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HERBAL MEDICINES IN FORENSIC TOXICOLOGY: CURRENT EVIDENCE, ANALYTICAL CHALLENGES, AND FUTURE PERSPECTIVES

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Abstract

The increasing global use of herbal medicines has expanded their relevance in forensic toxicology, particularly in cases involving accidental poisoning, intentional intoxication, herb–drug interactions, organ toxicity, product adulteration, and unexplained death. Although botanical products are commonly perceived as safe, many contain potent bioactive compounds capable of producing severe neurological, hepatic, cardiovascular, and renal toxicity. Their forensic investigation is complicated by complex phytochemical compositions, variable product quality, limited toxicological reference data, and the frequent presence of undeclared pharmaceuticals or contaminants.

This narrative review summarizes the forensic significance of herbal medicines, major toxicological mechanisms, relevant biological specimens, current analytical techniques, interpretative challenges, and medico-legal implications. Particular attention is given to toxicologically important plants such as Mitragyna speciosa, Aconitum spp., Datura stramonium, Nerium oleander, Cerbera odollam, and Aristolochia spp. The review also examines the application of liquid chromatography–tandem mass spectrometry, gas chromatography–mass spectrometry, high-resolution mass spectrometry, spectroscopic methods, DNA-based identification, metabolomics, chemical fingerprinting, and artificial intelligence in the detection and authentication of herbal constituents.

Current evidence indicates that the detection of a phytochemical confirms exposure but does not independently establish causation. Reliable forensic interpretation requires integration of toxicological findings with product analysis, botanical authentication, autopsy and histopathological observations, exposure history, and scene evidence. Major limitations include incomplete toxicological databases, scarce certified reference standards, postmortem redistribution, and the absence of validated toxic and lethal concentration ranges for most herbal compounds. Future progress will depend on standardized analytical protocols, expanded international databases, and stronger interdisciplinary collaboration to improve medico-legal decision-making and public health protection.

INTRODUCTION

Herbal medicines remain an important component of healthcare worldwide and are widely used for disease prevention, symptom management, and general health maintenance. Their popularity is supported by cultural traditions, accessibility, affordability, and the perception that natural products are safer than conventional medicines. However, medicinal plants contain biologically active secondary metabolites that may produce clinically significant toxicity when consumed in excessive doses, used for prolonged periods, prepared incorrectly, or combined with conventional drugs (World Health Organization [WHO], 2019).

The safety and toxicological profiles of herbal products are influenced by substantial chemical variability. Phytochemical composition may differ according to plant species, geographical origin, cultivation conditions, harvesting time, plant part, extraction method, processing, and storage. Consequently, products marketed under the same botanical or commercial name may contain different concentrations of active or toxic

constituents. This variability complicates dose assessment, product authentication, and causal interpretation in both clinical and forensic settings (Abubakar *et al.,* 2017; Raclariu *et al.,* 2018).

Herbal medicines may become relevant to forensic toxicology in cases of accidental poisoning, intentional intoxication, substance misuse, unexplained organ failure, herb–drug interactions, and unexpected death. Some therapeutically used plants may produce toxicity under specific conditions. Kratom (Mitragyna speciosa), for example, contains opioid-active alkaloids and has been identified in fatal multidrug intoxications, particularly when combined with opioids, benzodiazepines, alcohol, or other central nervous system depressants (Warner *et al.,* 2016). Other plants, including *Aconitum* spp., Datura stramonium, Nerium oleander, and Cerbera odollam, contain highly potent alkaloids or cardiac glycosides capable of causing severe neurological dysfunction, ventricular arrhythmias, and sudden death. Chronic exposure to *Aristolochia* spp. may also result in progressive nephrotoxicity and urothelial carcinogenesis.

Herb–drug interactions further increase the forensic significance of botanical products. Herbal constituents may alter drug absorption, metabolism, transport, or elimination through modulation of cytochrome P450 enzymes and membrane transporters. They may also produce additive or synergistic pharmacodynamic effects on coagulation, cardiac conduction, sedation, and respiratory function. St. John's wort, for instance, induces CYP3A4 and P-glycoprotein and may reduce systemic exposure to several therapeutic agents. Conversely, sedative herbal products may intensify central nervous system depression when combined with psychoactive medicines or alcohol (Nicolussi *et al.,* 2020). Product adulteration and contamination create additional toxicological challenges. Herbal supplements may contain undeclared pharmaceuticals, heavy metals, pesticides, microorganisms, mycotoxins, or substituted plant species. Products marketed for weight reduction, sexual enhancement, pain relief, or chronic disease management are particularly vulnerable to intentional adulteration. As product labels may not accurately represent actual composition, forensic assessment should include direct chemical and botanical examination of the suspected preparation (Opuni *et al.,* 2023; Posadzki *et al.,* 2013).

The analytical investigation of herbal exposure is more complex than routine testing for conventional drugs. Botanical preparations may contain hundreds of structurally diverse compounds, many of which undergo rapid or incompletely characterized metabolism. Routine toxicology panels may therefore fail to detect relevant phytochemicals. In addition, certified reference materials, validated metabolites, spectral-library data, and toxic or lethal concentration ranges are unavailable for many plant-derived substances. Although advanced techniques such as liquid chromatography–tandem mass spectrometry and high-resolution mass spectrometry have improved compound detection, identification of a phytochemical generally confirms exposure rather than causation (Maurer & Meyer, 2016).

Postmortem redistribution, chemical degradation, bacterial metabolism, and diffusion from gastric contents may further alter phytochemical concentrations after death. Because the postmortem behavior of most herbal constituents remains poorly characterized, analytical results must be interpreted together with specimen type, sampling site, product composition, medical history, autopsy findings, histopathology, and scene evidence (Abdelaal *et al.,* 2024). This narrative review examines the forensic significance of herbal medicines, major

toxicological mechanisms, relevant biological specimens, analytical approaches, interpretative challenges, medico-legal implications, and future perspectives. The conceptual relationship between sources of herbal exposure, forensic scenarios, biological specimens, analytical approaches, toxicological effects, and forensic interpretation is summarized in Figure 1. By integrating evidence from forensic toxicology, pharmacology, pharmacognosy, analytical chemistry, pathology, and molecular biology, this review aims to support more reliable investigations of herbal medicine-related poisoning and death.

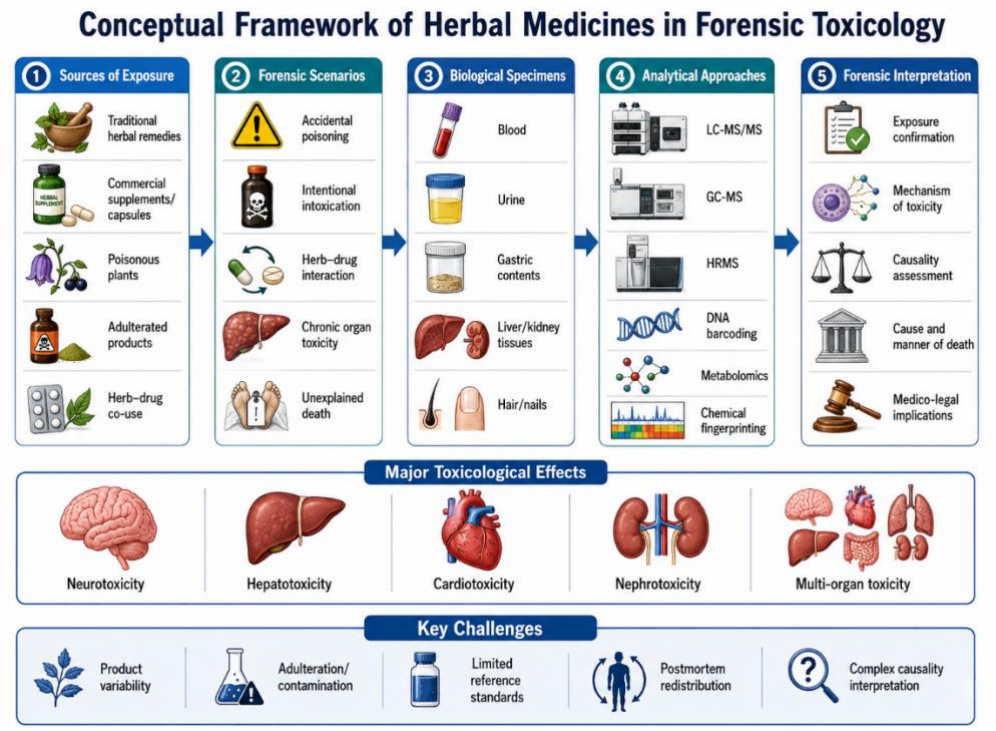

Figure 1. Conceptual framework of herbal medicines in forensic toxicology.

The framework illustrates the relationship between sources of herbal exposure, forensic scenarios, biological specimens, analytical approaches, major toxicological effects, interpretative challenges, and medico-legal outcomes.

HERBAL MEDICINES ASSOCIATED WITH FORENSIC CASES

Herbal medicines are increasingly encountered in forensic investigations involving acute poisoning, chronic organ injury, unexpected death, intentional intoxication, product adulteration, and clinically significant herb–drug interactions. Their forensic relevance arises from the presence of pharmacologically active secondary metabolites whose biological effects may become toxic under conditions of excessive exposure, prolonged administration, inappropriate preparation, individual susceptibility, or concurrent use with conventional medicines. Contrary to the widespread assumption that natural products are intrinsically safe, several medicinal plants contain compounds with narrow therapeutic margins and potentially lethal cardiovascular, neurological, hepatic, or renal effects.

Therapeutically used botanical products may become toxic when consumed in concentrated formulations or combined with other psychoactive substances. Kratom (*Mitragyna speciosa*) contains mitragynine and 7-

hydroxymitragynine, which interact with opioid receptors and may produce sedation, seizures, respiratory depression, and death, particularly in multidrug exposure. Kava (*Piper methysticum*) has been associated with clinically significant hepatotoxicity, whereas concentrated green tea extract may induce hepatocellular injury through oxidative stress and mitochondrial dysfunction. These examples demonstrate that toxicity may depend not only on botanical identity but also on extraction procedures, dosage, formulation, and patterns of use.

Several medicinal plants are intrinsically poisonous. *Aconitum* species contain diterpenoid alkaloids that disrupt voltage-gated sodium-channel inactivation and may precipitate refractory ventricular arrhythmias. *Datura stramonium* contains atropine, scopolamine, and hyoscyamine, producing a severe anticholinergic toxidrome characterized by agitation, delirium, hyperthermia, seizures, and cardiovascular instability. *Nerium oleander*, *Digitalis purpurea*, and *Cerbera odollam* contain cardiac glycosides that inhibit Na^+/K^+-ATPase, resulting in conduction abnormalities, hyperkalemia, ventricular dysrhythmias, and cardiac arrest. *Aristolochia* species contain aristolochic acids, which are strongly associated with progressive tubulointerstitial nephropathy and urothelial carcinogenesis, whereas pyrrolizidine alkaloids in Symphytum officinale may cause hepatic sinusoidal obstruction and liver failure.

The forensic interpretation of these exposures is complicated by the chemical heterogeneity of herbal preparations. Commercial and traditional products may contain several botanical species, incompletely characterized metabolites, contaminants, or undeclared synthetic pharmaceuticals. Moreover, parent compounds may be rapidly metabolized and absent from routine toxicological screening. Reliable assessment therefore requires integration of product examination, botanical authentication, toxicological analysis, pathological findings, clinical history, and scene investigation.

HERBAL MEDICINES IN FORENSIC TOXICOLOGY

The expanding use of herbal products has broadened the spectrum of substances relevant to forensic toxicology. Botanical preparations may contribute directly to fatal poisoning or indirectly through metabolic interactions, potentiation of prescribed drugs, contamination, adulteration, or botanical misidentification. Their evaluation differs from that of conventional pharmaceuticals because herbal formulations commonly contain multiple active constituents with variable concentrations, incompletely characterized pharmacokinetics, and limited human or postmortem reference data (Posadzki *et al.,* 2013; WHO, 2019).

Accidental intoxication may result from excessive dosing, incorrect preparation, prolonged self-medication, or substitution of the intended plant with a toxic species. The absence of standardized dosing is particularly problematic in homemade decoctions and traditional formulations, in which the final concentration of active constituents depends on botanical identity, the plant part used, extraction solvent, temperature, and duration of preparation. Fatal or severe events have also resulted from recreational misuse, intentional self-poisoning, and criminal administration of toxic plants (Aćimović, 2025; Sacco *et al.,* 2025; Zheng *et al.,* 2025).

In suspected intentional poisoning, plant fragments, seeds, herbal powders, capsules, preparation equipment, online purchase records, and residual products recovered from the scene may provide important

circumstantial evidence. The toxicological significance of these materials should be established through botanical identification and chemical analysis, as visual examination alone may be inadequate once the material has been powdered, extracted, or incorporated into a multi-ingredient formulation (Abubakar *et al.,* 2017; Raclariu *et al.,* 2018).

Herb–drug interactions constitute another major forensic concern. These interactions may be pharmacokinetic, involving changes in absorption, metabolism, transport, or elimination, or pharmacodynamic, involving enhancement or antagonism of drug effects. St. John's wort induces CYP3A4 and P-glycoprotein through activation of the pregnane X receptor, potentially reducing systemic exposure to immunosuppressants, anticoagulants, antiretroviral agents, oral contraceptives, and several other medicines. The magnitude of interaction is influenced by the hyperforin content of the herbal preparation (Nicolussi *et al.,* 2020).

Pharmacodynamic interactions may also contribute to adverse or fatal outcomes. Herbal substances with sedative or opioid-like effects may potentiate alcohol, benzodiazepines, opioids, and other central nervous system depressants. Similarly, botanical products with antiplatelet, anticoagulant, sympathomimetic, or cardioactive effects may increase the toxicity of conventional medicines acting on the same physiological systems. In such cases, death may result from combined toxicodynamic effects even when no individual substance is present within a conventionally recognized fatal range (Nicolussi *et al.,* 2020; Warner *et al.,* 2016).

A further challenge is the adulteration of botanical products with undeclared pharmaceuticals. Products marketed for weight reduction, sexual enhancement, pain management, or metabolic disease may contain phosphodiesterase inhibitors, stimulants, corticosteroids, nonsteroidal anti-inflammatory drugs, or hypoglycemic agents. Chemical and microbial contamination with heavy metals, pesticides, mycotoxins, and pathogenic organisms has also been documented. Accordingly, forensic laboratories should combine targeted testing for suspected phytochemicals with broad screening for pharmaceuticals, contaminants, and unexpected xenobiotics (Opuni *et al.,* 2023; Posadzki *et al.,* 2013).

TOXICOLOGICAL MECHANISMS

The toxicological effects of herbal medicines arise through multiple and frequently overlapping molecular pathways. Important mechanisms include disruption of neurotransmission, modulation of ion channels, generation of reactive metabolites, oxidative stress, mitochondrial dysfunction, DNA damage, inflammatory signaling, and activation of programmed cell death. The resulting clinical phenotype depends on the responsible phytochemical, dose, duration of exposure, metabolic activation, tissue distribution, and individual susceptibility.

Neurotoxicity may result from direct interactions with neurotransmitter receptors or membrane ion channels. Mitragynine and 7-hydroxymitragynine produce opioid-like effects that may contribute to central nervous system depression and impaired respiratory function. Tropane alkaloids from *D. stramonium* antagonize muscarinic receptors, producing neuropsychiatric and autonomic abnormalities. Aconitine additionally produces both neurological and cardiovascular toxicity through persistent activation of voltage-gated sodium channels (Aćimović, 2025; Coulson *et al.,* 2017; Warner *et al.,* 2016).

Hepatotoxicity is commonly associated with the metabolic conversion of phytochemicals into reactive intermediates. These metabolites may bind cellular macromolecules, deplete glutathione, impair mitochondrial respiration, generate reactive oxygen species, and initiate inflammatory or immune-mediated injury. Kava, concentrated green tea extract, black cohosh, pyrrolizidine alkaloid-containing products, and several multi-ingredient supplements have been implicated in herb-induced liver injury. Nevertheless, causal attribution remains challenging because many reported cases involve incompletely characterized products, concurrent medication use, and insufficient exclusion of alternative hepatic diseases (Ballotin *et al.,* 2021; Bunchorntavakul & Reddy, 2013; Teschke *et al.,* 2013).

Cardiotoxicity may occur through interference with sodium, potassium, or calcium channels or through inhibition of membrane ion pumps. Aconitine causes persistent sodium-channel activation and malignant ventricular arrhythmias, whereas cardiac glycosides from oleander and *Cerbera* inhibit Na^+/K^+-ATPase. The resulting alteration of intracellular sodium and calcium concentrations may produce conduction disturbances, bradyarrhythmias, ventricular tachyarrhythmias, and cardiac arrest. Because gross and microscopic cardiac findings may be nonspecific, chemical confirmation is frequently essential in postmortem investigations (Coulson *et al.,* 2017; Menezes *et al.,* 2018; Sacco *et al.,* 2025).

Nephrotoxicity may result from direct tubular cytotoxicity, oxidative stress, endothelial injury, or DNA-adduct formation. Aristolochic acids undergo enzymatic reduction to reactive intermediates that form persistent DNA adducts and produce progressive tubulointerstitial fibrosis. Chronic exposure is additionally associated with characteristic mutational signatures and increased urothelial cancer risk. Renal injury may also be caused or intensified by heavy metals, pesticides, undeclared pharmaceuticals, or toxic metabolites present in insufficiently regulated herbal products (IARC, 2002, 2022; Opuni *et al.,* 2023).

Oxidative stress and mitochondrial dysfunction represent common pathways linking organ-specific toxicity. Excessive formation of reactive oxygen and nitrogen species damages membrane lipids, proteins, mitochondrial DNA, and nuclear DNA. Loss of mitochondrial membrane potential reduces adenosine triphosphate production and promotes cytochrome *c* release, followed by caspase activation and apoptosis. Extensive injury may progress to necrosis, systemic inflammation, circulatory collapse, and multi-organ failure. These mechanisms are not specific to herbal exposure and should therefore be interpreted as biologically supportive rather than independently diagnostic findings (Ballotin *et al.,* 2021; Bunchorntavakul & Reddy, 2013).

BIOLOGICAL SPECIMENS IN HERBAL FORENSIC INVESTIGATION

Appropriate specimen selection is essential because phytochemicals vary substantially in absorption, metabolism, distribution, stability, and postmortem behavior. No single matrix provides complete information regarding exposure and toxicological significance; therefore, multiple complementary specimens should be collected whenever possible.

Peripheral blood, particularly femoral blood, is generally preferred for evaluating systemic exposure. It may contain parent compounds, active metabolites, and pharmaceutical adulterants that were circulating near the time of death. Interpretation remains constrained by postmortem redistribution, chemical instability, and the

absence of established toxic or fatal ranges for most herbal constituents. Central blood should be interpreted cautiously because it is more susceptible to passive diffusion from adjacent organs and gastric contents (Abdelaal *et al.,* 2024).

Urine is useful for confirming exposure because it often contains higher concentrations of metabolites and provides a longer detection window than blood. However, urinary concentrations primarily reflect elimination and cannot generally be correlated directly with toxic effect. Gastric contents are particularly informative in acute oral poisoning because they may contain unmetabolized toxins, plant fragments, seeds, capsules, powders, or liquid preparations. Their analysis can confirm recent ingestion and guide targeted toxicological testing (Zheng *et al.,* 2025).

Liver and kidney tissues are valuable when blood findings are negative or equivocal. The liver may retain parent compounds and metabolites generated during biotransformation, whereas the kidneys may contain compounds undergoing renal elimination. Tissue analysis is especially relevant when hepatotoxicity or nephrotoxicity is suspected and may be correlated with histopathological evidence of target-organ injury. However, tissue concentrations should not be interpreted as directly equivalent to antemortem blood concentrations.

Alternative matrices may provide additional temporal information. Hair and nails may support the assessment of repeated or chronic exposure and remain useful in decomposed remains. Oral fluid primarily reflects recent exposure but may be influenced by oral contamination and low analyte concentrations. Vitreous humor is relatively protected from bacterial contamination and postmortem decomposition, although distribution data for most phytochemicals remain limited. Results from alternative matrices should therefore be interpreted according to their specific incorporation mechanisms and analytical limitations (de Campos *et al.,* 2022).

Specimen selection should be guided by the suspected substance, route and timing of exposure, survival interval, postmortem interval, decomposition status, and available analytical method. Correct preservation, temperature control, contamination prevention, documentation, and chain of custody are essential. Interpretation should be based on concordance among specimens rather than on an isolated analytical result.

CHALLENGES IN FORENSIC INTERPRETATION

Forensic interpretation of herbal medicine-related findings remains difficult because the detection of a phytochemical confirms exposure but does not necessarily establish toxicity or causation. Most herbal constituents lack validated therapeutic, toxic, and lethal concentration ranges, particularly in postmortem specimens. Consequently, measured concentrations cannot always be directly associated with the severity of intoxication or the cause of death. The distinction between analytical detection and causal attribution is illustrated by postmortem data on kratom, as shown in Figure 2.

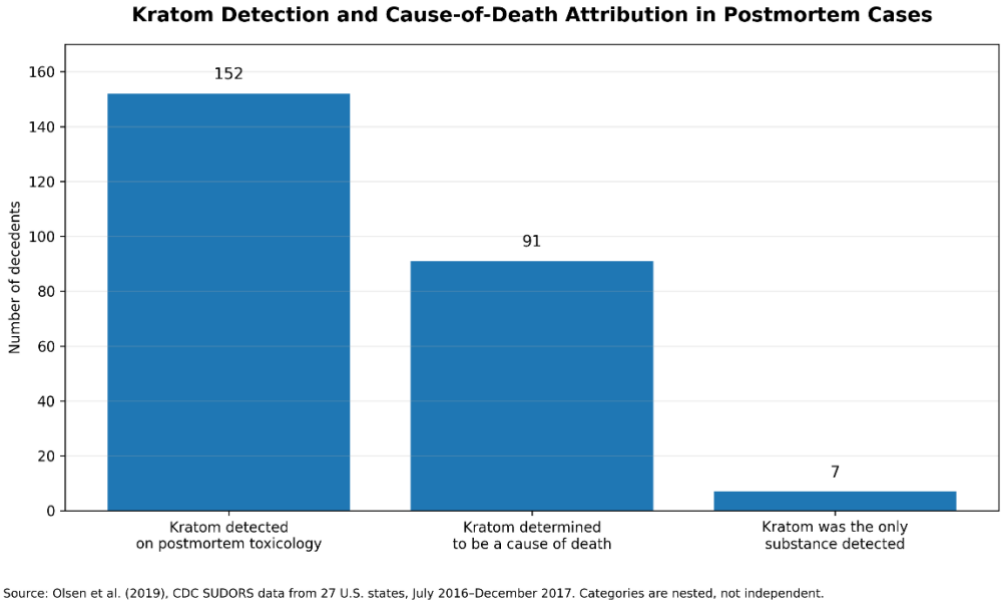

Figure 3. Kratom detection and cause-of-death attribution in postmortem cases.

Among 152 overdose decedents with kratom detected during postmortem toxicological analysis, kratom was determined to be a cause of death in 91 cases, while it was the only substance detected in seven cases. The categories are nested and not independent. Data were derived from Olsen et al. (2019). The chemical variability of herbal products represents an additional source of uncertainty. Products marketed under the same botanical name may differ substantially in species composition, plant parts, extraction methods, active-constituent concentrations, and manufacturing quality. Herbal preparations may also contain undeclared pharmaceuticals, heavy metals, pesticides, microbial contaminants, or incorrectly substituted species, making product labels unreliable indicators of actual exposure (Opuni *et al.,* 2023; Posadzki *et al.,* 2013).

Analytical interpretation is further limited by incomplete spectral databases, scarce certified reference standards, and insufficient characterization of phytochemical metabolites. Routine toxicological screening may therefore fail to detect uncommon plant toxins or may provide only tentative compound identification. Although high-resolution mass spectrometry improves broad and non-targeted screening, many detected molecular features remain unannotated or require confirmation with authentic reference materials (Maurer & Meyer, 2016).

Postmortem redistribution, degradation, hydrolysis, bacterial metabolism, and diffusion from gastric contents may alter toxin concentrations after death. These processes remain poorly characterized for most herbal compounds, making the interpretation of postmortem blood and tissue concentrations particularly uncertain (Abdelaal *et al.,* 2024). Furthermore, multidrug exposure and underlying disease may produce toxic effects that overlap with those of botanical compounds.

Causal interpretation should therefore be based on the totality of evidence, including product analysis, botanical authentication, toxicological findings from multiple specimens, autopsy and histopathological observations, exposure chronology, medical history, and scene investigation. Analytical limitations, competing causes, and the level of identification certainty must be reported transparently to avoid

overinterpretation and ensure scientifically defensible medico-legal conclusions (American Academy of Forensic Sciences, Academy Standards Board [AAFS ASB], 2019, 2020; Teschke *et al.,* 2013)

MEDICOLEGAL IMPLICATIONS

Herbal medicine-related findings may influence determination of the cause and manner of death, criminal investigation, civil liability, regulatory enforcement, and public health intervention. Detection of a phytochemical establishes exposure but does not independently prove causation. Medico-legal conclusions should therefore be based on integrated evaluation of toxicological results, autopsy findings, histopathology, medical history, product composition, and scene investigation. The manner of death may be accidental, suicidal, homicidal, natural, or undetermined. Accidental cases may involve excessive dosing, incorrect preparation, botanical misidentification, contamination, adulteration, or herb–drug interactions. Intentional ingestion of a poisonous plant may support a suicidal classification, whereas evidence of covert administration may raise concern for homicide. These determinations require strong analytical and circumstantial support because toxic and lethal concentration ranges remain undefined for many phytochemicals.

Herbal materials recovered from the scene should be treated as forensic evidence. Plant fragments, capsules, powders, liquids, packaging, labels, purchase records, and preparation equipment should be documented, preserved, and transferred under a verifiable chain of custody. Chemical analysis and molecular botanical identification may be necessary to determine the actual composition of the product and establish a relationship between scene evidence and compounds detected in biological specimens. Forensic experts must clearly distinguish confirmed exposure, biological plausibility, contribution to death, and definitive causation. Expert opinions should explain analytical limitations, possible interactions, postmortem changes, competing causes, and the degree of certainty associated with the conclusion. Reports should communicate laboratory findings accurately and avoid unsupported interpretation of low-level or incidental detections (AAFS ASB, 2020).

Herbal-related cases may also generate liability for manufacturers, distributors, healthcare professionals, traditional practitioners, and online sellers when products are contaminated, adulterated, incorrectly labeled, or marketed without adequate safety information. Forensic findings may support pharmacovigilance investigations, product recalls, regulatory warnings, and preventive public health measures. Scientifically rigorous investigation of herbal medicines therefore has significance beyond individual case resolution and contributes to broader consumer protection.

FUTURE PERSPECTIVES

Future development of herbal forensic toxicology will depend on the integration of advanced analytical technologies, standardized methodologies, and interdisciplinary collaboration. High-resolution mass spectrometry and non-targeted screening are expected to improve the detection of previously unrecognized phytochemicals, metabolites, contaminants, and pharmaceutical adulterants. Retrospective analysis of full-

scan datasets may also allow previously analyzed cases to be reassessed when new plant toxins or biomarkers are identified (Maurer & Meyer, 2016).

Metabolomics and other multi-omics approaches may provide characteristic molecular signatures of herbal exposure and organ-specific toxicity. Combining metabolomics with genomics, proteomics, and transcriptomics could improve understanding of individual susceptibility, toxicological mechanisms, and herb–drug interactions. These approaches may be particularly useful when parent compounds are extensively metabolized or no longer detectable in postmortem specimens. DNA barcoding, mini-barcoding, and metabarcoding are expected to strengthen botanical authentication, particularly in processed and multi-ingredient products. However, molecular identification should be combined with chemical analysis because the presence of plant DNA does not establish phytochemical concentration, bioavailability, or toxic potency (Parveen *et al.,* 2016; Raclariu *et al.,* 2018).

Artificial intelligence and machine-learning methods may assist with spectral annotation, chemical-fingerprint classification, product authentication, and the identification of toxicological patterns. Nevertheless, forensic implementation will require representative training datasets, external validation, algorithmic transparency, and expert supervision to ensure that results remain reproducible and legally defensible (Shen *et al.,* 2026).

Comprehensive international databases containing validated mass spectra, metabolites, toxicokinetic information, case data, and postmortem concentrations are also required. Increased availability of certified reference materials, standardized specimen-collection protocols, and interlaboratory proficiency testing would improve analytical comparability. Finally, collaboration among forensic toxicologists, pharmacists, botanists, pathologists, clinicians, regulatory authorities, and poison-control centers will be essential for improving pharmacovigilance, identifying hazardous products, and strengthening the scientific basis of herbal medicine-related death investigations.

CONCLUSION

Herbal medicines have become increasingly relevant in forensic toxicology because their use may be associated with accidental poisoning, intentional intoxication, herb–drug interactions, organ toxicity, product adulteration, and fatal outcomes. Their complex phytochemical composition, variable quality, and frequent use without professional supervision create substantial challenges for analytical detection and medico-legal interpretation.

The identification of a herbal constituent in a biological specimen confirms exposure but does not independently establish causation. Reliable forensic conclusions require integration of toxicological findings with botanical authentication, product analysis, autopsy and histopathological observations, medical history, exposure chronology, and scene evidence. Particular caution is required because toxic and lethal concentration ranges remain unavailable for most phytochemicals, while postmortem redistribution, degradation, multidrug exposure, and underlying disease may substantially influence interpretation (Abdelaal *et al.,* 2024; Teschke *et al.,* 2013).

Advanced analytical techniques, including LC-MS/MS, high-resolution mass spectrometry, DNA-based identification, metabolomics, and chemical fingerprinting, have considerably improved the investigation of complex herbal exposures. However, incomplete toxicological databases, limited certified reference standards, and insufficiently standardized laboratory protocols remain important barriers (Maurer & Meyer, 2016; Raclariu *et al.,* 2018).

Future progress will require harmonized analytical guidelines, expanded international databases, validated reference materials, and stronger collaboration among forensic toxicologists, pharmacists, botanists, pathologists, clinicians, and regulatory authorities. Strengthening these areas will improve the scientific reliability of cause-of-death determination, support defensible medico-legal conclusions, enhance pharmacovigilance, and contribute to safer use of herbal medicines.

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