Technological Advancements in Herbal Medicine: Enhancing Efficacy, Safety, and Accessibility

Md Shamsuddin Sultan Khan [1]*, Saiful Islam [2], Chun Gunag Li [3], Mohsin Ahmed [4]

Abstract

Background: Herbal medicine, an ancient practice involving plant-based substances for therapeutic purposes, has been significantly transformed by modern technology. These advancements have enhanced the efficacy, safety, and accessibility of herbal remedies, addressing historical limitations related to accuracy and consistency in traditional methods. Methods: This review examines the historical context of herbal medicine and explores major technological advancements such as sophisticated extraction techniques, analytical methods, and formulation technologies. We analyze specific case studies and applications demonstrating the impact of these technologies, and discuss ongoing challenges and future directions for the field. Results: The integration of modern technologies has revolutionized the field of herbal medicine. Techniques like supercritical fluid extraction (SFE), pressurized liquid extraction (PLE), and microwave-assisted extraction (MAE) have significantly improved the efficiency, selectivity, and purity of herbal extracts. Advanced analytical methods, including high-performance liquid chromatography (HPLC) and nuclear magnetic resonance (NMR) spectroscopy, have enhanced the characterization and standardization of herbal products. Formulation technologies, such as nanotechnology and encapsulation, have increased the bioavailability and stability of herbal compounds. Conclusion: Technological advancements have addressed many traditional challenges in herbal medicine, leading to safer, more effective, and consistent products. However, issues related to regulatory approval, standardization, and the need for extensive clinical trials remain. Future research should focus on establishing global standards for herbal medicine production, conducting large-scale clinical trials, and exploring the potential of artificial intelligence and machine learning in predicting therapeutic outcomes and identifying new bioactive compounds. These efforts will ensure the continued evolution and integration of herbal medicine into modern therapeutic practices.

Keywords: Herbal medicine, Technological advancements, Traditional methods, Extraction techniques, Analytical tools.

Significance | This review describes the technology advancement in the herbal medicine field and their impact on developing extraction, quality assurance, and customized therapies for better treatment.

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Editor Muhammad Asif, Ph.D., And accepted by the Editorial Board April 18, 2019 (received for review February 11, 2019)

Introduction

Herbal medicine, a practice with roots stretching back thousands of years, has been central to human health and wellness across various cultures and civilizations. The reliance on plant-based substances for therapeutic purposes is well-documented in ancient texts, such as the Ebers Papyrus from Egypt, the Charaka Samhita from India, and the Materia Medica from China. These traditional practices laid the groundwork for modern herbal medicine, emphasizing the importance of a holistic approach to health, which integrates mind, body, and spirit (Ebbell, 1937; Dash, 2009; Unschuld, 1986).

The field of herbal medicine has undergone a significant

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Please Cite This:
Md Shamsuddin Sultan Khan, Saiful Islam (2019). "Technological Advancements in Herbal Medicine: Enhancing Efficacy, Safety, and Accessibility", Australian Herbal Insight, 1(1),1-12,20053

transformation with the advent of modern technology. The integration of advanced extraction methods, sophisticated analytical tools, and innovative formulation technologies has revolutionized the way herbal medicines are researched, developed, and utilized. These technological advancements have not only enhanced the efficacy and safety of herbal remedies but also addressed many historical challenges associated with the consistency and standardization of herbal products (Heinrich & Bremner, 2012).

Historically, the preparation and use of herbal medicines were based largely on empirical knowledge passed down through generations. While these methods were effective to some extent, they often lacked the precision required to meet contemporary therapeutic standards. The development of sophisticated technologies, such as supercritical fluid extraction (SFE), pressurized liquid extraction (PLE), and microwave-assisted extraction (MAE), has significantly improved the efficiency, selectivity, and purity of herbal extracts. These advancements have enabled the production of high-quality herbal products that meet rigorous regulatory and scientific criteria (Sekhon, 2011).

Moreover, the introduction of advanced analytical methods, such as high-performance liquid chromatography (HPLC), nuclear magnetic resonance (NMR) spectroscopy, and mass spectrometry (MS), has greatly enhanced the characterization and standardization of herbal medicines. These tools allow for precise identification and quantification of bioactive compounds in herbal products, ensuring their consistency and therapeutic efficacy. Furthermore, the application of nanotechnology and encapsulation techniques in herbal formulation has improved the bioavailability and stability of herbal compounds, making them more effective in treating various health conditions (Yang et al., 2012).

Despite these advancements, the integration of modern technology in herbal medicine is not without its challenges. Issues related to regulatory approval, standardization across different regions, and the need for extensive clinical trials persist. The complexity of herbal products, which often contain multiple active ingredients, adds to the difficulty in ensuring consistent quality and efficacy. Additionally, the global nature of herbal medicine requires the establishment of international standards to ensure uniformity in production and quality control (Heinrich & Bremner, 2012).

In conclusion, while modern technology has greatly enhanced the field of herbal medicine, ongoing research and development are necessary to overcome the remaining challenges. Future efforts should focus on conducting large-scale clinical trials, establishing global standards for herbal medicine production, and exploring the potential of artificial intelligence and machine learning in predicting therapeutic outcomes and identifying new bioactive compounds. These advancements will ensure the continued evolution and integration of herbal medicine into modern therapeutic practices (Heinrich & Bremner, 2012).

2.Historical Perspective

The use of plants for medicinal purposes is as old as human civilization itself. Ancient texts from various cultures, including the Ebers Papyrus from Egypt (Ebbell, 1937), the Ayurvedic texts from India (Dash, 2009), and the Materia Medica from China (Unschuld, 1986), provide detailed accounts of the medicinal properties of numerous plants. These traditional practices laid the foundation for modern herbal medicine, emphasizing the importance of holistic approaches to health and wellness (Heinrich & Bremner, 2012).

2.1 The Ancient Egyptian Medicine:

The Ebers Papyrus is among the earliest and most extensive medical manuscripts from ancient Egypt, dating to approximately 1550 BCE. It has more than 700 prescriptions and treatments, many of which call for the usage of juniper (*Juniperus communis*), garlic (*Allium sativum*), and aloe (*Aloe barbadensis*), among other plants. Egyptian doctors were adept in preparing and treating a wide range of illnesses, from skin conditions to stomach issues, with these herbal remedies (Ebbell, 1937).

2.2 Ayurveda:

Ayurveda is a traditional form of medicine that has been used for over 3,000 years in India. Many medicinal plants and their applications are described in Ayurvedic classics, such as the Sushruta Samhita and the Charaka Samhita. In Ayurvedic medicine, plants like neem (*Azadirachta indica*), ashwagandha (*Withania somnifera*), and turmeric (*Curcuma longa*) play crucial roles. These books containing the text strongly emphasize the use of natural remedies to preserve health and fend against illness, as well as the significance of balance in the body's systems (Dash, 2009).

2.3 Traditional Chinese Medicine (TCM):

Herbal medicine plays a major role in Traditional Chinese Medicine (TCM), which has a millennium-long history. Hundreds of medicinal plants and their therapeutic applications are listed in the Materia Medica, a book credited to the ancient Chinese herbalist Shen Nong. In Traditional Chinese Medicine (TCM), ginseng (*Panax ginseng*), ginger (*Zingiber officinale*), and licorice (*Glycyrrhiza glabra*) are among the herbs used by the practitioners to help the body regain harmony and balance (Unschuld, 1986).

2.4 The Unani Medicine:

Greco-Arabic medicine, or Unani medicine, is based on the theories of classical Greek physicians like Hippocrates and Galen. These theories were then expanded upon and improved

upon by scientists from the Arab and Persian worlds, most notably Avicenna (Ibn Sina). The Unani medical system uses a range of plant-based medicines and emphasizes the equilibrium of the body's humors (blood, phlegm, yellow bile, and black bile).

Avicenna's Canon of Medicine (Al-Qanun fi al-Tibb) and other Unani books contain extensive information about the application of herbs in treating a wide range of illnesses (Gruner, 1930). Senna (*Senna alexandrina*), saffron (*Crocus sativus*), and fennel (*Foeniculum vulgare*) are common herbs used in Unani medicine.

Traditional herbal medicine preparation methods typically involve simple techniques such as drying, powdering, boiling, and macerating plants to extract their active compounds. While these methods were effective to some extent, they often resulted in products with variable potency and purity. The lack of standardization and quality control posed significant challenges to the scientific community's widespread acceptance of herbal medicines (Heinrich & Bremner, 2012).

3. Traditional Methods and Challenges:

Herbal medicines were traditionally made using basic processes like drying, powdering, boiling, and macerating plants to extract their active ingredients. Although these techniques yielded products with varying potencies and purity levels, they were effective. The scientific community faced significant obstacles in widely accepting herbal medications because of the absence of standards and quality control (Figure 1, Table 1).

4. Technological Advancements in Herbal Medicine

Herbal medicine has gained popularity since the development of modern science and technology. Thanks to methods like mass spectrometry, chromatography, and molecular biology, the identification and measurement of active plant chemicals may now be done with greater accuracy. Standardized extracts and formulations have enhanced herbal remedies' safety, effectiveness, and uniformity (Heinrich & Bremner, 2012).

5. Extraction Techniques

Modern extraction techniques have revolutionized how active compounds are isolated from medicinal plants. Techniques such as chromatography, mass spectrometry, and molecular biology have allowed for more precise identification and quantification of active compounds in plants. This has led to the development of standardized extracts and formulations, improving the consistency, efficacy, and safety of herbal medicines. While still in use, traditional methods such as maceration and decoction have been supplemented by advanced techniques that offer higher efficiency, selectivity, and purity.

6. Supercritical Fluid extraction (SFE)

Supercritical Fluid Extraction (SFE) is a widely used method to extract desired components from plant matrices using supercritical fluids as solvents (Figure 2). A supercritical fluid is a substance that exhibits properties intermediate between those of a liquid and a gas, achieved when the substance is subjected to temperature and pressure conditions above its critical point (King, 2014; Choudhary & Sekhon, 2011). For carbon dioxide (CO_2), the critical temperature is 31.1°C (87.9°F), and the critical pressure is 73.8 bar (1070 psi). Above these conditions, CO_2 becomes a supercritical fluid, allowing it to diffuse through solids like a gas and dissolve substances like a liquid (Reverchon & De Marco, 2006).

Supercritical CO_2 is the most commonly used solvent in SFE due to its advantageous characteristics, such as being non-toxic, non-flammable, and environmentally friendly. The SFE process typically involves several steps. First, the plant material is dried and milled into a fine powder to maximize the surface area for extraction. This prepared material is then loaded into an extraction vessel. Supercritical CO_2 is generated by pumping CO_2 to conditions above its critical temperature and pressure, creating the supercritical fluid (Herrero, Cifuentes, & Ibañez, 2006). During the extraction phase, the supercritical CO_2 passes through the plant material, dissolving the target bioactive components (Herrero et al., 2006). The extracted compounds and CO_2 are then sent to a separator, where the reduction in pressure causes the CO_2 to revert to its gaseous state, separating it from the extracted compounds (Reverchon & De Marco, 2006). Finally, the extracted components are collected for further use and processing.

This method is particularly advantageous for isolating bioactive compounds while maintaining their stability and avoiding the use of harmful organic solvents, making it a preferred technique in industries such as pharmaceuticals, food, and cosmetics.

Supercritical Fluid Extraction (SFE) offers numerous advantages, making it a preferred method for isolating bioactive compounds. One of its primary benefits is its ability to perform selective extraction, enhancing the purity and potency of extracts by adjusting the pressure and temperature to target specific components (Herrero et al., 2006). Additionally, SFE utilizes carbon dioxide (CO_2) as a solvent, which is non-flammable, non-toxic, and environmentally friendly. The CO_2 completely evaporates after the extraction process, leaving no residual solvents in the final product (Reverchon & De Marco, 2006).

The method also preserves the bioactivity of heat-sensitive compounds due to the relatively low temperatures used during the process (King, 2014). Furthermore, SFE is a fast and efficient extraction technique, often outperforming conventional methods in terms of extraction efficiency and yield (Reverchon & De Marco, 2006). As a green extraction technology, SFE has minimal environmental impact since CO_2 can be recycled within the system, aligning with sustainable practices (Herrero et al., 2006).

SFE is widely applied in the extraction of essential oils, nutraceuticals, and phytopharmaceuticals. Notable examples include the extraction of curcumin from turmeric (Curcuma longa), as well as cannabinoids and terpenes from cannabis

(Cannabis sativa) (Herrero et al., 2006; King, 2014; Reverchon & De Marco, 2006). These applications demonstrate the versatility and efficiency of SFE in producing high-quality extracts for use in various industries, including pharmaceuticals, food, and cosmetics.

7. Pressurized Liquid Extraction (PLE) Combined with Ultrasound-Assisted Extraction (UAE):

Pressurized Liquid Extraction (PLE), also known as Accelerated Solvent Extraction (ASE), is an advanced method used to extract bioactive compounds from plant materials. This technique involves the use of solvents at elevated pressures and temperatures to optimize the extraction process for greater efficiency and speed (Mustafa & Turner, 2011; Choudhary & Sekhon, 2011). The process begins with preparation, where plant material is dried and milled into a fine powder to increase its surface area for extraction. The prepared material is then loaded into an extraction vessel, and a suitable solvent—such as water, ethanol, or a mixture of both—is pumped into the chamber. The extraction cell is subsequently pressurized up to 200 bar and heated to temperatures typically ranging from 50°C to 200°C (Wang & Weller, 2006). Under these conditions, the solvent penetrates the plant material more effectively, dissolving the target compounds. The solvent containing the extracted compounds is then collected and evaporated to concentrate the extract (Herrero, Cifuentes, & Ibañez, 2006).

PLE offers numerous advantages over traditional extraction methods. It is highly efficient, significantly reducing extraction time and solvent consumption while providing superior performance (Mustafa & Turner, 2011). Additionally, PLE enables selective extraction of specific compounds by adjusting the temperature and pressure settings (Wang & Weller, 2006). The method is environmentally friendly, often utilizing green solvents such as water or ethanol, thereby minimizing the environmental impact (Herrero et al., 2015). Moreover, PLE achieves higher yields and purer bioactive compounds compared to conventional techniques (Mustafa & Turner, 2011).

To further enhance efficiency and improve the purity and yield of the extract, a pre-treatment using ultrasonic waves can be applied at the start of the process. During this ultrasound-assisted pre-treatment, cavitation bubbles form in the solvent and burst, creating microjets that break down plant cell walls. This mechanical action facilitates the release of bioactive compounds, improving the overall extraction efficiency (Mason & Chemat, 2011). Together, PLE and ultrasound-assisted pre-treatment represent powerful tools for extracting high-quality bioactive compounds for use in various applications.

7. Microwave Assisted Extraction (MAE):

Microwave-Assisted Extraction (MAE) is a cutting-edge method that efficiently extracts bioactive compounds from plant materials by heating liquids in contact with the materials using microwave radiation (Figure 3). This technique offers several advantages over traditional methods, utilizing the unique heating properties of microwaves to enhance the efficiency and effectiveness of the extraction process (Zhang et al., 2011; Choudhary & Sekhon, 2011). The MAE process begins with the preparation of plant material, where it is dried and ground into a fine powder to maximize the surface area for extraction. The powdered material is then combined with a suitable solvent in a microwave-transparent container. When microwave radiation is applied, the microwaves penetrate the container, rapidly heating the solvent and plant tissues. This localized heating breaks down cell walls, facilitating the release of intracellular bioactive compounds into the solvent (Eskilsson & Björklund, 2000). Once the extraction is complete, the mixture is filtered to separate the liquid extract, which contains the desired bioactive components, from the solid plant residues (Chemat et al., 2012).

By leveraging microwave-induced rapid heating, MAE improves extraction efficiency and reduces processing time. This innovative approach represents a significant advancement in bioactive compound extraction technology, finding applications across various industries, including pharmaceuticals, nutraceuticals, and cosmetics.

Microwave-Assisted Extraction (MAE) offers numerous advantages over conventional extraction techniques, making it a preferred method in various applications. One significant advantage of MAE is its efficiency, as it significantly reduces extraction time, often completing the process in just a few minutes (Zhang et al., 2011). Additionally, the method enables increased extraction yields by effectively breaking down plant cell walls, thereby facilitating the release of bioactive compounds (Chemat et al., 2012). MAE also requires less solvent compared to traditional methods, making it an environmentally friendly and sustainable choice (Lucchesi et al., 2004). Furthermore, its rapid heating and short processing times result in lower energy consumption, enhancing its cost-effectiveness (Zhang et al., 2011). MAE ensures superior quality of extracts, especially for heat-sensitive compounds, by minimizing thermal degradation (Eskilsson & Björklund, 2000).

The efficiency of MAE can be attributed to two primary mechanisms. First, dielectric heating occurs when microwaves cause polar molecules, such as water, to oscillate, generating heat. This heat aids in breaking down cell walls and increasing the solubility of target compounds, thereby enhancing the extraction process (Chemat et al., 2012). Second, enhanced mass transfer results from pressure differentials within the plant matrix caused by

rapid heating and cooling cycles, which promote the release of bioactive compounds into the solvent (Zhang et al., 2011).

MAE is widely used for extracting various bioactive compounds, including carotenoids from single cells, taxanes from Taxus biomass, essential fatty acids from microalgae and oilseeds, phytosterols from medicinal plants, polyphenols from green tea, and essential oils from multiple sources. This technique is also instrumental in producing cost-effective herbal extracts, making it valuable in the nutraceutical, pharmaceutical, and cosmetic industries (Chemat et al., 2012; Lucchesi et al., 2004; Zhang et al., 2011) (Table 2).

8. Solid Phase Extraction (SPE)

Solid-phase extraction (SPE) is a widely utilized sample preparation method for isolating, concentrating, and purifying analytes from complex matrices, including herbal materials. It relies on a solid adsorbent material, typically housed within a cartridge or disk, to selectively extract specific target compounds from a liquid sample (Chen, Qu, & Qiu, 2010; Choudhary & Sekhon, 2011). The SPE process involves several key steps:

Conditioning: The SPE cartridge is conditioned with a solvent to activate the solid phase and prepare it for sample loading.

Sample Loading: A liquid sample containing the herbal extract is introduced to the SPE cartridge, where target analytes are adsorbed onto the solid phase (Chen et al., 2010).

Washing: Unwanted matrix components are removed by washing the cartridge with a solvent, leaving only the target analytes bound to the solid phase.

Elution: An appropriate solvent is used to elute the adsorbed analytes, yielding a concentrated and purified extract in the eluted solution (Kim, Goodner, Park, & Choi, 2011).

Solvent Removal: The solvent is evaporated from the eluted solution, leaving the isolated target compounds, which may undergo further filtration to complete the extraction process.

SPE offers numerous advantages. It enhances selectivity, enabling the selective extraction of target analytes and improving the purity of the final extract (Chen et al., 2010). The method also boosts concentration, as it can isolate analytes from large sample volumes, enhancing sensitivity for subsequent analyses (Kim et al., 2011). Additionally, SPE is highly efficient, allowing for the simultaneous processing of multiple samples, thereby increasing throughput (Chen et al., 2010). Another benefit is its ability to significantly reduce interference from the sample matrix, resulting in cleaner extracts and more reliable analytical outcomes (Kim et al., 2011).

SPE is particularly effective for extracting polyphenols from plants for analytical purposes and isolating alkaloids from medicinal plants, which can then be further purified for therapeutic applications (Kim et al., 2011; Chen et al., 2010). Its versatility and precision make it a preferred method for the preparation of herbal extracts in various scientific and industrial applications.

9. Analytical Techniques

The characterization and standardization of herbal medicines have been greatly enhanced by modern analytical techniques. High-performance liquid chromatography (HPLC) and gas chromatography-mass spectrometry (GC-MS) are widely used to identify and quantify bioactive compounds in herbal extracts. These techniques provide high sensitivity, resolution, and reproducibility, ensuring the consistency and quality of herbal products.

9.1 High-Performance Liquid Chromatography (HPLC)

HPLC functions according to the chromatographic principles, which include separating a mixture into its constituent parts by means of interactions between a stationary phase and a mobile phase. There are essentially two types of HPLC techniques: high-pressure HPLC (pressure greater than 20 bar) and low-pressure HPLC (usually under 5 bar)used for the isolation and purification of herbal compounds (Choudhary, N., & Sekhon, B. S. ,2011; Snyder, Kirkland, & Dolan, 2011). The most effective method for quality control of the Chinese herbal medication Gan-Cao (licorice) at the moment is the combination of HPLC and LC/MS (Choudhary, N., & Sekhon, B. S. ,2011). In analytical HPLC, the degree of solute purity and the amount of chemical that can be produced in a unit of time are key factors to take into account, along with resolution, sensitivity, and rapid analysis time. Can separate complex mixtures into individual components with high precision also capable of detecting compounds at very low concentrations (ppm to ppb levels) (Snyder et al., 2011; Zuo et al., 2002). It is applicable to a wide range of compounds, including non-volatile and thermally unstable substances and also provides precise and accurate quantification of compounds (Fan & Qian, 2005; Kim & Kim, 2002).

9.2 High-Performance Thin Layer Chromatography (HPTLC):

An improved version of thin-layer chromatography (TLC) that provides increased resolution, sensitivity, and repeatability is called high-performance thin-layer chromatography (HPTLC) (Choudhary, N., & Sekhon, B. S. ,2011). Similar to TLC, HPTLC uses the same fundamental principles to separate compounds according to how well they adhere to a stationary phase (usually a silica gel plate) and a mobile phase (a solvent system). Nevertheless, HPTLC uses more sophisticated methods and tools to get better outcomes, such as using automated applicators, chromatographic developments, UV detectors for detection, and documentation software that generates detailed chromatograms (Wagner & Bladt, 1996; Reich & Schibli, 2007; Harborne, 1998). It has certain advantages over HPLC, such as providing a clear separation of compounds, which helps in the identification of individual compounds with the capability of analyzing compounds

simultaneously, reducing the analysis time and labor (Wagner & Bladt, 1996; Reich & Schibli, 2007; Harborne, 1998). This technique can be applied to a wide range of compounds, is suitable for both quantitative and qualitative analysis, and is more cost-effective than HPLC, making it more accessible for continuous or regular analysis (Harborne, 1998; Reich & Schibli, 2007).

9.3 Ultra Performance Liquid Chromatography (UPLC):

The enhanced version of high-performance liquid chromatography (HPLC) is called ultra- performance liquid chromatography (UPLC). It utilizes smaller particle sizes in the chromatographic columns and operates at higher pressures, which significantly enhances the efficiency of the separation process (Nováková & Vlcková, 2009). In contrast to the 3-5 mm particles used in conventional HPLC, UPLC columns use sub-2-micron particles, usually 1.7 microns. Better separation results from the increased surface area for interactions caused by the lower particle size (Nováková & Vlcková, 2009; Wu et al., 2013). The use of smaller size particle for separation increases both efficiency and sensitivity resulting in more accurate identification and separation along with increased sensitivity for less abundant compound (Nováková & Vlcková, 2009; Wu et al., 2013; Chen et al., 2008; Choudhary, N., & Sekhon, B. S. ,2011).

9.4 Supercritical Fluid Chromatography (SFC):

Supercritical fluid chromatography (SFC) is an advanced chromatographic method for compound separation and analysis that uses supercritical fluids as the mobile phase (Yang et al., 2012; Choudhary, N., & Sekhon, B. S. ,2011). Certain compounds that are not easily handled by liquid or gas chromatography can be separated and determined using SFC. Natural goods, medications, food, and pesticides are just a few of the things to which SFC has been applied (West & Lesellier, 2008). The mobile phase in supercritical fluid combustion (SFC) is primarily carbon dioxide (CO_2) at a temperature and pressure above its critical values. Supercritical CO2 is an ideal solvent for chromatography because it possesses both liquid-like solvating power and gas-like Diffusivity (Yang et al., 2012). Supercritical CO2 is frequently mixed with organic solvents (modifiers) such as methanol or ethanol to modify its polarity and increase its ability to dissolve polar molecules (West & Lesellier, 2008).

9.5 Thermal analysis of herbal drugs:

Differential thermal analysis (DTA), differential scanning calorimetry (DSC), and thermogravimetric analysis (TGA) have been used to investigate physical and chemical alterations in a range of items, including herbal medications. They have also been used to investigate medicine excipient compatibility and pre-formulation (Choudhary, N., & Sekhon, B. S. ,2011). TGA can be run in sub-ambient conditions to test ethanol in herbal preparations.

9.6 Infrared spectroscopy:

Based on vibrational transitions, infrared (IR) and Fourier transform infrared (FTIR) spectroscopy are two efficient analytical methods used to detect and analyze chemical compounds (Lin & Harnly, 2010). An interferometer is used in FTIR, a more advanced form of IR spectroscopy, to simultaneously gather all of the spectrum data. The infrared spectrum is then obtained by performing a mathematical Fourier transform on this data (Sampaio et al., 2015; Choudhary, N., & Sekhon, B. S. ,2011). Compared to conventional IR spectroscopy, FTIR has a number of benefits, such as higher speed, sensitivity, resolution, and versatility. FTIR and IR are used to determine the precise functional groups (such as hydroxyl, carbonyl, and aromatic rings) in herbal extracts (Sampaio et al., 2015).

9.7 Nuclear Magnetic Resonance (NMR) Spectroscopy:

It is another powerful analytical tool used in herbal medicine research. NMR allows for the detailed structural elucidation of complex molecules, facilitating the identification of active constituents and their interactions within the extract (Choudhary, N., & Sekhon, B. S. ,2011).

10. Formulation Technologies

Advancements in formulation technologies have addressed many challenges associated with the delivery and stability of herbal medicines.

10.1 Nanotechnology

It has emerged as a promising approach to enhance the bioavailability of poorly soluble herbal compounds. Researchers can improve their absorption and efficacy by incorporating bioactive molecules into nanoparticles, liposomes, or nano-emulsions (Bhattacharyya et al., 2017; Bhattacharyya et al., 2017).

10.2 Encapsulation

These techniques, such as microencapsulation and coacervation, protect sensitive bioactive compounds from degradation and ensure their controlled release. These methods enhance the stability and shelf-life of herbal products, making them more convenient for consumers (Banerjee, 2018; Bhattacharyya et al., 2017).

10.3 Biotechnology

Biotechnological approaches have opened new avenues for producing and optimizing medicinal plants such as:

10.4 Genetic engineering

It allows for modifying plant genomes to enhance the production of desired compounds or introduce new therapeutic properties. For example, researchers can insert genes encoding for specific enzymes involved in the biosynthesis of bioactive molecules, leading to increased yields and potency (Banerjee, 2018; Baskaran et al., 2017).

Plant cell culture techniques and Metabolic Engineering

Hairy root and suspension cultures offer a sustainable and controlled method for the production of bioactive compounds, which is essential for ensuring a consistent supply of high-quality

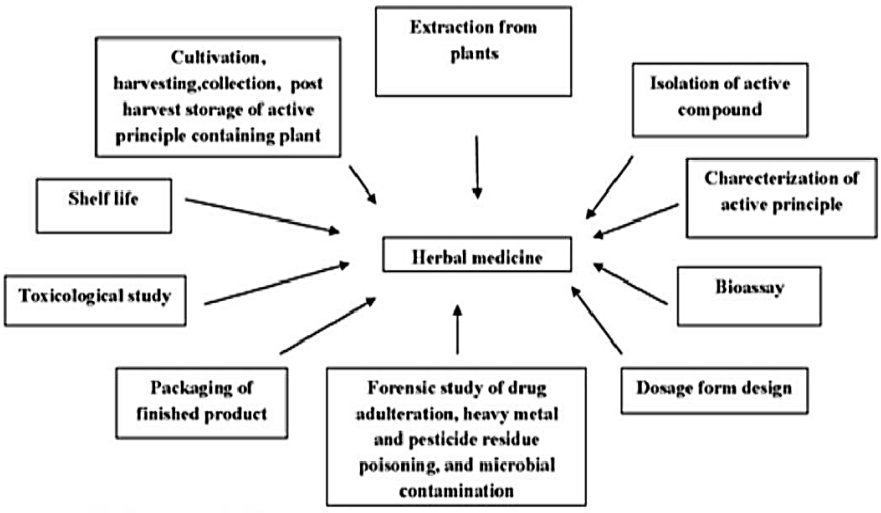

Figure 1. Different domains of herbal medicine.

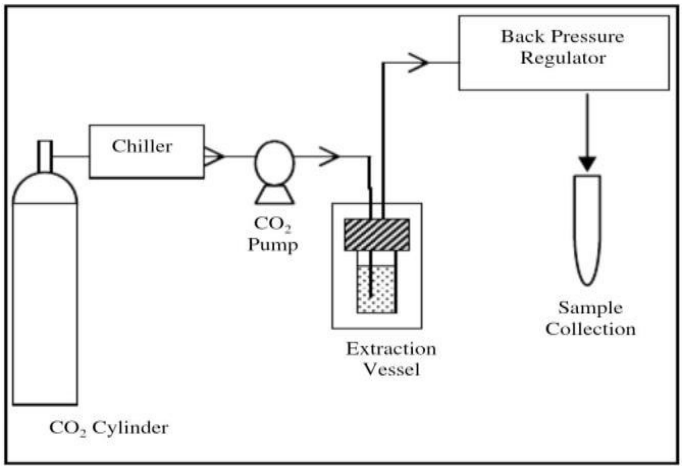

Figure 2. This a flow diagram of supercritical fluid extraction system.

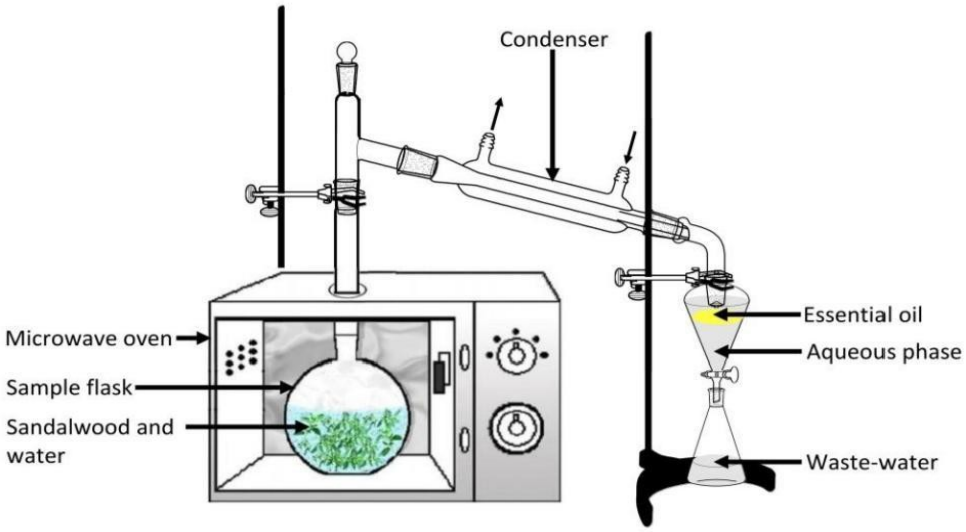

Figure 3. Diagram showing the microwave-assisted extraction.

Table 1. Current Conventional Medical Systems in Various Nations.

Country	Traditional system of medicine
Bangladesh	Unani and Ayurved
India	Ayurveda, Siddha
Japan	Kampo
Pakistan	Indusynunic
China	Chinese herbal medicine
Korea	Hanbang
Middle East	Islamic and Unani
Europe	Aromatherapy, homeopathy, botanicals and herbalism
Africa	Many traditional medicine systems used by various tribes like Muti, Ifá etc. and made operational by sangomas or izinyangas, traditional healers etc..
USA, Australia	Western Herbal medicine

Table 2. A few more recent methods of extraction.

New extraction Techniques	Uses
Supercritical Fluid extraction (SFE)	Improved extraction efficiency and pesticide residues analysis is possible
Pressurized Liquid Extraction (PLE) and PLE combined with ultrasound-assisted extraction and solid phase extraction	Increased yield and decreased time and solvent consumption and protects sensitive compounds
Microwave assisted extraction (MAE) technique and different statistical optimization strategies	Extracts can directly used for HPLC
Ultrasonic extraction	Increased extraction efficiency and reduced extraction time

Table 3. The benefits and challenges associated with the technological advancements in herbal medicine

Pros	Cons
Enhanced extraction efficiency	High cost of advanced technologies
Improved qualitycontrol and standardization	Potential loss of traditional knowledge
Increased bioavailability and efficacy	Regulatory and approval challenges
Personalized medicine possibilities	Need for extensive clinical trials
Sustainable production of rare species	Risk of adulteration and contamination
Greater accessibility via digital platforms	Dependence on technology and infrastructure
Safer and more consistent products	Intellectual property and patent issues

herbal ingredients. These cultures can be efficiently scaled up in bioreactors, providing a reliable source of plant-based compounds for use in the pharmaceutical, cosmetic, and food industries (Banerjee, 2018; Canter et al., 2005). By cultivating these systems in controlled environments, it is possible to overcome the challenges of raw material variability and the environmental constraints that typically affect the cultivation of medicinal plants. This method not only increases production efficiency but also ensures the consistent quality of bioactive compounds, making it an attractive alternative to traditional plant harvesting methods.

Despite the many benefits of technological advancements in herbal medicine, there are still several challenges that must be addressed. As outlined in Table 3, while modern technologies offer enhanced extraction efficiency and the potential for personalized medicine, they also come with high costs and regulatory challenges that may slow their widespread adoption. For example, advanced techniques like Supercritical Fluid Extraction (SFE) and High-Performance Liquid Chromatography (HPLC) offer better standardization and quality control (Banerjee, 2018), yet the financial investment required to implement these technologies is often a barrier, particularly for smaller producers. Moreover, the loss of traditional knowledge, regulatory hurdles, and the need for extensive clinical trials are significant obstacles to the full integration of these technologies into the mainstream herbal medicine industry. Additionally, the risk of adulteration and contamination remains a concern, particularly when traditional herbs are combined with modern technologies.

Applications of modern technology in herbal medicine have been demonstrated in various case studies. For instance, the use of SFE has enabled the extraction of high-purity curcumin from turmeric, enhancing its potential therapeutic uses. Clinical studies have shown that curcumin formulations in nanoparticle form exhibit better bioavailability and have demonstrated efficacy in treating several malignancies and inflammatory diseases (Sahoo et al., 2024; Seyedebrahimi et al., 2022). Another example is the identification of specific ginsenosides in ginseng, responsible for its pharmacological effects, through Gas Chromatography-Mass Spectrometry (GC-MS) analysis (Kim & Park, 2021). This scientific validation has paved the way for the widespread use of standardized ginseng extracts in dietary supplements and functional foods, further illustrating the power of advanced technologies in enhancing the therapeutic potential of herbal products.

However, despite these advancements, standardization remains a critical issue. Standardization ensures that each dose of a herbal product contains a consistent amount of bioactive compounds, thereby guaranteeing its therapeutic effect. Without proper standardization, there is a risk of variability in the composition and potency of herbal formulations, which can lead to adverse effects, allergic reactions, or interactions with other drugs (Sekhon, B. S., 2011). Techniques such as Thin Layer Chromatography (TLC) and High-Performance Thin Layer Chromatography (HPTLC) fingerprint profiles are instrumental in ensuring the authenticity, purity, and strength of herbal products and polyherbal formulations, which combine multiple herbs for synergistic effects (Choudhary, N., & Sekhon, B. S., 2011). These methods are crucial for safeguarding the quality and safety of herbal medicines, as well as for ensuring the consistency of multi-ingredient formulations.

Despite the promising advancements in herbal medicine technology, there are several obstacles that remain. As highlighted in Table 3, the need for extensive clinical trials to validate the safety and efficacy of technologically advanced herbal products is a significant challenge. The regulatory landscape for herbal medicines is often inconsistent across different regions, further complicating the global acceptance and distribution of these products. To overcome these challenges, large-scale clinical trials and the establishment of international guidelines for the manufacturing and quality assurance of herbal remedies are essential. In addition, the potential of emerging technologies such as machine learning and artificial intelligence (AI) to identify new bioactive compounds and predict treatment outcomes presents an exciting opportunity for future development in herbal medicine (Sahoo et al., 2024).

11. Discussion

The development of herbal medicine technology should focus on the integration of modern scientific advancements with traditional practices, recognizing both the potential benefits and inherent challenges. Recent progress in biotechnology, particularly through omics technologies such as genomics, proteomics, and metabolomics, has significantly enhanced our understanding of herbal medicines. These technologies offer detailed insights into the molecular composition and mechanisms of action of herbal compounds, facilitating better standardization and quality control (Heinrich & Bremner, 2012). By identifying specific bioactive compounds and understanding their interactions within the body, these innovations hold the potential to not only improve the efficacy of herbal medicines but also to ensure their safety and consistency in a way that was not possible with traditional methods.

Despite these technological advances, numerous challenges remain that must be addressed for successful integration into the herbal medicine sector. One significant issue is the lack of standardization across the global herbal medicine industry. Although sophisticated technologies such as High-Performance Liquid Chromatography (HPLC), Supercritical Fluid Extraction (SFE), and Ultra-Performance Liquid Chromatography (UPLC) have played pivotal roles in enhancing the quality and consistency of herbal products, regional disparities in regulations and quality control standards continue to pose substantial barriers (Kunle et al., 2012). This lack

of uniformity in regulatory practices can prevent herbal products from achieving widespread acceptance in international markets. Additionally, environmental factors, such as variations in soil quality, climate, and cultivation practices, can dramatically affect the growth and composition of medicinal plants, further complicating efforts to establish standardized processes for herbal medicine production. As a result, even with advanced technologies ensuring product consistency, the inherent variability in raw materials remains a significant obstacle.

Furthermore, while technological advancements have enhanced our ability to analyze bioactive compounds within herbal products, there is still a pressing need for robust clinical validation to demonstrate the safety and efficacy of these medicines. Many herbal products are widely used in traditional medicine, but often without the scientific evidence needed to support their claims in modern healthcare settings. The absence of large-scale, well-controlled clinical trials contributes to skepticism within the scientific community and among healthcare professionals (Patwardhan et al., 2005**;** Gottfried **et al, 2015**). Conducting these trials would not only bolster the credibility of herbal medicines but also promote their integration into mainstream medical systems, offering patients a broader range of scientifically validated treatment options. Establishing a stronger evidence base through clinical studies will help address concerns over the safety and efficacy of herbal remedies, which is essential for gaining regulatory approval and increasing acceptance among health professionals.

The regulatory environment surrounding herbal medicines also presents a significant challenge. Currently, the regulation of herbal products varies widely from region to region, with some countries classifying herbal medicines as dietary supplements rather than as pharmaceutical drugs. As a result, herbal products often do not undergo the same rigorous testing for safety, efficacy, and quality as conventional drugs. This lack of harmonized regulations can lead to inconsistencies in product quality, posing potential risks to consumers and diminishing confidence in herbal medicines (Mukherjee, 2002**;** Fong et al,1996). A unified global framework for regulating herbal products, alongside technological advancements in quality control, could help ensure the safety, efficacy, and consistency of these medicines. Such a framework would foster greater consumer trust and contribute to the overall credibility of the herbal medicine sector.

Looking to the future, emerging technologies such as artificial intelligence (AI) and machine learning (ML) offer exciting possibilities for the development of herbal medicines. AI and ML could be leveraged to predict treatment outcomes, analyze vast datasets of herbal compounds, and identify novel bioactive compounds with potential therapeutic benefits. These technologies could also streamline the production process, improving efficiency, reducing costs, and optimizing formulations for better bioavailability and therapeutic effectiveness. The integration of AI and ML into the herbal medicine sector could significantly enhance the precision and personalization of treatments, contributing to more targeted and effective healthcare solutions. With the proper integration of these technologies, herbal medicine could evolve into a highly sophisticated and evidence-based component of modern healthcare.

12. Conclusion

In conclusion, the integration of modern technologies into herbal medicine offers numerous benefits, including enhanced efficiency, improved quality control, and the possibility of personalized treatments. However, challenges such as regulatory barriers, the need for clinical validation, and the potential loss of traditional knowledge must be addressed for these technologies to be successfully implemented. With continued research and development, and the collaboration between traditional knowledge and modern science, herbal medicine has the potential to become an increasingly valuable component of personalized healthcare.

Author contributions

M.A. and S.I. contributed to the conception and design of the study. C.G.L. performed data analysis and interpretation. M.S.S.K. supervised the project and contributed to the critical revision of the manuscript. All authors participated in drafting the manuscript, approved the final version for submission, and agreed to be accountable for all aspects of the work.

Acknowledgment

The authors were grateful to their department.

Competing financial interests

The authors have no conflict of interest.

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