

From soil to shelf: challenges and opportunities in medicinal plant research

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ABSTRACT

Medicinal plants playing a vital role in traditional healthcare, have emerged as a cornerstone in the development of modern pharmaceuticals. Increasing global demand for natural therapies, along with advances in science and technology, is transforming the medicinal plant sector. This review highlights emerging trends like DNA barcoding for identifying and conserving medicinal plants, as well as the use of genomics, nanotechnology, and artificial intelligence in medicinal plants. Despite this progress, the sector faces challenges, including biodiversity depletion, adulteration, lack of standardization, weak regulatory frameworks, biopiracy, and climate-related threats. Addressing these issues needs global collaboration to ensure sustainable cultivation, ethical resource use, and effective quality control. The integration of cutting-edge tools with traditional knowledge offers a promising path toward developing safe, effective, and eco-friendly plant-based healthcare solutions.

Key words: Biodiversity conservation, Medicinal plants, Pharmaceuticals, Sustainable cultivation, Traditional knowledge, Quality control

With growing global interest in natural therapies and sustainable living, medicinal plant industry is undergoing significant changes. Medicinal plants have been used by humans for thousands of years, forming the foundation of traditional healing systems across cultures (Das, 2014). Ancient systems like the Charaka Samhita, Unani medicine, and Patanjali's practices highlight the importance of medicinal plants in managing various health conditions. However, this surge in demand is accompanied by complex challenges ranging from biodiversity loss and quality control issues to regulatory and ethical concerns, limit its full potential (Raju and Das, 2024). At the same time, emerging technologies such as genomics, nanotechnology, artificial intelligence, and DNA barcoding are opening new opportunities for innovation, quality enhancement, and sustainable use in medicinal plant conservation (Singh *et al.*, 2025; Nazar *et al.*, 2025). Although limited literature is available, most studies cover only a few aspects of medicinal plant research. This review highlights current trends, challenges, and future directions, emphasizing the need for an integrated approach. It addresses key issues across the entire value chain, from soil to shelf, and promotes the use of both traditional knowledge and modern science to create safe, effective, and eco-friendly plant-based products.

Current trends in medicinal plant research

Medicinal plant research is undergoing rapid growth driven by technological advancements, evolving consumer

preferences, and greater integration with modern healthcare systems. There is a rising global demand for herbal medicines, nutraceuticals, and cosmeceuticals as people seek safer, natural alternatives to synthetic drugs (Sarkar *et al.*, 2024). This trend is encouraging industrial investment and policy support for the development of plant-based products. At the same time, traditional knowledge is being scientifically validated, leading to its incorporation into mainstream medicine and expanding therapeutic options. Advanced tools such as genomics, metabolomics, and artificial intelligence are also being increasingly used for plant identification, quality assurance, and drug discovery, making research more precise and efficient (Singh *et al.*, 2025). These developments collectively signal a strong shift toward innovation, sustainability, and holistic healthcare in medicinal plant sector.

DNA barcoding in authentication and conservation

The DNA barcoding is a powerful molecular tool used to verify the botanical identity of medicinal plants and prevent adulteration. By analysing short, standardized genetic sequences, it ensures the authenticity, safety, and quality of herbal products (Nazar *et al.*, 2025). Since its introduction, technique has evolved to include advanced methods like high-resolution melting (HRM), next-generation sequencing (NGS), and metabarcoding, enabling the identification of multiple species within complex samples (Mahima *et al.*, 2022). Technologies such as DNA microarrays further enhance rapid screening capabilities. As the herbal medicine market expands,

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DNA barcoding supported by comprehensive databases of authentic and adulterant species plays a crucial role in quality control, biodiversity conservation, and future drug discovery.

Use of nanotechnology

Nanotechnology is revolutionizing medicinal plant research by enhancing the delivery, stability, and effectiveness of plant-derived compounds. Many phytochemicals have poor solubility, low bioavailability, and rapid degradation, limiting their therapeutic potential. Nano-formulations such as nanoparticles and nanocapsules overcome these challenges by improving absorption, targeting specific organs, and reducing toxicity (Singh *et al.*, 2025). This enables lower dosages with enhanced efficacy. Additionally, plant extracts are increasingly used in the green synthesis of nanoparticles, offering sustainable and eco-friendly applications such as herbal herbicides and antimicrobial agents. The integration of nanotechnology with herbal medicine opens new avenues for developing safer, more efficient plant-based therapies.

AI, Machine Learning and GIS

Artificial Intelligence (AI), Machine Learning (ML), and Geographic Information Systems (GIS) are revolutionizing medicinal plant research and conservation. AI and ML tools, such as Convolutional Neural Networks (CNNs) and pre-trained models like VGG16 and VGG19, are being used to predict bioactivity, identify plant species, optimize extraction methods, and discover synergistic phytochemical interactions (Dey *et al.*, 2024). India is the first country to use AI to digitize traditional medical knowledge through the Traditional Knowledge Digital Library (TKDL), covering Ayurveda, Siddha, Unani, and Sowa-Rigpa to preserve ancient practices and support research. These technologies also support remote identification of rare or inaccessible plant species through drone imagery and automated analysis. Simultaneously, remote sensing and GIS technologies help map the spatial distribution of medicinal plants, identify potential cultivation zones, and monitor endangered species (Hirapara *et al.*, 2024). By integrating environmental variables, GIS enables predictive modeling and precision farming, aiding sustainable cultivation and resource management (Singh *et al.*, 2025). Together, these advanced tools enhance research, conservation, and commercialization of medicinal plant resources.

Application of genetics and biotechnology

Genetics and biotechnology play a crucial role in improving the quality, yield, and sustainability of medicinal

plants. Tools like genome sequencing, molecular markers, and CRISPR-Cas9 enable precise gene editing to enhance traits such as metabolite production, disease resistance, and adaptability (Singh *et al.*, 2025; Raju *et al.*, 2025). Techniques like RNA-seq and RAD-seq help identify genes linked to biosynthesis and support conservation and breeding efforts. Tissue culture methods, including callus and cell suspension cultures, allow controlled, large-scale production of bioactive compounds. Cryopreservation of synthetic seeds ensures long-term conservation and sustainable propagation of elite medicinal plant germplasm. Omics-based tools namely genomics, transcriptomic, metabolomics, and proteomics along with bioinformatics platforms, are essential for understanding biosynthetic pathways, and selecting elite genotypes, ensuring a consistent and high-quality raw material supply for pharmaceutical industries (Yang *et al.*, 2023).

Challenges

Despite significant advancements, the medicinal plant sector faces several critical challenges that limit its sustainable growth and potential. Unsustainable harvesting and overexploitation of wild plant populations have led to the decline of many valuable species, pushing some toward extinction (Nayak *et al.*, 2025). Habitat destruction due to urbanization, agriculture, and deforestation further threatens plant biodiversity. Additionally, the illegal trade of herbal materials and the lack of standardized regulations contribute to quality issues, adulteration, and loss of consumer trust. Inadequate enforcement of conservation laws and insufficient cultivation efforts exacerbate these problems. Addressing these challenges requires coordinated action in conservation, cultivation, regulation, and awareness to ensure the long-term viability and integrity of medicinal plant resources. The major challenges hindering the growth of medicinal plant sector are discussed (Fig. 1).

Biodiversity loss and overexploitation

Unregulated wild harvesting and habitat destruction are critically threatening medicinal plant biodiversity. Many valuable species like *Nardostachys jatamansi* (Jatamansi), *Picrorhiza kurroa* (Kutki), *Commiphora wightii* (Guggul), and *Rauwolfia serpentina* (Sarpagandha) are becoming endangered due to overexploitation and slow natural regeneration. This not only disrupts ecological balance but also jeopardizes the sustainability of traditional and modern healthcare systems. Urgent steps like sustainable harvesting, habitat conservation, cultivation, strict bans on wild collection, and seed banking are vital to protect medicinal plants for future generations (Das, 2021).



Fig. 1. Overview of major challenges in medicinal plant sector

Adulteration and contamination

Adulteration and contamination of herbal formulations pose significant threats to public health and the integrity of traditional medicine systems. Common issues include the substitution of genuine herbs with inferior or unrelated species, presence of different part of same plant. *Saraca asoca* (Ashokatree) is often adulterated with the bark of *Polyalthia longifolia*, an ornamental tree with no equivalent medicinal value (Devan and Warriar, 2021). Additionally, contamination from heavy metals, pesticides, and microbial toxins due to poor handling and

storage further compromises safety. These challenges highlight the urgent need for strict quality control measures, including DNA barcoding, chemical profiling, and adherence to Good Agricultural and Collection Practices (GACP) to ensure the authenticity, purity, and efficacy of herbal products (Sarkar *et al.*, 2024). Common adulterants in medicinal plants and their detection methods are outlined (Table 1).

Quality control and standardization

Inconsistencies in plant identity, cultivation conditions, and processing methods often lead to variability in the quality and efficacy of herbal medicines. The concentration of active compounds in most medicinal plants can vary significantly due to differences in soil conditions, climate, and post-harvest handling practices. Such variability poses challenges in ensuring safety, therapeutic consistency, and global acceptance. Standardization through DNA barcoding, HPTLC/HPLC profiling, and adherence to Good Agricultural and Collection Practices (GACP) and pharmacopoeial guidelines is essential to maintain quality, build consumer trust, and meet international regulatory standards (Das, 2023).

Regulatory and trade barriers

The absence of harmonized global regulations creates major challenges for the development and international trade of medicinal plant products. Due to their multi-component nature, herbal formulations often do not fit into existing pharmaceutical or dietary supplement categories, leading to regulatory ambiguity. EU laws require extensive safety data for herbal products,

Table 1: Common adulteration in medicinal plants and their detection methods

Medicinal plant	Part used	Common adulterant	Method of detection	References
<i>Rauwolfia serpentine</i> (Sarpagandha)	Root	<i>Rauwolfia tetraphylla</i> (Devil-pepper)	HPTLC (high-performance thin-layer chromatography) and LC/MS analysis Microscopy, Alkaloid profiling, DNA Barcoding	Sulaiman <i>et al.</i> (2020)
<i>Asparagus racemosus</i> (Shatavari)	Root tubers	<i>Hemidesmus indicus</i> (Anantamul)	HPTLC, Microscopy	Rai <i>et al.</i> (2012)
<i>Centella asiatica</i> (Mandukparni)	Whole plant	<i>Hydrocotyle sibthorpioides</i> (Water Pennywort)	DNA barcoding, HPTLC	Maulidiani <i>et al.</i> (2012)
<i>Eclipta alba</i> (Bhringraj)	Whole plant	<i>Wedelia calendulacea</i> (Water Zinnia)	HPTLC, DNA barcoding, FT-IR, HPTCL	Vadivel <i>et al.</i> (2017).
<i>Glycyrrhiza glabra</i> (Licorice)	Root	<i>Abrus precatorius</i> (Rosary Pea)	Chemical profiling (TLC, HPLC), Microscopy	Kumar <i>et al.</i> (2022)
<i>Terminalia arjuna</i> (Arjuna)	Bark	<i>T. bellirica</i> (Baheda)	HPTLC	Tulsi and Vidhu (2022)
<i>Mallotus philippensis</i> (Kamala)	Glandular hair powder from fruit	<i>Bixa Orellana</i> (Annatto)	HPTLC, UV-Vis Spectroscopy, Microscopy	Gangwar <i>et al.</i> (2014)
<i>Commiphora wightii</i> (Guggul)	Resin	<i>Boswellia serrata</i> (Salai guggul)	HPTLC, DNA barcoding, HPLC, GC-MS	Bhardwaj and Alia (2019)

while the U.S. classifies them as dietary supplements with limited health claims (Silpi, 2025). Ayurvedic products like Triphala and ashwagandha face export hurdles due to differing standards across countries. This lack of regulatory alignment delays approvals, restricts market access, and discourages global investment in the herbal sector.

Biopiracy and intellectual property issues

Biopiracy, the commercial exploitation of traditional knowledge without proper consent or benefit-sharing, poses serious ethical and legal concerns in the medicinal plant sector. Cases like patenting of neem and turmeric by foreign entities, despite their long-standing traditional use in India, highlight the issue. Similarly, *Hoodia gordonii* (Kalahari cactus) traditionally used by the San people to curb hunger and thirst, was commercialized without initially acknowledging their knowledge (Wynberg and Chennells, 2009). Although frameworks like the Nagoya Protocol aim to address such issues, inconsistent implementation especially in developing countries continues to challenge fair access and benefit-sharing.

Limited infrastructure and resources

The development of the medicinal plant sector is significantly constrained by inadequate infrastructure, limited funding, and a lack of skilled personnel, especially in developing countries. Despite rich biodiversity, many regions lack advanced laboratories, modern equipment, and institutional support necessary for high-quality research and commercialization, which in turn hampers standardization, value addition, and access to global markets. Strengthening infrastructure, investing in capacity-building, and fostering public-private partnerships are essential to fully realize the potential of medicinal plants (Raju and Das, 2024).

Climate change impacts

Climate change significantly threatens the growth, distribution, yield, and phytochemical integrity of medicinal and aromatic plants (MAPs). Altered temperature regimes, irregular rainfall patterns, and frequent extreme weather events such as droughts, storms, and floods disrupt cultivation cycles and reduce the availability and quality of plant-derived bioactive components (Das *et al.*, 1999). Medicinal plants often show reduced yields and altered phytochemical profiles under stress, compromising therapeutic efficacy. Shifts in phenology and geographic distribution of wild medicinal species further highlight their vulnerability. These changes challenge sustainable harvesting, cultivation, and conservation, necessitating urgent development of climate-resilient practices, germplasm preservation, and

adaptive management strategies to safeguard the future of medicinal plant resources.

Market fragmentation

The global medicinal plant market is highly fragmented due to the vast diversity of herbal products, traditional healing systems, and region-specific practices. Different countries follow their own systems such as Ayurveda in India, Traditional Chinese Medicine (TCM) in China, Unani in the Middle East, and Kampo in Japan, each with unique formulations, plant sources, and therapeutic philosophies (Rohan *et al.*, 2024; Ansari, 2021). *Glycyrrhiza glabra* (Mulethi) is used differently in Ayurveda and TCM, resulting in variations in processing, dosage, and intended use. Such cultural diversity makes it difficult to establish common standards for quality, safety, and effectiveness. This fragmentation makes global marketing difficult as regulations, labeling rules, and consumer expectations vary widely across countries. As a result, manufacturers often face difficulties in aligning their products with international standards, limiting scalability and cross-border trade. Greater collaboration among countries, development of global herbal monographs, and harmonized regulatory frameworks are essential to overcome these barriers and strengthen the global medicinal plant market.

Future directions for research and development

Future research in medicinal plants must adopt strategic, interdisciplinary approaches to overcome current limitations and unlock new opportunities. Key areas include genetic improvement through biotechnology, precision farming for optimized cultivation, and advanced extraction methods like supercritical fluid and nano-based techniques for enhanced efficacy. Technologies such as DNA barcoding and blockchain are strengthening quality control and traceability, while tools like AR (Augmented Reality), VR (Virtual Reality) are revolutionizing education and research. By integrating traditional knowledge with modern science and fostering collaboration among researchers, farmers, and policymakers, these innovations can ensure sustainable cultivation, improved product quality, and global competitiveness of herbal medicines.

Sustainable cultivation and biodiversity conservation

Sustainable cultivation of medicinal plants is essential amid habitat loss, climate change, and shrinking farmland. Eco-friendly practices like organic farming, *in vitro* propagation, and tissue culture help conserve resources and protect ecosystems, ensuring long-term availability

of plant material (Nayak *et al.*, 2025). Innovative methods such as hydroponics, vertical gardening, and orchard integration provide space-efficient and climate-resilient cultivation options. Advanced systems like aeroponics and controlled-environment agriculture offer precise growth control, consistent bioactive compound production, and reduced ecological impact. Climate-smart agriculture and robust *in situ* and *ex situ* conservation are vital for protecting genetic diversity and strengthening supply chains (Das and Sharma, 2014). Scientific institutions and industries are also promoting sustainable sourcing through eco-friendly harvesting and biotechnological approaches.

Advanced drug discovery and phytopharmaceutical development

The integration of cutting-edge technologies such as artificial intelligence (AI), network pharmacology, and genetic engineering is revolutionizing drug discovery from medicinal plants. AI-driven platforms can rapidly screen vast phytochemical libraries to predict bioactivity, toxicity, and potential therapeutic targets. Machine learning models have been used to identify novel anti-cancer compounds from *Taxus brevifolia* and anti-inflammatory agents from *Curcuma longa* (Chunarkar-Patil *et al.*, 2024). Network pharmacology allows researchers to understand the multi-target, multi-pathway mechanisms of complex herbal formulations like Triphala or Ashwagandha, providing scientific validation for traditional uses. Genetic engineering and synthetic biology techniques are now being employed to enhance metabolite production, as seen in engineered microbes producing artemisinin (originally from *Artemisia annua*) on a commercial scale (Pulice *et al.*, 2016). These interdisciplinary tools not only accelerate the development of safer and more effective phytopharmaceuticals but also bridge traditional knowledge with modern drug innovation, paving the way for next-generation herbal therapeutics.

Expansion of personalized and integrative medicine

The rise of personalized and integrative medicine is reshaping the future of healthcare by combining plant-based therapies with conventional treatments tailored to an individual's genetic makeup, lifestyle, and health condition. Advances in pharmacogenomics allow for the customization of herbal interventions, enhancing efficacy and minimizing adverse effects (Shaman, 2024). Integrative approaches are also gaining ground in managing chronic diseases (Kalariya *et al.*, 2023; Bora *et al.*, 2019). Personalized Ayurveda, which aligns constitution types (Prakriti) with genomic data, is another emerging trend. This fusion of traditional wisdom with modern precision

medicine improves treatment outcomes, reduces side effects, and enhances overall patient satisfaction.

Enhanced quality control and global standardization

Ensuring the quality, safety, and efficacy of medicinal plant products requires robust quality control measures and globally harmonized standards. Techniques such as HPTLC and HPLC-based metabolite fingerprinting, along with DNA barcoding, are increasingly used to authenticate plant species and detect adulterants. Regulatory frameworks like the Central Drugs Standard Control Organisation (CDSCO), Ayurvedic Pharmacopoeia of India (API), and adherence to Good Manufacturing Practices (GMP) set clear benchmarks for herbal medicine quality. Institutions implementing Good Agricultural and Collection Practices (GACP) further ensure consistency and sustainability (Raju and Das, 2024). Resources like the Traditional Knowledge Digital Library (TKDL) safeguard against biopiracy, while the Herbal Drugs Consultative Committee (HDCC) contributes to regulatory guidance. International cooperation with organizations such as WHO and the U.S. Pharmacopeia supports the global standardization of herbal products, enhancing safety and export potential (Rohan *et al.*, 2024). Integrating modern innovations like green extraction methods, nano-formulations, and high-throughput omics platforms alongside machine learning for precision breeding will accelerate the development of safe, effective, and standardized herbal medicines worldwide.

Ethical bioprospecting and benefit-sharing

Ethical bioprospecting ensures that the exploration and commercialization of medicinal plant resources respect indigenous knowledge and comply with biodiversity regulations. It involves obtaining prior informed consent (PIC), ensuring equitable benefit-sharing, and acknowledging the contributions of local communities (Wynberg and Chennells, 2009). India's Traditional Knowledge Digital Library (TKDL) was developed to prevent biopiracy by documenting indigenous knowledge and making it accessible to patent examiners. Future research must align with frameworks like the Nagoya Protocol, ensuring that local custodians of biodiversity are recognized and rewarded fairly. This approach not only protects community rights but also promotes sustainable and inclusive innovation in the medicinal plant sector.

Climate resilience research

Climate resilience research is vital for sustaining medicinal plant cultivation amid changing environmental conditions. Climate change, including rising temperatures and disrupted seasonal patterns, adversely affects

medicinal plant growth, yield, and phytochemical composition particularly secondary metabolites (Das *et al.*, 2016). To meet global demand and enhance climate resilience, region-specific cultivation of selected elite varieties under appropriate agro-climatic conditions is being promoted (Saran *et al.*, 2025). In parallel, DMAPR has effectively carried out the screening of germplasm suitable for cultivation under low-water conditions in various medicinal plants (Das, 2010). Developing climate-resilient cultivars and adapting cropping systems like intercropping and using drought-tolerant species can help maintain productivity and quality. Integrating predictive climate models and precision farming tools will further support adaptive strategies, ensuring the long-term viability of medicinal plant resources.

CONCLUSION

From soil to shelf, the journey of medicinal plants sector is filled with both challenges and opportunities. While issues like habitat loss, poor quality control, and regulatory gaps pose serious concerns, there is great promise in sustainable cultivation, scientific innovation, and community involvement. Strengthening research, conserving biodiversity, protecting traditional knowledge, and ensuring fair benefit-sharing are key to unlocking the full potential of this sector. Support from institutions like NMPB and DMAPR, along with coordinated efforts across all stakeholders, can lead to a future where medicinal plants play a vital role in health care, rural development, and environmental sustainability. Consumer awareness, improved education about medicinal plants, and the integration of traditional wisdom into modern practices will further enhance the credibility, acceptance, and responsible use of herbal products.

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