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Geographical Impact on Quality Control and Standards of Medicinal Plants in Indian environmental conditions: An overview

Arun Meena[1], Binay Sen[2]

[1]Ph.D. scholar, Department of Dravyaguna, Faculty of Ayurveda, Institute of Medical Science, Banaras Hindu University, Varanasi-221005 India

[2]Assistant Professor Department of Dravyaguna, Faculty of Ayurveda, Institute of Medical Science, Banaras Hindu University, Varanasi-221005 India

Abstract

India's diverse agro-climatic regions serve as a rich repository of medicinal plants, which play a crucial role in both traditional medicine and modern pharmaceuticals. The quality, efficacy, and safety of these plants are significantly influenced by geographic factors. With 15 agro-climatic zones, India is home to approximately 960 medicinal plant species, of which 178 are actively traded, with an annual consumption exceeding 100 metric tons. Despite this potential, India's share in the global herbal market remains low, accounting for only 0.5% of AYUSH and value-added product exports in 2017-2018. The WHO emphasizes the importance of integrating traditional medicine into universal healthcare while ensuring quality, safety, and efficacy. However, concerns persist regarding the quality of Indian AYUSH products, particularly the presence of toxic heavy metals like lead, mercury, and arsenic. To address these concerns, advanced analytical techniques such as High-Performance Thin Layer Chromatography (HPTLC), High-Performance Liquid Chromatography (HPLC), and Fourier-transform infrared spectroscopy (FT-IR) are necessary for quality assessment. This paper aims to enhance understanding of how geographic factors—such as climate, soil composition, altitude, and water availability—impact the chemical composition of key medicinal plants, including Aloe *barbadensis miller* (Aloe vera), *Withania somnifera* (Ashwagandha), and *Curcuma longa* (Turmeric). It also discusses the challenges in standardizing quality control for medicinal plants in India and proposes strategies for harmonizing standards to account for regional variability, ensuring that Indian herbal products meet international quality benchmarks.

Keywords: Agroclimatic Regions, Geographical, Efficacy, AYUSH, Quality Control.

1. Introduction

India's rich biodiversity and varied agroclimatic conditions make it one of the world's most significant producers of medicinal plants. From the alpine ecosystems of the Himalayas to the tropical forests of Kerala, India's diverse geographical landscape provides an ideal environment for the growth of a wide range of medicinal plants.[1] However, the geographical variation in temperature, soil types, precipitation, and altitude significantly impacts the growth, chemical composition, and quality of these plants.[2]

The Indian government has identified 15 agroclimatic zones, each with distinct environmental conditions, influencing the cultivation and quality of medicinal plants. Understanding the geographic influence on the quality control of medicinal plants is crucial to ensure the safety, efficacy, and standardization of plant-based medicines used in both traditional systems like Ayurveda and modern pharmaceuticals [3]. This paper aims to explore how the geography of different Indian agroclimatic regions impacts the quality control of medicinal plants and how these factors can be integrated into standardized quality control mechanisms for medicinal plant products.[4]

2 Result

2.1 Agroclimatic Zones of India and Their Influence on Medicinal Plant Quality

India's agroclimatic zones can be broadly categorized into several distinct regions, including the Himalayan region, the North Eastern Hills, the Indo-Gangetic plains, the Central plateau, and the Deccan plateau, each with unique climatic and soil conditions that affect the growth and chemical composition of medicinal plants.[5,6]

2.1.1 Himalayan Region

The Himalayan region, with its high altitudes and cooler temperatures, is home to several medicinal plants known for their adaptogenic properties, such as *Picrorhiza kurroa* (Kutki) and *Rheum emodi* (Indian Rhubarb). The cold climate and high UV exposure in this region result in higher concentrations of secondary metabolites, making these plants more potent.[7]

2.1.2 North Eastern Hills

The North Eastern Hills are characterized by high rainfall and rich biodiversity, making this region a hub for medicinal plant cultivation. Plants like *Zingiber officinale* (Ginger) and *Centella asiatica* (Gotu Kola) thrive here. However, the high humidity levels can also affect plant drying and storage, making post-harvest quality control a critical issue.[8,9]

2.1.3 Indo-Gangetic Plains

The Indo-Gangetic plains are characterized by fertile alluvial soils and moderate climatic conditions. This region is a significant producer of medicinal plants such as *Withania somnifera* (Ashwagandha) and *Ocimum sanctum* (Tulsi)[10] . The uniformity of climate and soil conditions in this region contributes to the consistent quality of these medicinal plants.[11]

2.1.4 Central Plateau and Hills

The Central Plateau is a semi-arid zone with varied soil types, including red, black, and lateritic soils. Plants like *Boswellia serrata* (Indian Frankincense) and *Commiphora wightii* (Guggul) are native to this region. The arid conditions and mineral-rich soils influence the resin production in these plants, which are key to their medicinal properties.[12-15]

2.1.5 Western and Eastern Coastal Plains

The coastal plains of India, with their tropical climate and saline soils, are ideal for growing plants like *Aloe vera* and *Azadirachta indica* (Neem). However, the proximity to saline water and humid conditions can lead to challenges in maintaining plant quality, particularly in terms of microbial contamination.[16,17]

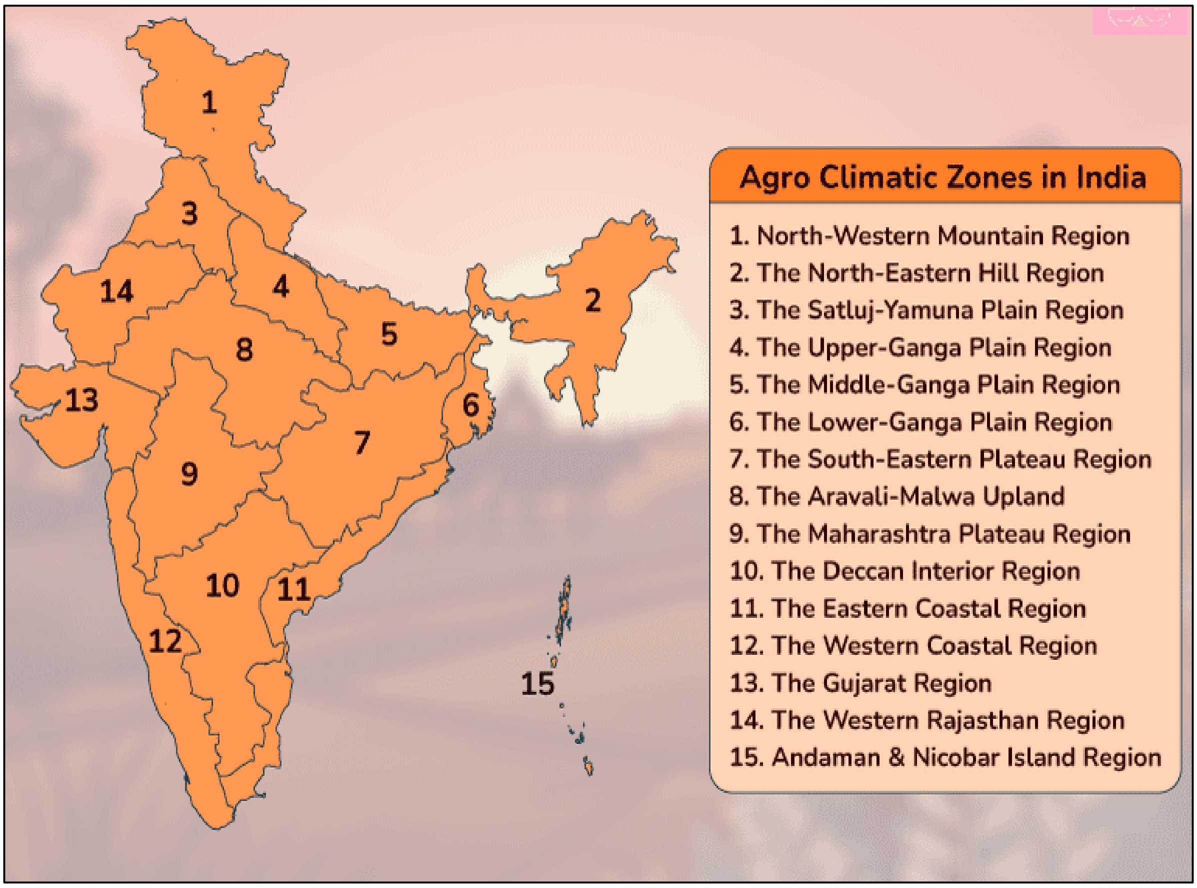

Figure 1 Indian Argo climatic region.

2.2. Geographical Factors Influencing the Quality of Medicinal Plants in India[18-28]

Geographical Region	Environmental Conditions	Impact on Medicinal Plants	Examples of Medicinal Plants
Himalayan Region	High altitude, cold temperatures, significant snowfall, low to moderate rainfall, varied soil types (loamy, rocky).	Adapted to extreme cold and high-altitude conditions, plants tend to have higher concentrations of bioactive compounds such as alkaloids and flavonoids.	*Aconitum* (Aconite), *Rhodiola rosea*, *Angelica*
Indo-Gangetic Plains	Fertile alluvial soil, high rainfall (monsoon), moderate temperatures, high humidity.	Fertile soil supports a wide range of medicinal plants, contributing to diverse phytochemical profiles, including antioxidants, anti-inflammatory agents, and digestive aids.	*Coriander* (Coriandrum sativum), *Turmeric* (Curcuma longa), *Fennel* (Foeniculum vulgare)
Western Ghats	Tropical climate, heavy rainfall, high biodiversity, lateritic and fertile soils.	Rich flora with diverse secondary metabolites such as alkaloids, saponins, and terpenoids; plants used for antimicrobial, anti-inflammatory, and adaptogenic purposes.	*Ashwagandha* (*Withania somnifera* Linn.), *Cinnamon* (Cinnamomum verum), *Coleus forskohlii*
Deccan Plateau	Semi-arid, moderate temperatures, black soil, low to medium rainfall, rocky terrain.	Plants in this region are drought-resistant, rich in compounds with therapeutic properties for bone health, skin conditions, and digestive disorders.	*Bael* (Aegle marmelos), *Brahmi* (Bacopa monnieri), *Guduchi* (Tinospora cordifolia)
Coastal Regions	High humidity, saline environment, sandy soils, tropical climate,	Coastal plants exhibit unique salt tolerance, often used for skin	*Coconut* (Cocos nucifera), *Sea buckthorn*

	moderate to high rainfall.	treatments, inflammation, and respiratory health.	(Hippophae rhamnoides), *Andrographis paniculata*
Eastern Plateau & Hills	Tropical to subtropical climate, humid conditions, well-drained hilly soils.	Rich in bioactive compounds, these plants are utilized for their therapeutic effects on the respiratory, immune, and digestive systems.	*Tulsi* (Ocimum sanctum), *Neem* (Azadirachta indica), *Sarpagandha* (Rauvolfia serpentina)
Sundarbans & Islands	Wetland ecosystem, humid, saline, brackish water, influenced by tidal conditions.	Saline-tolerant and medicinal plants that help with detoxification, wound healing, and antimicrobial treatments.	*Mangrove* species, *Kalmegh* (Andrographis paniculata)
Arid & Desert Regions	Extremely dry, hot climate, sandy soil, low rainfall, sparse vegetation.	Drought-resistant plants, with compounds beneficial for dehydration, skin protection, and digestive health.	*Aloe Vera* (Aloe barbadensis), *Guggul* (Commiphora wightii), *Opuntia* (Cactus)
North-East India	High rainfall, humid, subtropical to tropical climate, hilly, forested terrain.	High biodiversity of medicinal plants used for respiratory, digestive, and anti-inflammatory health, as well as for detoxification.	*Sarpagandha* (Rauvolfia serpentina), *Turmeric* (Curcuma longa), *Piper longum*
Western Dry Region	Hot, arid climate, low rainfall, alkaline soil, desert vegetation.	Rich in plants with anti-inflammatory, antipyretic, and digestive properties, adapted to extreme dryness.	*Opuntia* (Cactus), *Guggul* (Commiphora wightii), *Strychnos* species

Table 1 Geographical Impact on Medicinal Plants in India.

2.2.1 Climate

Climate, including temperature, precipitation, and humidity, plays a critical role in determining the chemical composition of medicinal plants. Temperature influences the metabolic pathways in plants, thereby affecting the production of active compounds such as alkaloids, phenols, and flavonoids. For instance, *Withania somnifera* (Ashwagandha), grown in drier regions of Madhya Pradesh and Rajasthan, has been shown to produce higher concentrations of withanolides compared to those grown in more humid climates.[29]

Similarly, in regions with high humidity, such as Kerala and West Bengal, medicinal plants like *Curcuma longa* (Turmeric) tend to have higher curcumin content due to the favorable growing conditions, but they are also more susceptible to post-harvest contamination by fungi and bacteria, which can compromise quality.[30]

2.2.2 Soil Composition

The soil type and its nutrient profile are critical in determining the quality of medicinal plants. The mineral content, pH, and organic matter in the soil affect the uptake of nutrients and water, directly influencing the synthesis of bioactive compounds. For example, the rich black soils of Maharashtra and Gujarat support the growth of plants like *Commiphora wightii* (Guggul), known for its resin used in Ayurvedic treatments.[31]

In contrast, the acidic soils of the Himalayan region provide an ideal environment for plants like *Picrorhiza kurroa*, which produces high levels of picroside, a compound used for treating liver disorders. The variation in soil types across India’s agroclimatic zones thus plays a vital role in influencing the medicinal efficacy of plants.[32]

2.2.3 Altitude

Altitude has a profound effect on medicinal plant quality, particularly on plants grown in mountainous regions. Higher altitudes are associated with lower temperatures, higher UV radiation, and lower oxygen levels, which trigger stress responses in plants, leading to the production of higher levels of secondary metabolites.[33]

For example, the medicinal plant *Rheum emodi* (Indian Rhubarb), found in the Himalayan region, contains higher levels of anthraquinones at higher altitudes. Similarly, *Artemisia annua*, grown in high-altitude regions of Uttarakhand, has shown higher artemisinin content, a compound crucial for treating malaria. Altitude, therefore, significantly affects the therapeutic value of medicinal plants.[34]

2.2.4 Water Availability and Quality

Water availability, especially in arid and semi-arid regions of India, plays a crucial role in medicinal plant quality. Plants under water stress, such as those in Rajasthan and Gujarat, often produce higher concentrations of secondary metabolites as a defense mechanism. For example, plants like *Aloe vera* from these regions show higher levels of polysaccharides and anthraquinones.[35]

However, water quality, particularly contamination from industrial pollutants, can negatively affect the quality of medicinal plants. In industrial areas such as Punjab and Maharashtra, medicinal plants grown near polluted water sources have been found to contain heavy metals such as lead and cadmium, which pose serious health risks.[36]

2. 3 Quality Control and Standardization Challenges in Indian Agroclimatic Zones

2.3.1 Variation in Active Compounds

One of the key challenges in ensuring the quality control of medicinal plants is the geographical variability in the concentration of active compounds. For instance, *Curcuma longa* (Turmeric) from Tamil Nadu may have different curcumin content compared to turmeric from Odisha due to differences in climate, soil composition, and agricultural practices. This variation makes it difficult to develop uniform standards for medicinal plant products.[37]

2.3.2 Post-Harvest Management

Post-harvest practices, such as drying, storage, and transportation, are critical in maintaining the quality of medicinal plants. In humid regions like Kerala, improper drying can lead to fungal contamination, which affects the safety of the plant material. In contrast, in arid regions, plants may lose their moisture too quickly, leading to a degradation of volatile oils and other compounds.[38]

The lack of standardized post-harvest practices across different agroclimatic regions poses a challenge to maintaining consistent quality in medicinal plants. There is a need for region-specific guidelines that address the unique post-harvest challenges of each agroclimatic zone.[39]

2.3.3 Regulatory Gaps

The regulation of medicinal plants in India is governed by various bodies, including the Ministry of AYUSH and the National Medicinal Plants Board (NMPB). However, there is often a lack of coordination between these regulatory bodies, leading to discrepancies in quality control standards. Additionally, the existing guidelines, such as the Good Agricultural and Collection Practices (GACP), do not fully account for the geographical variability in plant quality.

There is a need for more comprehensive regulations that take into account the specific environmental factors affecting medicinal plant quality in each agroclimatic zone. This would ensure that medicinal plants meet consistent safety and efficacy standards, regardless of their geographical origin.

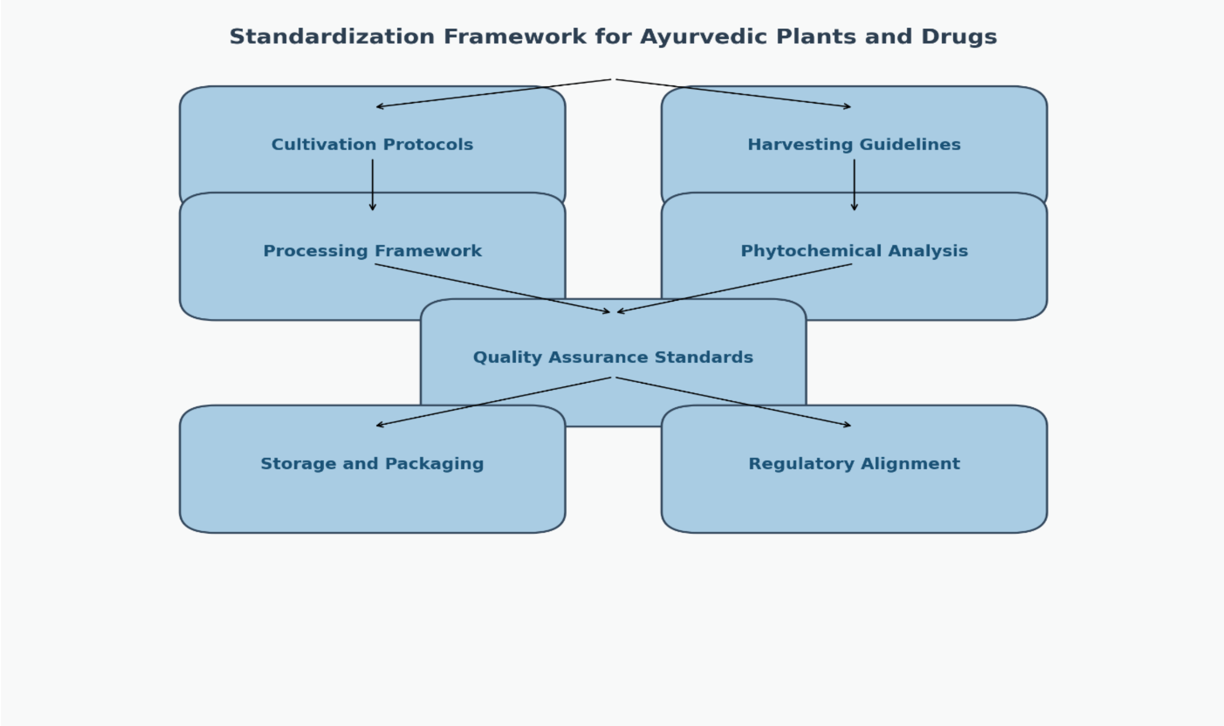

Figure 2: Standardization of ayurvedic plant and drug diagram

2.4 Standardization

Standardization is a fundamental aspect of quality control in herbal drug production. It involves the establishment of definitive standards, inherent characteristics, and precise qualitative and quantitative parameters that collectively ensure the quality, efficacy, safety, and consistency of herbal medicines. This process is grounded in the development and agreement upon technical specifications, informed by rigorous experimentation and empirical observations. These standards define the specific attributes of herbal formulations, thereby serving as a critical instrument in the overarching framework of quality assurance. [40]

Standardization refers to the systematic implementation of measures throughout the manufacturing and quality assurance processes to guarantee consistent and reproducible quality in herbal medicines. This encompasses the entire development spectrum, from the cultivation and growth of the plant to its clinical deployment. It also includes the adjustment of herbal drug formulations to a predetermined concentration of specific active constituents, achieved through the addition of excipients or the combination of herbal drugs or their preparations. Furthermore, the "evaluation" of a drug involves rigorous verification of its authenticity, comprehensive assessment of its quality and purity, and precise identification of any adulteration, ensuring adherence to established regulatory and scientific standards.[41-42]

2.4.1 Importance of Establishing Standards

Establishing rigorous standards for medicinal plants across varying geographical regions is essential to ensuring their quality, safety, and therapeutic efficacy. Geographical factors such as soil composition, climate, altitude, and seasonal conditions profoundly influence the phytochemical profiles of medicinal plants, leading to potential variability in their bioactive constituents and pharmacological effectiveness. Standardization mitigates these challenges by defining clear and measurable criteria for quality, potency, and consistency. This ensures that medicinal plants sourced from diverse regions conform to uniform quality benchmarks, enabling their reliable use in global markets. It also facilitates compliance with international regulatory standards, enhancing the credibility and marketability of herbal products.[43]

Moreover, standardized protocols encompass cultivation, harvesting, processing, and storage practices, minimizing risks of contamination, degradation, and adulteration. Through precise identification and quantification of active compounds, standardization supports the development of reproducible and effective herbal formulations. By ensuring consistent therapeutic outcomes, standardization builds confidence among consumers, healthcare practitioners, and researchers. It also underpins scientific studies and clinical trials by providing uniform materials for investigation. Additionally, it promotes sustainable utilization of plant resources, encourages biodiversity conservation, and fosters the equitable integrationof traditional and modern healthcare systems.

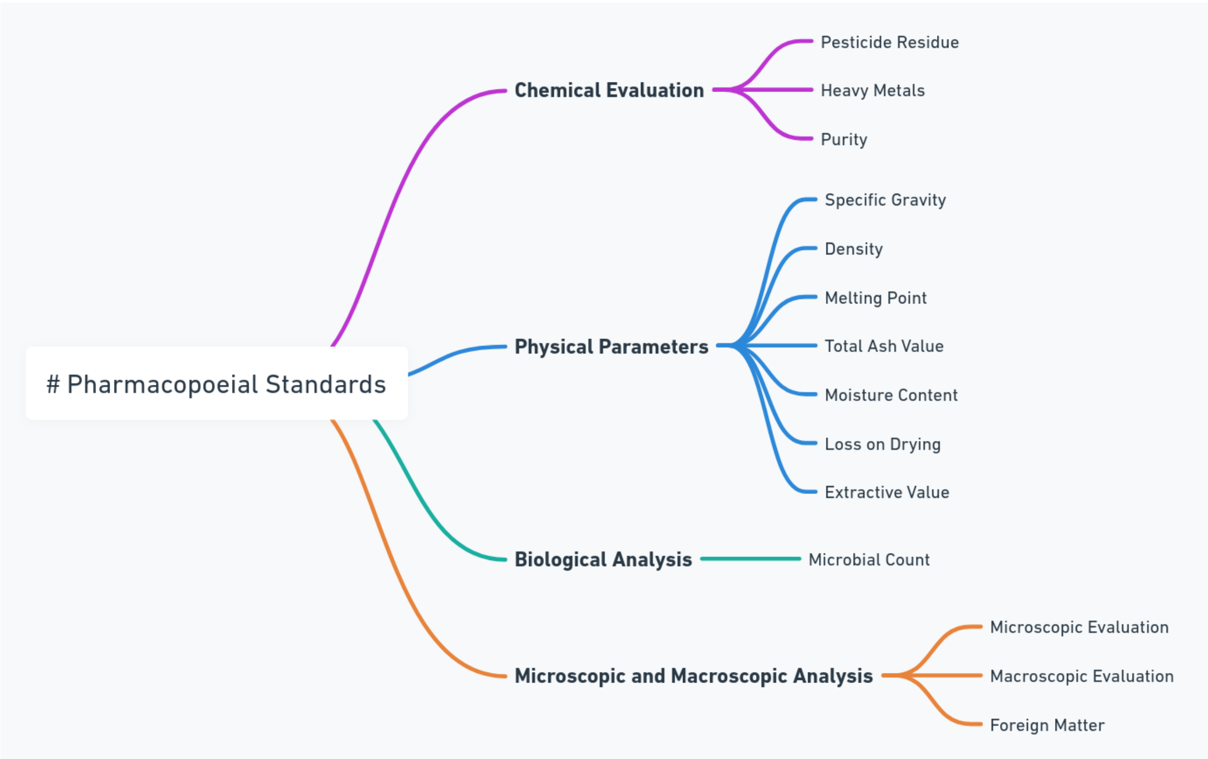

Figure 3: Pharmacopeial standards

2.4.2 Who guidelines for quality standardized herbal formulations

The World Health Organization (WHO) guidelines for quality control and standardization of herbal plants emphasize:

a) **Authenticity**: Ensure correct identification of plant species.
b) **Sourcing**: Use reliable, sustainable sources for raw materials.
c) **Contaminant Testing**: Check for pesticides, heavy metals, and microbiological contaminants.
d) **Moisture Content**: Monitor to prevent microbial growth and degradation.
e) **Active Compounds**: Standardize concentration of active ingredients.

f) **Storage Conditions**: Maintain proper storage to preserve quality.
g) **Processing**: Ensure appropriate methods to retain medicinal properties.
h) **Labeling**: Provide accurate, clear information on composition.
i) **Safety**: Assess toxicity and side effects.
j) **Good Manufacturing Practices**: Follow established manufacturing guidelines.

In traditional medicine systems, remedies are commonly prepared as water decoctions or ethanol extracts. Therefore, the plant materials used must be authentic and free from contaminants such as pesticides, heavy metals, microbes, and radioactive substances. The plant material is typically subjected to a single or repeated solvent extraction, or water decoction, as outlined in ancient texts. The resulting extract must be tested for its biological activity using standard models. The bioactive extract should be standardized based on its active ingredients or key compounds, along with chromatographic profiles (e.g., TLC, HPTLC, HPLC,HRMS) to ensure consistency and quality.[44]

2. 5. Strategies for Harmonizing Quality Control Standards

2. 5.1 Geographical Indication (GI) Labeling

One strategy for addressing geographical variability in medicinal plant quality is the implementation of Geographical Indication (GI) labeling. This system would certify that a particular medicinal plant is grown in a specific region known for its optimal growing conditions. For example, *Ashwagandha* from Madhya Pradesh or *Turmeric* from Kerala could be labeled with a GI tag, ensuring consumers of the quality and origin of the product. [45]

2.5.2 Region-Specific Quality Control Standards

To harmonize quality control standards, it is essential to develop region-specific guidelines for the cultivation, harvesting, and processing of medicinal plants. This would involve setting mi2nimum standards for active compound concentrations, pesticide use, and post-harvest handling practices that are tailored to each agroclimatic zone.[46]

2. 5.3 Use of Advanced Analytical Techniques

The use of modern analytical techniques such as High-Performance Liquid Chromatography (HPLC), Gas Chromatography-Mass Spectrometry (GC-MS), and Near-Infrared Spectroscopy (NIRS) can help ensure the quality of medicinal plants by accurately measuring the concentration of active compounds. These techniques should be integrated into routine quality control procedures to provide reliable data on the chemical composition of medicinal plants from different regions.[47]

2.5.4 Chromatography

The process of isolating individual components from a herbal mixture is crucial for identification and bioactivity assessment. Chromatography serves as an effective analytical technique for separating and quantifying a wide range of compounds, even in complex samples. Methods such as paper chromatography(PC), thin-layer chromatography(TLC), gas chromatography(GC), high-performance liquid chromatography(HPLC),High-Resolution Mass Spectrometry(HRMS) and capillary electrophoresis(CE) are commonly used for this purpose.[48-50]

Thin-Layer Chromatography (TLC) is widely used in the phytochemical analysis of herbal medicines due to its ability to quickly analyze herbal extracts with minimal sample preparation. It provides both qualitative and semi-quantitative data on the resolved compounds. In TLC fingerprinting, data recorded with a high-performance TLC (HPTLC) scanner include chromatograms, retardation factor (Rf) values, the color of separated bands, their absorption spectra, λ max, and shoulder inflections of all separated bands. These, along with profiles obtained after derivatization with various reagents, form the sample's TLC fingerprint. HPLC fingerprinting involves recording chromatograms, retention times of peaks, and absorption spectra (using a photodiode array detector) with different mobile phases. Similarly, Gas-Liquid Chromatography (GLC) is used to generate fingerprint profiles of volatile and fixed oils from herbal drugs.[51] Preparative HPLC comes in two types: low-pressure (typically under 5 bar) and high-pressure (above 20 bar). HPTLC is also employed for simultaneous assays of multiple components in multi-component formulations, often requiring smaller mobile phase quantities compared to HPLC. It is widely utilized in the pharmaceutical industry for process development, detecting adulterants in herbal products, identifying pesticide residues, mycotoxins, and ensuring the quality control of herbs and health foods.[52]

3. Discussion

India's exceptional biodiversity and diverse agroclimatic conditions offer immense potential for the cultivation of medicinal plants. However, this same diversity introduces significant challenges in ensuring consistent quality and standardization of plant-based medicinal products.[53] Variability in environmental factors such as climate, soil composition, altitude, and water availability across regions profoundly influences the phytochemical composition, bioactive compounds, and overall therapeutic efficacy of medicinal plants[54]. For instance, plants from high-altitude Himalayan regions tend to produce higher concentrations of secondary metabolites due to environmental stress, while fertile Indo-Gangetic plains yield consistent phytochemical profiles. These variations underscore the need for region-specific approaches to quality control [55].

Standardizing medicinal plant quality across agroclimatic zones is complex. Climatic factors like humidity in coastal areas can lead to microbial contamination, while arid regions may experience rapid degradation of volatile compounds[56]. Advanced analytical techniques such as High-Performance Liquid Chromatography (HPLC), Gas Chromatography-Mass Spectrometry (GC-MS), and High-Performance Thin-Layer Chromatography (HPTLC) play a pivotal role in quantifying and profiling active compounds to ensure product consistency. [57-58] Additionally, implementing Geographical Indication (GI) labeling and harmonizing region-specific cultivation, harvesting, and post-harvest management practices are essential for mitigating variability.[59] Adherence to international guidelines, such as WHO's standards for herbal formulations, can further enhance the reliability and global acceptance of Indian medicinal plants. A comprehensive framework combining scientific rigor, technological advancements, and regulatory alignment is essential to leverage India's agroclimatic diversity while ensuring the safety, efficacy, and quality of medicinal plants in traditional and modern healthcare systems.

4. Conclusion

India’s agroclimatic diversity significantly impacts the quality, phytochemical composition, and therapeutic properties of medicinal plants, posing both opportunities and challenges for quality control and standardization. Variations in climate, soil, altitude, and water availability influence the bioactive compounds, necessitating a robust framework to ensure consistency. Strategies like Geographical Indication (GI) labeling, region-specific cultivation practices, and advanced analytical methods (e.g., HPLC, GC-MS) are vital to achieving global quality benchmarks. Harmonizing standards with WHO guidelines will enhance the credibility and marketability of India’s medicinal plants. By addressing these challenges, India can support the growth of its traditional medicine and pharmaceutical sectors, ensuring the production of safe, effective plant-based medicines for domestic and international markets.[60]

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