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Advanced technologies for herbal medicine development: Modern approaches to authentication, extraction, phytochemical analysis, and standardization

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Abstract

Background: Herbal medicines have formed an integral component of healthcare systems since ancient times and continue to play an important role in contemporary therapeutics. Given the growing global demand for herbal products, assurance of their quality, safety, and efficacy has become increasingly important. Advanced technologies for herbal medicine provide scientific approaches to improving plant identification, extraction, standardization, and quality control.

Methods: Relevant literature on herbal medicine technology was reviewed, with emphasis on plant authentication methods, chromatographic techniques, and advanced extraction procedures used in the analysis and standardization of herbal medicines. Modern analytical methods, including thin-layer chromatography (TLC), high-performance thin-layer chromatography (HPTLC), high-performance liquid chromatography (HPLC), column chromatography, and paper chromatography, play important roles in the separation, identification, and quantification of phytoconstituents.

Results: Advanced extraction methods, including supercritical fluid extraction, pressurized liquid extraction, and ultrasound-assisted extraction, enhance extraction efficiency while preserving the potency and stability of bioactive compounds.

Conclusion: Advanced technologies have increased the reliability of herbal medicines by improving their identification, testing, and preparation. Integrating traditional knowledge with scientific standards and rigorous regulation can support the safer and more reliable use of herbal remedies in contemporary healthcare.

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Highlights

What is current knowledge?

Herbal medicines are widely used; however, their quality, safety, and consistency can vary considerably. Appropriate identification, testing, and standardization therefore remain essential.

What is new here?

This article demonstrates how modern methods, including advanced extraction procedures, chromatographic techniques, and plant authentication, can improve the reliability and scientific rigor of herbal medicines.

Introduction

The medicinal use of herbs represents one of the oldest forms of healthcare known to humankind and has been practiced across diverse cultures for centuries (1). Despite substantial advances in synthetic pharmaceuticals, medicinal plants continue to play an important role in healthcare systems worldwide (2). Herbal medicines are widely preferred because of their natural origin, affordability, and therapeutic potential.

In recent years, growing interest in alternative and complementary medicine has driven rapid expansion of the global herbal market. However, inadequate standardization, variability in raw materials, and deficiencies in quality control have raised concerns regarding safety and efficacy (3,4). Advanced herbal medicine technology seeks to address these challenges through the application of scientific principles to plant identification, extraction, formulation, and quality assessment.

Herbal medicine technology integrates multiple disciplines, including pharmacognosy, phytochemistry, biotechnology, analytical chemistry, and pharmaceutical sciences (5,6). The development of advanced analytical and extraction techniques has substantially improved the isolation, characterization, and standardization of bioactive phytochemicals, thereby strengthening the scientific credibility of herbal medicines.

Methods

A systematic literature search was conducted to identify relevant evidence on advanced herbal medicine technology. Electronic databases, including PubMed, Scopus, Google Scholar, and ScienceDirect, were searched for articles published between 2010 and 2024. Search terms such as advanced herbal medicine technology, novel herbal medicine delivery systems, modern extraction techniques, standardization of herbal medicines, and phytopharmaceuticals were used individually and in combination.

Only English-language review articles, research papers, and authoritative reports addressing technological advances in herbal medicine development were included. A schematic workflow of advanced herbal medicine technology is presented in Figure 1, illustrating the stages from plant authentication to extraction, analysis, and standardization.

Figure 1. Schematic representation of the advanced herbal drug technology workflow

Regulatory and standardization aspects of herbal medicines

The global acceptance of herbal medicines depends largely on compliance with regulatory requirements and standardization protocols. International organizations, including the World Health Organization (WHO), the United States Food and Drug Administration (US-FDA), and the European Medicines Agency (EMA), have developed guidelines to ensure the quality, safety, and efficacy of herbal medicinal products.

WHO guidelines

WHO emphasizes adherence to Good Agricultural and Collection Practices (GACP) and Good Manufacturing Practices (GMP), as well as quality control of raw materials, including limits on microbial contamination, pesticide residues, heavy metals, and aflatoxins.

US-FDA perspective

In the United States, many herbal products are generally classified and regulated as dietary supplements when they are not intended to diagnose, treat, cure, or prevent disease. Products classified as dietary supplements must comply with current Good Manufacturing Practice (cGMP) requirements, including provisions concerning quality, safety, and appropriate labeling. However, when a product has been clinically developed and demonstrated to treat a disease, the Food and Drug Administration regulates it as either an over-the-counter or prescription drug and applies more stringent requirements.

EMA guidelines

EMA requires documentation of traditional use, safety data, pharmacovigilance, and quality specifications, including chromatographic fingerprinting and marker-based standardization.

Need for standardization

Standardization ensures batch-to-batch consistency, accurate identification of plant materials, and reproducible therapeutic effects. It includes:

1. Authentication of plant species
2. Phytochemical profiling
3. Quantification of marker compounds
4. Stability testing
5. Validation of analytical methods

These regulatory frameworks connect traditional herbal knowledge with modern scientific validation.

Advantages of herbal medicines

1. Herbal remedies can be effective in treating minor conditions such as burns, rashes, and wounds (1).
2. They may be useful in managing major chronic conditions, including heart failure, diabetes, hypertension, hyperlipidemia, arthritis, migraine, and depression. (6).
3. Herbal medicines are generally more economical and accessible than synthetic drugs (5).

Disadvantages of herbal medicines

1. Variability in plant sources may result in inconsistent therapeutic effects.
2. Herbal medicines often have a slower onset of action than conventional pharmaceuticals (6).
3. Side effects may be unknown or unpredictable.
4. There is a high risk of allergic reactions.

Applications of advanced herbal technology

1. Functional and designer foods
2. Cosmetics and personal care products
3. Biopesticides and agricultural formulations (6)

Plant identification and authentication

Accurate identification and authentication of medicinal plants are essential stages in herbal medicine development. The therapeutic efficacy of herbal formulations depends on the use of the correct plant species and plant part, as well as appropriate harvesting conditions and processing methods (7).

Taxonomic approach

Taxonomic identification involves documenting the botanical name, family, habitat, geographical location, collection season, and plant part used. Appropriate documentation helps ensure the authenticity of the raw material (7).

Macroscopic evaluation

Macroscopic evaluation involves assessing morphological characteristics, including size, shape, color, surface features, and texture, with the naked eye or under low magnification (1).

Microscopic evaluation

Microscopic analysis focuses on anatomical characteristics, including stomata, trichomes, fibers, starch grains, and vascular tissues, which are useful for distinguishing closely related species (1).

Chromatographic techniques in herbal analysis

Chromatographic techniques are widely used to separate, identify, and quantify phytochemicals in herbal medicines (8,9).

TLC: Rapid identification and fingerprint analysis (7).

HPTLC: High-resolution profiling and quality control (10).

HPLC: Qualitative and quantitative determination of bioactive compounds (3,8).

Column chromatography: Isolation and purification of phytochemicals (11,12).

Paper chromatography: Preliminary separation of water-soluble compounds (13-15)

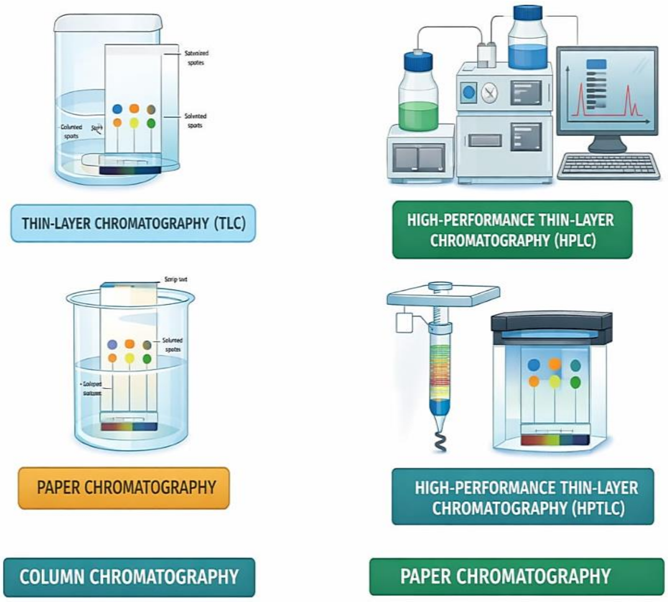

Figure 2. Overview of chromatographic techniques used in herbal medicine analysis

Advanced extraction techniques

Advanced extraction techniques, including supercritical fluid extraction, pressurized liquid extraction, and ultrasound-assisted extraction, improve extraction efficiency and selectivity while preserving thermolabile bioactive compounds.

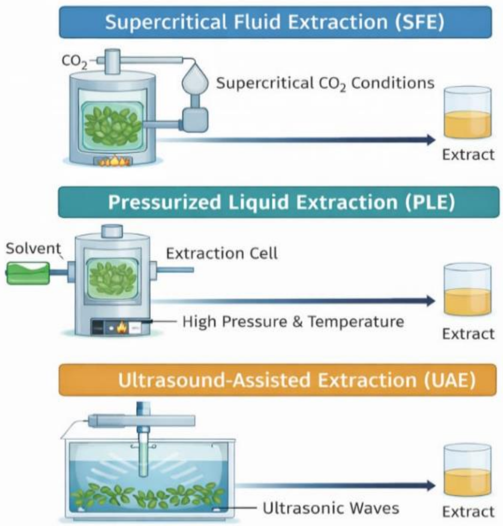

Figure 3. Overview of advanced extraction techniques, including supercritical fluid extraction, pressurized liquid extraction, and ultrasound-assisted extraction

Supercritical Fluid Extraction (SFE): Uses supercritical CO_2 as a solvent, enabling selective extraction, minimal solvent residues, and improved environmental safety (16-26).
Pressurized Liquid Extraction (PLE): Enhances extraction efficiency through elevated temperature and pressure while reducing solvent consumption (27-30).
Ultrasound-Assisted Extraction (UAE): Enhances extraction through acoustic cavitation, thereby reducing extraction time and energy consumption (31-33).

Conclusion

Advanced herbal medicine technology has contributed substantially to improving the quality, safety, and efficacy of herbal medicines. The application of modern plant-authentication methods, chromatographic techniques, and advanced extraction technologies promotes the standardization, reproducibility, and therapeutic reliability of herbal formulations. Integrating traditional knowledge with scientific validation can enhance the global acceptance of herbal medicines in contemporary healthcare. Strict adherence to international regulatory guidelines and standardized analytical procedures is essential for integrating herbal medicines into modern healthcare systems worldwide.

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Ethical Statement

Because this is a review article that does not involve original research data, ethical approval was not required.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Sakshi Anil Avhad contributed to the study conception, literature collection, and manuscript preparation. Kiran K. Shinde contributed to the critical review and supervision of the manuscript. All authors read and approved the final manuscript.

Data Availability Statement

Data sharing is not applicable because no new data were generated or analyzed in this study.

Use of Artificial Intelligence

No artificial intelligence tools were used in preparing this manuscript.

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