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Review Article

Adulteration in Herbal Medicines: A Comprehensive Review on Types, Detection, and Health Impacts

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ABSTRACT

Background: Adulteration of herbal medicines is a large-scale issue that compromises the quality, safety, and therapeutic effect of herbal drugs. It entails deliberate substitution, contamination, and incorporation of undeclared synthetic compounds, which often leads to serious adverse health effects. **Objectives:** This review critically examines the prevalence, character, and public health impact of herbal adulteration. It also specifies present advancements in identification methods and persistent gaps in methods and authentication. **Materials and Methods:** A critical literature review of world case studies, pharmacopoeial reports were taken. Emphasis was placed on the prevalence of adulteration of widely used herbal medicines. Both traditional methods of analysis (chromatographic and spectroscopic) and the newer tools, like artificial intelligence-based systems for authentication and classification, were considered. **Results:** Substitution adulteration is the most common, up to 70-90% in prevalent herbs like *Coscinium fenestratum, Embelia ribes,* and *Saraca asoca*. Various commercial preparations were detected to contain undeclared synthetic adulterants like corticosteroids, NSAIDs, and sildenafil. Heavy metals, microplastics, and pesticides as impurities add a triple burden of exposure, resulting in oxidative stress, endocrine disruptions, neurotoxicity, reproductive toxicity, and microbiome disruption. Though non-destructive, quick authentication techniques, most notably AI-powered image recognition and spectral analysis, are on the horizon, their application in daily quality control is still limited. **Conclusion:** Harmonized international regulation, more robust quality control measures, and better pharmacovigilance systems are needed urgently. Integrating interdisciplinary collaboration, building capacity, and enhancing consumer education will be key to controlling adulteration and the long-term credibility and safety of herbal medicines.

Keywords: Adulteration, Artificial Intelligence, Chromatography, Herbal Drugs, Machine Learning, Pharmacovigilance, Toxic Effects.

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INTRODUCTION

The application of medicinal herbs has been a fundamental component of medical systems worldwide, from ancient societies to modern times. In the last decades, a widespread renewal of interest in natural remedies has been fostered by a perceived safety of natural products, growing concern about side effects of synthetic drugs, and an increased interest in holistic health and wellness solutions.[1] The renewed interest, though, has raised to the center stage a paramount and insidious problem: i.e. medicinal herb adulteration. Adulteration is the intentional or unintentional replacement, addition, or mixing of true herbal material with substandard, depleted, or even poisonous material. Adulteration can be practiced in the form of replacement of morphologically identical but chemically or therapeutically weaker plant species, addition of chemical synthetics, incorporation of depleted or spent plant material, or admixture of non-medicinal vegetative material with true drugs.[2] In some, the adulteration is intentional on account of economic incentives like unavailability of the original raw material, exorbitant prices of the original material, or in order to maximize profit margins. In others, adulteration is unintentional due to reasons like confusion caused by local naming practices, lack of botanical knowledge, or because it is hard to find and identify the original plant species. The implications of adulteration in medicinal plants are deep-seated and far-reaching.[3] At the most basic level, adulteration compromises the therapeutic effectiveness and safety of herbal remedies, putting consumers at risk of adverse health effects from less effective to severe toxicity. Introduction

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of substandard or toxic ingredients not only dilutes the value of herbal medicines but also erodes public trust in traditional and alternative medicine systems. Moreover, the ubiquitous prevalence of adulteration of herbal products poses significant challenges to their standardization, quality control, and regulation, which renders it impossible to ensure their safety and efficacy in domestic as well as foreign markets.[4]

Several interrelating factors have attributed to the rising rate of adulteration in the herbal medicine sector. The continued overharvesting of natural resources, industrialization, and rampant deforestation has led to the loss and, in other cases, the extinction of the critical medicinal plants. This deficiency, combined with a continuously increasing global demand for herbal drugs, has provided fertile ground for the outbreak of adulterant of raw drugs.[5] Also, a deficiency in proper quality control practices, unfavorable regulatory norms, and less training among collectors and traders all contribute to this problem. The heterogeneity of herbal mixtures, include a range of herbal constituents, also makes it more difficult in identification of adulterants. Adulteration detection in pharmaceutical plants has made tremendous progress since the past.[6] Although macroscopic and microscopic analysis has remained conventional and still continues to play an essential role in the initial assessment of herbal material, the advances in analytical chemistry have introduced sophisticated chromatographic and spectroscopic techniques capable of detecting and measuring adulterants with great precision. In more recent years, Machine Learning (ML), Deep Learning (DL) and Artificial Intelligence (AI) algorithms have also been incorporated to continue enhancing the efficiency and sensitivity of adulteration detection, enabling quick screening and quality control of herbal products at an expanded scale. This includes the development and implementation of robust quality control strategies, the establishment of standard regulatory systems, and the promotion of good cultivation and harvesting practices. Human resource capacity building for adequate education and training of all sectors in the manufacture, value chain, and regulation of herbal medicinal products is also important.[7] Through its promotion of increased awareness and vigilance, the herbal medicine fraternity can collectively ensure the integrity, safety, and therapeutic value of medicinal herbs in the wake of growing challenges. Though earlier reviews have discussed herbal adulteration, few have discussed both traditional methods of detection and particular case studies in addition to recent technological improvements. This review fills the gap by categorizing adulteration types and critically assessing both traditional and new authentication methods, such as the increasing role of AI and ML. By contrast of analytical tools with AI-based models and use of real-life regulatory reports, it provides an integrated pharmacogenetic, phytochemical, and computational view towards strengthened detection of adulteration. Through such a thorough analysis, the article aims to be part of the debate on how to ensure the authenticity, quality, and safety of medicinal herbs in a rapidly changing and interconnected marketplace.

TYPES OF ADULTERATION

Substitution with inferior commercial varieties

Adulteration takes place largely by substitution with commercial varieties morphologically similar but chemically or therapeutically inferior. It is a conscious attempt to augment gains. For instance, *Cassia angustifolia* (*Arabian Senna*), *Cassia obovata* (Dog senna), are usually employed to adulterate authentic Senna (*Cassia acutifolia*). Likewise, Japanese ginger (*Zingiber mioga*) can be employed to replace medicinal ginger (*Zingiber officinale*). According to studies about 80 percent of *Saraca asoca* were adulterated with *Polyalthia longifolia* because it is cheap as compared to original Ashoka and causes side effects due to having different chemical constituents.[7] Figure 1A shows adulteration with lower commercial varieties, where imperfect or unrelated herbals are utilized in place of the reliable herbal, compromising therapeutic action.

Adulteration using artificially manufactured substances

Synthetic substances that look like the actual drug and mixed with the raw drug. Some typical instances are the production of artificial paraffin wax, yellow-colored to resemble beeswax, or basswood used in place of actual nutmeg. Artificial invert sugar is sometimes mixed with natural honey to adulterate it. According to US market herbal market 12% of herbals contained artificial material. Figure 1B depicts the use of artificially synthesized substances added to herbal formulations to mimic natural constituents or falsely enhance pharmacological action.[8]

Substitution by exhausted drugs

Exhausted plant material, from which the active chemical compounds have already been isolated, is used again and wrongly marketed as the original crude drug. This method is prevalent in drugs with volatile oils, like fennel and cloves. At times, when the extraction is completed, plant material is dyed artificially to match the natural pigmentation, as is the case with saffron and red rose petals. In Nigeria 40% of *Withania somnifera* contained exhausted material in root powder after extraction process decrease efficacy by 90%.[9] Figure 1C illustrates the recycle of exhausted herbals that have already been isolated results decrease in potency of herbal material.

Substitution by superficially similar inferior natural substances

In such cases, the adulterant does not have any chemical, pharmacological, or botanical similarity to the genuine crude drug. Yet, because of superficial appearance, it is employed to mislead purchasers. Leaves of *Ailanthus glandulosa* can be replaced with *Atropa belladonna*, senna, or peppermint leaves. Saffron can be adulterated by safflower, and peach kernel oil can be used to simulate olive oil. Giloy (*Tinospora cordifolia*) famous herb in Ayurvedic industry having huge health benefits. However, 56% *Tinospora crispa* is used in place of original giloy because of similar lookalike can be dangerous if consumed due to difference in chemical properties.[10] Figure 1D represents the adulteration practice including superficially lookalike herbals, which can mislead customers and avoid detection because of physical resemblance.

Addition of synthetic products

In order to enhance the perceived quality of a drug, synthetic ingredients are sometimes incorporated. This involves adding citral to lemon oil or benzyl benzoate to balsam of Peru. Although it will mimic the anticipated scent or taste, it detracts from the authenticity and safety of the herbal remedy. According to World Health Organization (WHO) bulletin, 20-30% of herbal market samples across South Asia was adulterated with synthetic material.[11] Figure 1E highlights the mixing of man-made chemical material, like dyes or synthetic actives, which may cause harmful effects when utilized in herbal formulations.

Adulteration using vegetative matter of the same plant

In a few instances, vegetative plant parts (which lack the active principles) are blended with the drug. These include the incorporation of liverworts and epiphytes on bark fragments into *Cascara* or *Cinchona*, and excess stems into drugs such as *Lobelia* or *Stramonium*.[12] Figure 1F demonstrates the presence of vegetative parts which are not therapeutically active but are used to increase the volume of herbal formulations.

Adulteration with toxic materials

Adulterants that are poisonous may cause severe health risks. Such adulterants include big stones inserted into bales of liquorice root, limestone fragments in asafetida, lead balls in opium, and glass fragments in colophony. Barium sulfate or manganese dioxide used to adulterate cochineal is other examples. According to a study, 2% of Ayurvedic formulations include lead (Pb) levels exceeding 10 ppm, which has been linked to brain toxicity and Chinese herbal have 5% pesticide residues above with chlorpyrifos results in liver toxicity.[13] Figure 1G presents toxic adulteration, where harmful products are deliberately used, cause chronic side effects to human health.

Adulteration of powdered drugs

Powdered medicinal drugs are more prone to adulteration because of the facility of mixing. Some of the usual adulterants are powdered olive stones mixed with gentian, liquorice, or pepper powders; brick powder mixed with powdered barks; red sanders wood in chilli powders; and dextrin mixed with powdered *ipecacuanha*.[13] Indian Pharmacopoeia Commission highlights that >25% powdered herbal preparations were adulterated with exhausted ingredients. This practice decreases the therapeutic action of the herbal material; Figure 1H highlights the difficulty of identification of adulteration in powdered of herbals, which often meticulously lookalike original material in color and texture.[13]

Direct or intentional adulteration

These encompass all intentional types of adulteration, including substitution with poorer quality products, spent drugs, artificial principles, or unrelated plant material. It is commonly driven by financial considerations and can or cannot have immediate health consequences, but it detracts from therapeutic effectiveness.[11] *Zingiber officinale* (ginger) is sometimes visually substituted with Japanese ginger, making it a case of morphological adulteration. Another example is the addition of synthetic drugs like diclofenac and ibuprofen to herbal formulations, which represents pharmaceutical adulteration aimed at enhancing perceived therapeutic effects.

Indirect or unintentional adulteration

This type of adulteration occurs because of ignorance, confusion, or unscientific practices. Adulteration in herbal drugs by mistake is frequently due to confusion over local nomenclature, for example, name "Parpatha" being used for various plants in Ayurveda (*Fumaria parviflora*) and Siddha (*Mollugo pentaphylla*). It may also occur through misidentification, such as the confusion of *Mesua ferrea* (Nagakesar) with *Calophyllum inophyllum*, or through lack of the authentic plant, as with the use of *Hypericum patulum* in place of *Hypericum perforatum*. Morphological or olfactory similarities, such as those seen in red dyestuff-yielding plants *Ventilago madraspatana* and *Arnebia euchroma*, are another factor. Thoughtless collection and scarce knowledge of plants also add to the likelihood of accidental adulteration. Such examples demand urgent requirement for regulatory laws, analytical techniques to make sure authenticity of herbals.[6]

Reasons for Adulteration

Adulteration of botanical medicines stems from the reasons of scarcity, excessive price, toxicity, morphological likeness, and ignorance of the plant. Lack of availability of herbals because of harvesting, seasonal alteration, or geographical differences leads to substituted with lower-quality or inactive herbals, decrease effectiveness.[6] Exorbitant in market value also motivate intentional adulteration for financial gain.[5,6] Substitution has also been necessitated by safety issues, e.g., nephrotoxic *Aristolochia fangchi* has been substituted with *Stephania tetrandra*,[14] and hepatotoxic *Actaea racemosa* and Symphytum officinale are replaced with *Trifolium pratense, Angelica sinensis*, PA-free comfrey, *Valeriana officinalis,* and *Passiflora incarnata*.[15-17] While focused on toxicity minimization, such substitutions impact therapeutic uniformity and patient safety.[18,19] Adulteration also occurs due to misidentification, such as *Mesua ferrea* (Nagakesar) being substituted with *Calophyllum inophyllum* because of easier availability, even though there are morphological differences such as ovary organization.[6] *Mucuna pruriens* is also mistaken for *Mucuna utilis, Macroptilium deeringianum,* and *Canavalia ensiformis* because of seed similarity.[4,6] These factors underline the need of stringent detection and authentication procedure in herbal quality control. Various examples of adulterants shown in Table 1.

Techniques Used for Detection of Adulterants

Detection of adulteration in raw herbals starts with simple yet powerful tools like macroscopic and microscopic evaluation and powder microscopy, which remain foundational in pharmacogenetic analyses.

Macroscopy

It involves naked-eye visual inspection of the whole or chopped herb. It helps in the finding of physical adulterants on the basis of features like size, shape, color surface features, texture, odor, and fracture. For instance, macroscopic variation can detect adulterant of authentic seeds (*Mucuna pruriens*) with larger or colored ones such as *Macroptilium deeringiana* or *Mucuna utilis*.[20]

Microscopy

It gives a clearer picture by studying transverse sections or surface views of plant tissue under the microscope. It enables one to see internal structures like arrangement of cells, trichomes, vascular bundles, calcium oxalate crystals, starch grains, and secretory structures. These diagnostic characters are usually characteristic of a particular plant species and can distinguish between genuine materials and adulterants. For instance, in Nagakesar adulterated by *Mesua ferrea*, the latter has a two-celled ovary, whereas *Calophyllum inophyllum*, the adulterant, possesses one-celled ovary differentiable under microscopic examination.[14]

Powder microscopy

This becomes highly significant when the drug is in powder form, wherein macroscopic identification is not feasible. The powdered specimen is subjected to reagents such as chloral hydrate, phloroglucinol-HCl, or iodine and examined under a compound microscope. Key elements like starch grain types (simple or complex), trichome types (unicellular, multicellular, glandular), crystal type, and fiber types are described. The presence or absence of these typical features verifies the sample as genuine. For example, powdered bark of Asoka is distinguished from its adulterants such as *Polyalthia* or Kachnar on the basis of fiber type, vessel type, and crystal type.[13,12]

Hence, macroscopy and microscopy, especially powder microscopy, are invaluable, low-cost, and effective tools for daily quality assessment and adulteration detection of herbal medicines. They are the first line of defense in checking for identity and purity of medicinal plant material before subjecting it to higher-level methods like chromatography or DNA barcoding.

Different analytical techniques used for detecting adulterants

Chromatographic techniques

Chromatography is one of the most widely used methods for detecting adulterants due to its high separation efficiency and ability to analyze complex mixtures. Several types of chromatography are employed.

Thin-Layer Chromatography (TLC)

TLC is an easy, inexpensive, and quick technique employed for the separation of components in herbal matrices. Combined with densitometry, TLC can also measure adulterants like sibutramine, with validation parameters having high precision and accuracy. For example, Hayun and coworkers applied TLC-densitometry to determine sibutramine with a low LOD of 217.5 ng/spot and general recovery rate of 99.7%. The combination of Surface-Enhanced Raman Spectroscopy (SERS) with TLC enhances the sensitivity of detection for synthetic

Table 1: Different examples of adulterants of genuine drug.[14]

Genuine drug	Botanical name	Major adulterant	Botanical name
Aloes	*Aloe barbadensis*	Natal aloes	*Aloe barberae*
Asoka	*Saraca asoca*	False ashoka	*Polyalthia longifolia*
Bakula	*Mimusops elengi*	Kamala	*Nelumbo nucifera*
Bharangi	*Clerodendrum serratum*	Kantakari	*Solanum xanthocarpum*
Chavya	*Piper chaba*	Pippali	*Piper longum*
Digitalis	*Digitalis purpurea*	Primrose	*Primula vulgaris*
Liquorice	*Glycyrrhiza glabra*	Russian liquorice	*Glycyrrhiza echinata*
Tagar	*Valeriana wallichii*	Kustha	*Saussurea lappa*
Belladonna	*Atropa belladonna*	Black nightshade	*Solanum nigrum*

drugs within complex herbal matrices and provides a more sensitive option.[21] The TLC-SERS is a strong analyzer of analytes in complex herbal mixtures. A new universal silver nanoparticle colloid, was synthesized using N,N-Dimethyl formamide that can be applied both to hydrophilic and hydrophobic compounds. The optimized 2:1 system has good SERS enhancement and stability for 90 days. It facilitated effective characterization of herbal materials for lipid-lowering and respiratory health, providing rapid on-site quality control and adulteration detection. When integrated with techniques such as Gas Chromatography-Mass spectroscopy (GC-MS), Nuclear Magnetic Resonance (NMR) it helps in detecting major biochemical and molecular alteration in herbals.[22]

Liquid Chromatography (LC)

Ultra-Performance Liquid Chromatography (UPLC) and High-Performance Liquid Chromatography (HPLC) are highly appreciated for their good sensitivity, resolution, and capacity for screening multiple compounds simultaneously. For example, a combination of Ultra-Performance Liquid Chromatography with Quadrupole Time-of-Flight Mass Spectrometry has been utilized for detecting adulterants such as sildenafil, tadalafil, and other Phosphodiesterase-5 inhibitors in herbal drugs, with a gradient elution providing a sufficient separation. LC methods also have the tendency to use focused mobile phases and columns specific to the desired analytes with low detection limits and high reproducibility.[20]

Gas Chromatography (GC)

GC is particularly suited to unstable and thermally stable compounds. Although less frequently utilized than LC and TLC, gas chromatography can be extremely sensitive and specific, especially when used with mass spectrometry (GC-MS). More recent literature has utilized hydrogen as a carrier gas to improve on separation rate and cost, making GC more viable for use in routine analysis. GC-MS makes possible the ionization and fragmentation of each compound, which directly allows for the detection of adulterants through their mass spectra.[20]

Combination of chromatography with detectors

Current chromatographic techniques are most often accompanied by sensitive detectors like mass spectrometry and surface-enhanced Raman spectroscopy. As an example, SERS coupling with TLC enhances the sensitivity and selectivity of detection of undeclared synthetic drugs in herbal medicines with minimized interference from complex matrices.[22]

Spectroscopic Techniques

Spectroscopic methods leverage the interaction of electromagnetic radiation with chemical compounds to identify and quantify adulterants.

Infrared (IR) Spectroscopy

IR spectroscopy can be combined with chemometric techniques like partial least squares to analyze complex herbal matrices.

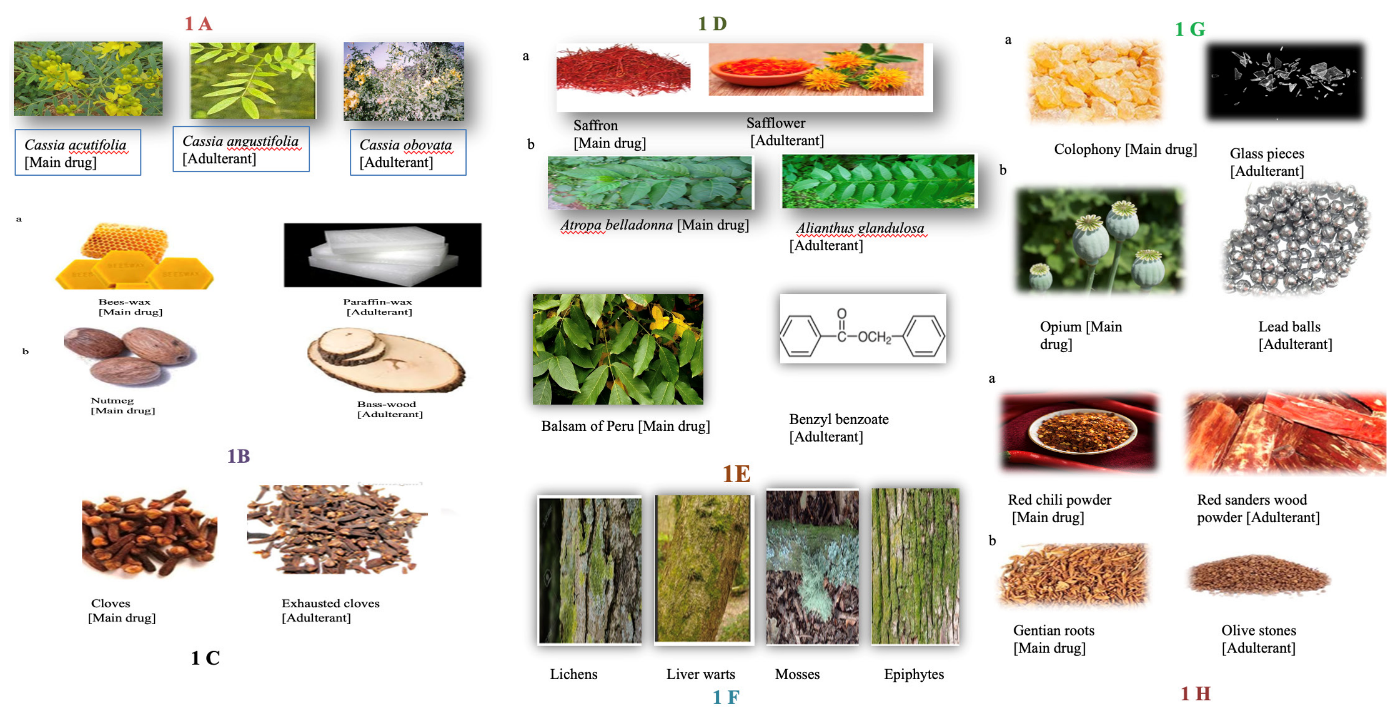

Figure 1: Examples of adulterations in herbal drugs; A: Substitution with inferior commercial varieties reducing therapeutic efficacy; B: Use of artificially synthesized substances mimicking herbal properties; C: Repackaging and sale of exhausted drugs with reduced active constituents; D: Adulteration using morphologically similar plant materials; E: Intentional mixing of synthetic chemicals to alter appearance or potency; F: Addition of non-medicinal vegetative parts or unrelated plant species; G: Inclusion of toxic adulterants posing serious health risks; H: Use of indistinguishable foreign substances in powdered herbal drugs.

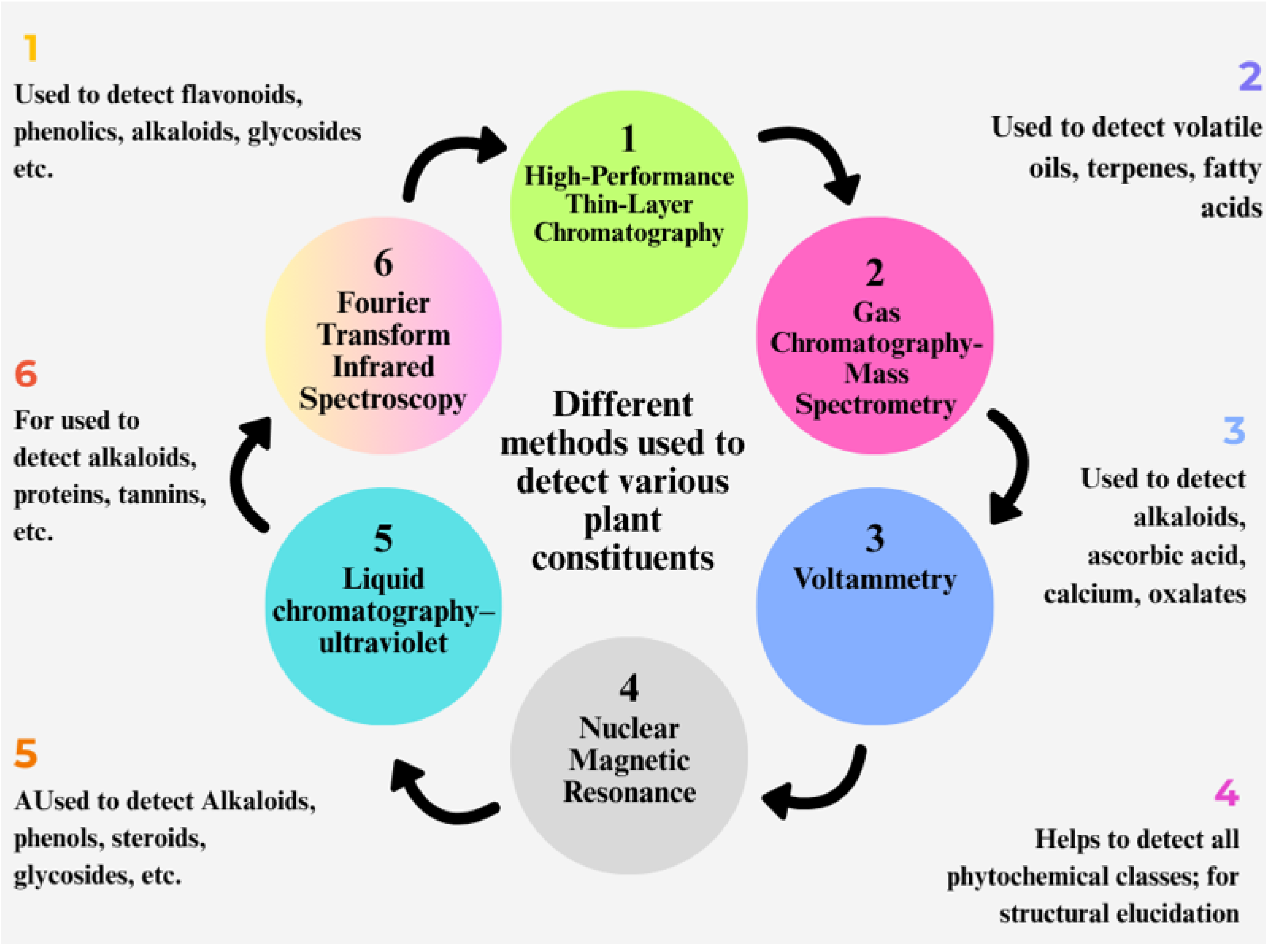

Figure 2: Comparative summary of analytical tools employed to identify adulterants in herbal drugs.

For instance, the IR-PLS method has been used to validate the detection of dexamethasone in herbal formulations, with high correlation coefficients indicating reliable measurement.

Nuclear Magnetic Resonance (NMR) Spectroscopy

NMR, especially low-field ^1H NMR, has proven effective in identifying and quantifying adulterants such as sibutramine and phenolphthalein in slimming supplements. Utilized this approach to analyze low concentrations of adulterants, demonstrating its high sensitivity and suitability for routine quality control.

UV-vis and spectrophotometry

These methods, often using partial least squares algorithms, enable rapid and sensitive detection of specific adulterants like dexamethasone. Validation parameters, such as low residual standard deviation and high recovery rates, indicate the robustness of these methods.

DNA-barcoading

DNA barcoding is a robust molecular tool for the authentication of herbals and adulteration detection. In a study, approximately 25-30 commonly traded Indian herbs were examined using two DNA markers (nr-ITS and psbA-trnH). Against authenticated Biological Reference Material (BRM), more than 200 market samples collected from 32 locations in South India indicated 12% adulteration. The technique provides accurate species-level identification, which is beyond classical approaches and facilitates quality control. Its incorporation into regulatory systems along with botanical authentication, chemical fingerprinting, and AI software can enhance traceability and security in the trade of herbals. In contrast to chromatographic and AI models, DNA barcoding is reproducible, taxonomically sound, and informative where morphology is ambiguous.[17] Figure 2 shows different methods used for detecting various herbal constituents.

Advances in analytical and AI-based technologies for herbal drug authentication and toxicity screening

The most recent advances in herbal drug authentication and toxicological testing utilize both the conventional methods (TLC, microscopy) and new mechanisms like DNA barcoding and AI. *Plumbago indica*, for instance, was successfully identified using TLC and ITS2-based DNA barcoding. DL enabled the conversion of DNA sequences to images that were processed by neural networks to identify species.[22] AI improves DNA sequencing through reducing human errors and revealing novel gene interactions. Intelligent detection instruments using

CCD cameras enhance accuracy in detecting toxic substances. Multi-modal platforms using TLC, UV-vis, and spectroscopy enable authentication of herbal medicines. AI techniques like Convolutional Neural Network (CNNs), Support Vector Machine (SVM), and Partial Least Squares Discriminant Analysis (PLS-DA) can recognize similar-looking samples using Raman data with overfitting avoided by validation methods (like k-fold and external testing), thus ensuring accurate, high-throughput herbal screening.[20]

Role of artificial intelligence in detecting adulteration in herbal products and applications

AI act an important role in certain the quality and safety of herbal formulation by identify adulteration. Common issues such as adding harmful material or utilization the false herbal parts decrease efficacy and cause chronic diseases. Methods such as spectroscopy and chromatography assist in identifying chemical fingerprints that are utilized by AI algorithms such as SVM and Artificial Neural Network (ANN) to identify anomalies.[23] AI also integrates with image analysis software to detect adulterants in micro-images and, when used with HPLC or GC-MS, correctly identifies authentic versus counterfeit samples. Cross-Industry Standard Process for Data Mining (CRISPR)-based technologies and multiplexing enable DNA-based adulterant detection in several samples simultaneously. Adulterant detection in herbal products has been demonstrated by AI with more than 90% accuracy and has outperformed conventional methods in speed and accuracy. As the demand increases, AI provides an efficient and effective solution for quality control and consumer protection. Naman and colloquies (2024) applied DL to identify *Cuminum cyminum* and its adulterants,[24] and MobileNetV2 for detection of *Capsicum annum* with 98.6% accuracy.[25] Transfer learning was applied in another study on cardamom with 95.5% accuracy,[26] and CNN-MobileNetV2 for raw chili with 97.9%.[27] Detection of *Ficus deltoidea* leaf images was boosted by Principal Component Analysis [PCA] to 99%.[28] Leaf Net of Barré and group augmented the Leaf snap dataset to get 99.6% accuracy on Flavia[29] PCA improved Probabilistic Neural Network [PNN] accuracy on Flavia to 95%.[30] OTSU thresholding was employed by Gao to detect 99% of leaves,[31] and level-set segmentation was employed by Nandyal with SVM getting 98% for trees.[32] Husin employed resizing, converting into grayscale, canny edge detection, with a success rate of 98.9%.[33] Singh employed various preprocessing techniques on ANN models of plant species with 98.8%.[34] Caglayan utilized shape and color features to improve classification.[35] A ResNet50-based DL system was trained on five leaf classes with high accuracy, such as 99.7% for papaya and 98.6% for rambutan.[36] Another research incorporated Two-Dimensional Correlation Spectroscopy [2D-COS] with ResNet for classification of Gentian species, enhancing

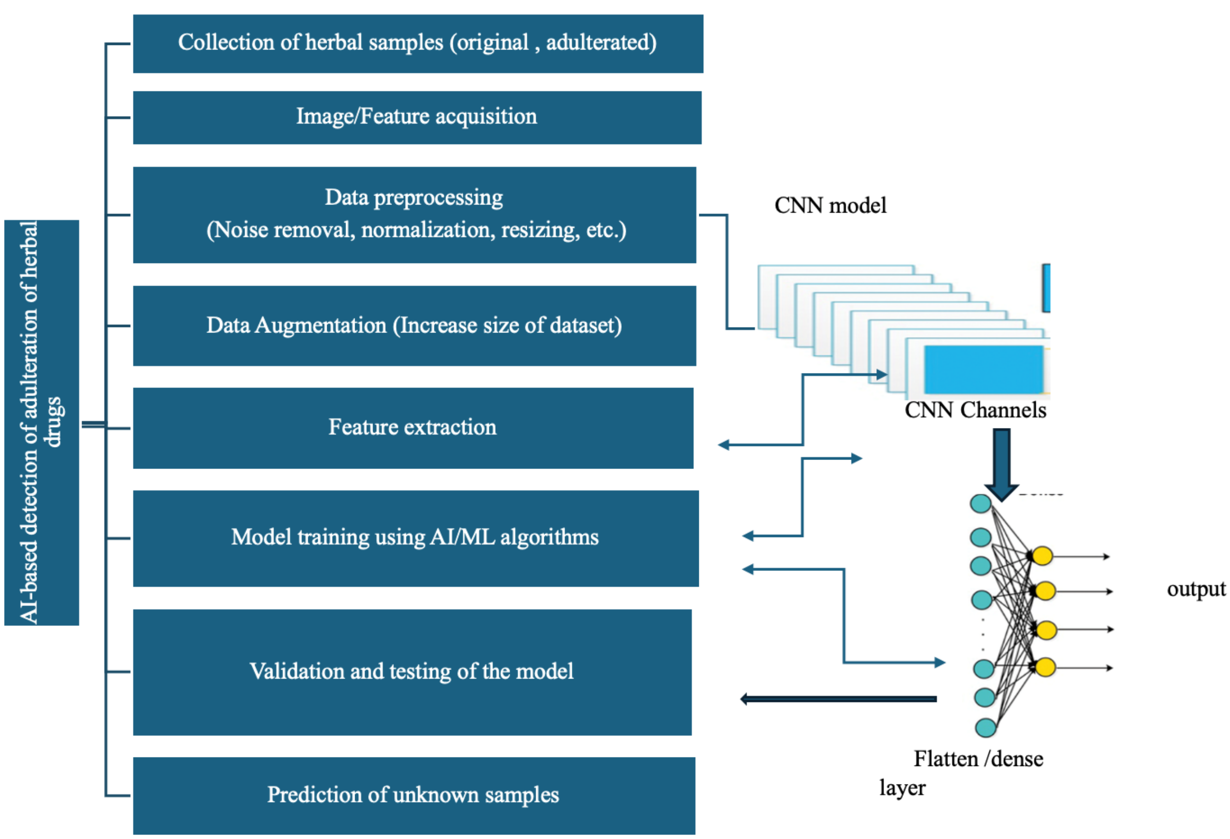

Figure 3: Overview of AI techniques including CNN used for authenticating herbal drugs on the basis of image and spectral data.

performance through data augmentation.[37] The ResNet50-Discriminant Principal Component Analysis model employed in detecting tomato leaf diseases had 99.28% accuracy with a detail-preserving mechanism.[38] Although having high accuracy, AI approaches are challenged by issues such as overfitting, black-box properties, and computationally heavy nature, making scalability and interpretability constrained.[39] Table 2 indicates the comparison in conventional and AI methods. Figure 3 gives work flow of AI in detecting adulterants.

LIMITATIONS OF AI MODELS IN HERBAL DRUG AUTHENTICATION

Alongside the advantages, certain limitations of AI must also be considered to ensure the balanced execution and interpretation. Figure 4 depicts the shortcomings of AI in detecting herbals.[39]

Importance of Monitoring Herbal Medicine Safety

Herbal products are consumed by millions of individuals worldwide to cure all sorts of ailments. Being popular and having a long history of traditional medicine use, most of these products remain outside national pharmacovigilance systems. This is a cause for concern, particularly since adverse effect and poisoning cases due to the use of herbal products are on the rise in many parts of the world. Safety monitoring of herbal products is now a public health concern. Ensuring that these products are safe and effective helps protect consumers and builds trust in traditional medicine systems.[40]

Regulatory challenges

One of the biggest challenges in herbal medicine safety is that countries do not have a standard regulatory system. The same herbal product can be defined as a food, supplement, or medicine based on local legislation. This inconsistency hinders the ability to define and regulate herbal medicines uniformly. For example, in the US, herbal supplements are covered by the Dietary Supplement Health and Education Act of 1994 hence, herbal supplements do not need new safety studies if they were on the market prior to 1994. The Food and Drug Administration has to establish harm instead of requiring manufacturers to establish safety. Further, poor coordination among regulatory authorities

Table 2: Difference in parameters in conventional and AI-integrated methods.

Techniques	Conventional techniques	AI-integrated techniques
Sensitivity	Moderate (µg-mg)	Higher (ng-µg), due to noise filtering and enhanced feature extraction.
Specificity	Low to moderate; overlaps in complex mixtures	High; multivariate models distinguish subtle spectral differences.
Accuracy and precision	Depends on operator skill and matrix complexity	Higher due to automated, data-driven decision-making.
Data interpretation	Manual; subject to human error and bias	Automated; patterns identified even in noisy or complex datasets.
Speed of analysis	Fast once calibrated	Fast and scalable with pre-trained models.
Robustness	Sensitive to matrix interferences and overlapping peaks	More robust against overlapping signals and environmental variations.
Required expertise	Basic-moderate (instrument handling + spectrum reading)	Moderate-high (requires chemometric/ML knowledge for model development).
Sample preparation	Easy to moderate	Same as conventional; analysis improvement is computational.
Instrumentation	UV-vis, IR, NMR, FTIR spectrometers	Same instruments + data analytics software (e.g., MATLAB, Python, Unscrambler).
Applications in herbals	Identification of known compounds, functional group detection	Quantification, adulteration detection, classification, fingerprinting of multi-herb matrices.
Limitations	Poor discrimination in complex or similar herbal matrices	Requires large labelled datasets for training; risk of model overfitting.

Table 3: Toxicological issues associated with herbal drug adulteration and contamination.[42]

Issue	Description	Examples	Risks
Substituted herbs	Use of morphologically similar but chemically different herbs.	Gloriosa superba with Ipomoea spp., *Morinda citrifolia* with *Moringa oleifera*.	Loss of efficacy, adverse effects.
Overconsumption	Excess use of authentic herbs may cause harm.	Ginseng (insomnia), Garlic (bleeding), Valerian (sedation).	Narrow therapeutic window, drug interactions.
Contaminants	Presence of heavy metals, pesticides, microbes, and microplastics.	Lead, arsenic, mercury in herbs; microplastics in teas.	Cumulative toxicity, inflammation, metabolic disorders.
Synthetic adulterants	Intentional addition of pharmaceuticals to enhance effects.	Sildenafil in sex tonics, steroids in creams.	Organ toxicity, hidden side effects, regulatory issues.
Chemical detection and analysis	Need for high-end tools to detect hidden toxins.	GC-MS/MS, Inductively Coupled Plasma -MS.	Ensures safety via contaminant identification.

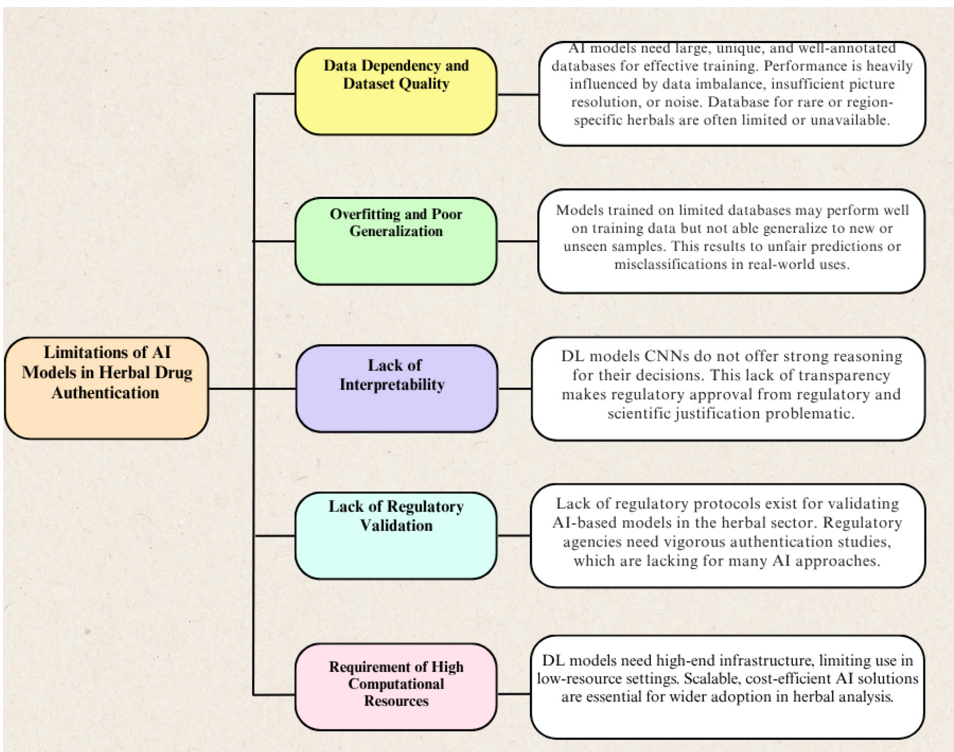

Figure 4: Disadvantages of AI in identification of different adulterants in herbals.

and pharmacovigilance centers is the most common practice, leading to poor safety data sharing and irregular monitoring.[41]

Adverse And Toxic Effects Arising From The Use And Adulteration Of Herbal Medicines

Toxic effects from adulteration or misuse of herbal drugs can arise through multiple pathways. These include substitution with chemically different species, excessive use, contamination, and deliberate synthetic adulteration. Table 3 below summarizes the key toxicological concerns and their implications.

CONCLUSION

In order to tackle adequately the increasing menace of adulteration of herbal products, there is a need for a strong multi-level approach. This involves not only harmonization of global quality standards like those promoted by the WHO, EU and AYUSH but also enforcement of GACP and GMP across the value chain. Sophisticated methods require to be combined to enhance transparency and traceability. DNA barcoding needs to be used to detect risky herbals like Ashoka, Giloy to detection botanical identity at every step of processing. Post-marketing surveillance and herbal pharmacovigilance systems need to be reinforced by establishing centralized adverse event reporting mechanisms and regular quality audits. Having an international database of adulteration cases patterned after WHO platforms-would aid in quick identification and knowledge sharing, particularly in the detection of region-specific or novel threats. For sustainability, education of stakeholders becomes imperative. Periodic training and capacity development amongst the cultivators, manufacturers, and traders will prevent adulteration at the source. Interdisciplinary academic-industry partnership and additional research and development investments especially towards AI-based fast-testing kits and smart quality checking devices will strengthen regulatory readiness and citizen confidence. Finally, a multidisciplinary, cooperative, and technology-based model is required not just to protect public health but also to restore international trust in the safety, purity, and efficacy of herbal medicines.

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ABBREVIATIONS

AI: Artificial Intelligence; **ANN:** Artificial Neural Network; **CNN:** Convolutional Neural Network; **EU:** European Union; **GC:** Gas Chromatography; **HPLC:** High-Performance Liquid Chromatography; **IR:** Infrared Spectroscopy; **LC:** Liquid Chromatography; **NMR:** Nuclear Magnetic Resonance; **SVM:** Support Vector Machine; **TCM:** Traditional Chinese Medicine; **UPLC:** Ultra-Performance Liquid Chromatography; **WHO:** World Health Organization.

CONFLICT OF INTEREST

The authors declared no conflicts of interest.

AUTHOR CONTRIBUTIONS

Ravjot Kaur, Tirath Choudhary, Ramandeep Kaur and Mansi Garg were responsible for the literature review and writing of the original manuscript. Dr. Abhilasha Jain and Nagendra Singh Chauhan helped in editing the manuscript. Dr. Ashish Baldi conceptualized, edited and revised the manuscript.

SUMMARY

Herbal adulteration is a global problem, and research has indicated contamination or substitution of up to 70-90% of some of the most commonly used medicinal plants. Adulteration is either intentional, for financial reasons, or accidental, through error in identification or substandard quality control. Adulteration effects the safety, efficacy, and integrity of herbal drugs and could result in adverse health consequences, therapeutic failure, and loss of consumer confidence. Detection techniques vary from conventional ones like organoleptic analysis, macroscopy, microscopy, and physicochemical tests to sophisticated analytical devices like chromatography, spectroscopy, and molecular methods like DNA barcoding. Of late, AI-dependent methods, especially image analysis and spectral data interpretation through ML, have appeared very promising with over 90% accuracy in adulterant detection. These methods are, however, confronted with issues like dataset dependency, model overfitting, and standardization. To meet the herbal adulteration challenge, enhancing regulatory standards, establishing strong pharmacovigilance systems, enhancing stakeholder awareness, and ensuring good agricultural and collection practices are key. Blending conventional and novel methods of authentication and backed by AI quality control can enhance the authenticity and safety of herbal medicine globally.

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