulterants, particularly in poorly regulated markets. Adulteration undermines safety and efficacy and damages trust [9]. Good Agricultural and Collection Practices (GACP) and Good Manufacturing Practice (GMP) adherence are uneven globally.

4.5. Regulatory Fragmentation and Evidentiary Expectations

Different jurisdictions classify botanical products inconsistently (dietary supplement vs. herbal drug vs. traditional medicine), producing fragmented regulatory pathways and variable evidentiary requirements (EMA, FDA, national authorities). This complicates global development and market access. WHO strategy documents call for harmonized standards and capacity building [9].

4.6. Intellectual Property, Benefit-Sharing, and Ethical Considerations

When plant leads are developed into commercial drugs, questions of traditional knowledge rights, access, and benefit-sharing arise. Compliance with the Nagoya Protocol and ethical engagement with indigenous communities are required but often inadequately addressed.

4.7. Sustainability, Biodiversity Loss and Supply-chain Constraints

High demand for wild-harvested medicinal plants can cause overexploitation. Sustainable cultivation, cultivation standardization, and synthetic/biotechnological production are necessary to prevent biodiversity loss and secure reliable supply [9].

5. Concrete Mitigation Strategies and Best Practices

5.1. Analytical and Standardization Strategies

1) Adopt metabolomics-based fingerprints (LC-MS/NMR) with chemometric QC thresholds rather than single-marker reliance [10].
2) Create public reference libraries for authenticated raw materials and extracts.
3) Standard operating procedures (SOPs) for cultivation, harvest time, drying, storage and extraction (GACP).

5.2. Clinical Development Recommendations

1) Preclinical pharmacology and toxicology must be done with the same chemically characterized extract that will be used in clinical trials.
2) Design RCTs that are adequately powered, randomized, double-blind, with clinically meaningful endpoints, PK/PD and biomarker substudies [10].

5.3. Safety and Pharmacovigilance Systems

1) Establish active pharmacovigilance for herbal products, integrating with national adverse event reporting systems.
2) Routine screening of marketed products for contaminants, adulterants, and reliable labeling [11].

5.4. Regulatory and Policy Actions

1) Harmonize regulatory pathways for botanicals through international guidance (WHO) and mutual recognition initiatives.
2) Provide development incentives (grants, public-private partnerships) for standardization and trials of high-priority botanical products.

5.5. Sustainability and Supply Solutions

1) Prioritize cultivation, good agricultural practices, and domestication of high-value species.
2) Support synthetic biology and plant-cell culture where ecological or scalability concerns exist [12].

6. Research Priorities and Future Directions

1) Invest in metabolomics and chemoinformatics to create public reference libraries linking chemistry to bioactivity [12, 13].
2) Fund multicenter RCTs for high priority botanical products using standardized extracts [13].
3) Combine omics, network pharmacology and AI for lead prioritization and to predict safety signals.
4) Scale sustainable production by supporting cultivation, domestication, and biotechnological synthesis [14, 15].
5) Strengthen regulatory harmonization and pharmacovigilance support low- and middle-income countries in building capacity to regulate and monitor herbal products [16].

7. Conclusion

Plant extracts hold considerable promise for modern therapeutics due to chemical diversity, multi-target action, and cultural acceptance. Modern analytical and biotechnological tools (metabolomics, systems pharmacology, synthetic biology, nanoformulations) open realistic paths to address historic limitations. However, overcoming variability and standardization problems, strengthening the quality of clinical evidence, ensuring safety through robust toxicology and pharmacovigilance, harmonizing regulatory pathways, and securing sustainable supply chains are essential. Coordinated, interdisciplinary action (scientists, regulators, industry, and communities) will be necessary to translate botanical promise into reliable, safe, and effective medicines.

Abbreviation

WHO	Worlh Health Organization
SOP	Standard Operating Procedure
AMR	Antimicrobial Resistance
GACP	Good Agricultural and Collection Practices
GMP	Good Manufacturing Practice
MS	Mass Spectroscopy
NMR	Nuclear Magnetic Resonance
LC	Liquid Chromatography

Author Contributions

Abubakar Ado Ibrahim: Conceptualization, Funding acquisition

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Sagir Isa Musa: Funding acquisition, Methodology

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Conflicts of Interest

The authors declared no conflicts of interest.

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