

Recent Advances in Forensic Botany: A Systematic Review

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Abstract—Forensic botany has emerged as an indispensable branch of forensic science, employing plant-derived evidence to assist in criminal, civil, environmental, and wildlife investigations. Botanical materials such as pollen grains, spores, leaves, seeds, fruits, wood fragments, fibres, roots, and phytochemical compounds frequently establish crucial links between crime scenes, suspects, victims, and objects. Although conventional forensic botany primarily depended upon morphological examination and taxonomic identification, remarkable advances in molecular biology, genomics, analytical chemistry, bioinformatics, artificial intelligence, and remote sensing have transformed the discipline into a highly sophisticated forensic tool. This systematic review examines recent developments in forensic botany with particular emphasis on DNA barcoding, environmental DNA (eDNA), forensic palynology, stable isotope analysis, phytochemical profiling, hyperspectral imaging, geographic information systems (GIS), and machine learning applications. The review further discusses the expanding role of botanical evidence in homicide investigations, clandestine grave detection, wildlife crime, illegal logging, narcotics trafficking, environmental offences, and disaster victim identification. In addition, the article critically evaluates current challenges, including methodological standardisation, contamination control, incomplete reference databases, and legal admissibility of botanical evidence. The review concludes that integrating traditional botanical knowledge with advanced molecular and computational technologies substantially enhances the reliability and evidentiary value of forensic investigations. Future interdisciplinary collaboration among botanists, forensic scientists, molecular biologists, and data scientists is expected to establish forensic botany as one of the most reliable scientific disciplines within modern forensic investigations.

Index Terms—Forensic Botany, Forensic Palynology, DNA Barcoding, Environmental DNA.

I. INTRODUCTION

Forensic science has undergone remarkable transformation during the past few decades, incorporating scientific disciplines that were once considered peripheral to criminal investigations. Among these emerging fields, forensic botany has established itself as a valuable scientific discipline that applies botanical knowledge to legal investigations. Plants continuously interact with humans and their environment, leaving behind biological traces that frequently become silent yet highly reliable witnesses in criminal cases. Unlike fingerprints or DNA evidence, which may be absent or deliberately destroyed, botanical evidence often persists unnoticed and provides objective information capable of linking suspects, victims, and crime scenes. Consequently, forensic botany has become an increasingly important component of multidisciplinary forensic investigations.

Forensic botany encompasses the study and analysis of all forms of plant-derived evidence, including pollen grains, spores, seeds, fruits, leaves, bark, roots, wood fragments, fibres, algae, fungi, and phytochemical constituents. These botanical materials can reveal valuable information concerning the geographical origin of an object, movement of individuals, concealment of bodies, estimation of post-burial intervals, and environmental conditions surrounding a crime scene. Since vegetation differs considerably according to climate, altitude, soil composition, and geographical location, plant evidence often provides highly specific ecological signatures that assist

forensic investigators in reconstructing criminal events with considerable precision.

Historically, the forensic application of plants can be traced back to the early twentieth century, when microscopic examination of pollen and wood fragments was first introduced into criminal investigations. One of the earliest documented cases involved the German criminologist Georg Popp, who successfully used pollen grains and botanical materials to connect a suspect with a murder scene in 1908. Since then, forensic botany has evolved from simple taxonomic identification into a multidisciplinary field integrating plant taxonomy, ecology, molecular genetics, chemistry, geography, remote sensing, and computational biology. Modern forensic laboratories now employ sophisticated analytical techniques capable of identifying plant species from minute or highly degraded biological samples, significantly expanding the evidentiary potential of botanical materials.

Recent advances in molecular biology have revolutionised forensic botany. DNA barcoding enables precise identification of plant species using short, standardised genetic markers, while next-generation sequencing (NGS) facilitates comprehensive genomic analysis of degraded botanical specimens. Environmental DNA (eDNA) analysis has further expanded forensic capabilities by detecting genetic material released into soil, water, or air, thereby allowing investigators to reconstruct vegetation communities associated with crime scenes even in the absence of visible plant remains. Simultaneously, analytical methods such as gas chromatography–mass spectrometry (GC–MS), liquid chromatography–mass spectrometry (LC–MS), Fourier transform infrared spectroscopy (FTIR), and stable isotope analysis have significantly improved the identification of phytochemicals and the determination of geographical origin.

The integration of artificial intelligence (AI), machine learning (ML), and geographic information systems (GIS) has introduced new dimensions to forensic botanical investigations. AI-assisted image recognition systems can rapidly classify leaves, pollen grains, seeds, and wood samples with remarkable accuracy, reducing human error and improving reproducibility. Machine learning algorithms are increasingly capable of analysing complex botanical datasets, while GIS and remote sensing technologies

facilitate vegetation mapping, clandestine grave detection, and environmental crime investigations across extensive geographical regions. These technological innovations have substantially enhanced the efficiency and reliability of botanical evidence in modern forensic practice.

Beyond homicide investigations, forensic botany now contributes significantly to numerous specialised areas of forensic science. Botanical evidence plays a crucial role in wildlife crime investigations by identifying illegally traded plant species and tracing timber origin in illegal logging cases. Similarly, forensic botany assists narcotics enforcement agencies in identifying cannabis, opium poppy, coca, and other illicit plant-derived substances. Environmental forensic investigations increasingly utilise botanical indicators to monitor pollution, habitat destruction, invasive species, and ecological damage resulting from illegal industrial activities. Furthermore, disaster victim identification frequently incorporates botanical evidence to reconstruct environmental conditions and establish victim movement following natural disasters or armed conflicts.

Despite these remarkable advances, several scientific and practical challenges continue to limit the widespread application of forensic botany. The absence of comprehensive global reference databases, inconsistencies in sampling protocols, contamination risks, geographical variation in vegetation, and limited judicial familiarity with botanical evidence remain significant obstacles. Furthermore, differences in regional flora often require highly specialised expertise, making standardisation difficult across international forensic laboratories. Addressing these limitations requires collaborative efforts among botanists, molecular biologists, forensic scientists, legal professionals, and policymakers to establish universally accepted analytical standards and quality assurance protocols.

Given the rapid technological progress achieved during the past decade, a comprehensive evaluation of recent developments in forensic botany is both timely and necessary. This systematic review aims to synthesise current knowledge regarding emerging molecular, analytical, and computational techniques employed in forensic botanical investigations. The review also examines their practical applications, evaluates existing limitations, and identifies future research directions that may further enhance the

reliability, admissibility, and scientific value of botanical evidence within modern forensic science.

II. METHODOLOGY

This systematic review was conducted to synthesise recent scientific developments in forensic botany and evaluate their applications in contemporary forensic investigations. The review primarily focuses on studies published between 2015 and 2025, a period characterised by rapid technological advancements in molecular biology, genomics, analytical chemistry, bioinformatics, and artificial intelligence that have significantly influenced forensic botanical research.

A comprehensive literature survey was performed using major academic databases, including Scopus, Web of Science, PubMed, ScienceDirect, SpringerLink, Taylor & Francis Online, Wiley Online Library, and Google Scholar. Search terms included combinations of keywords such as forensic botany, forensic palynology, DNA barcoding, environmental DNA, plant evidence, stable isotope analysis, forensic ecology, plant genomics, machine learning in forensic science, and remote sensing in forensic investigations. Boolean operators ("AND," "OR," and "NOT") were employed to refine search results and maximise retrieval of relevant literature.

The inclusion criteria comprised peer-reviewed journal articles, systematic reviews, review papers, and methodological studies focusing on the forensic application of botanical evidence. Studies addressing DNA-based plant identification, pollen analysis, phytochemical profiling, environmental DNA, isotopic techniques, artificial intelligence, and geographic information systems were prioritised. Articles not directly related to forensic investigations, conference abstracts lacking complete data, duplicate publications, and purely agricultural or ecological studies without forensic relevance were excluded.

The selected literature was critically analysed according to thematic categories, including the evolution of forensic botany, recent technological advances, practical forensic applications, methodological challenges, and future research prospects. Emphasis was placed on identifying emerging trends, evaluating analytical reliability, and assessing the potential integration of multidisciplinary approaches into routine forensic practice. The findings were synthesised narratively to provide a

comprehensive overview of the current state of forensic botany while highlighting knowledge gaps that warrant further scientific investigation.

III. EVOLUTION OF FORENSIC BOTANY

Forensic botany has evolved from a specialised branch of plant taxonomy into a sophisticated multidisciplinary science that integrates botany, molecular biology, ecology, chemistry, genetics, geospatial technology, and artificial intelligence. Although plant evidence has long been recognised as potentially valuable in legal investigations, its scientific application has expanded considerably over the past century owing to advances in analytical techniques and a deeper understanding of plant biology. Today, forensic botany contributes significantly to criminal investigations, environmental law enforcement, wildlife crime detection, disaster victim identification, and archaeological research.

The origins of forensic botany are commonly traced to the pioneering work of the German criminologist Georg Popp in the early twentieth century. In 1904 and later in 1908, Popp successfully demonstrated that microscopic examination of pollen grains, seeds, and plant fragments could establish links between suspects and crime scenes. In one of the earliest documented forensic cases, botanical materials found on a suspect's clothing matched vegetation at the murder site, thereby providing compelling corroborative evidence. This landmark investigation established the scientific foundation for the forensic application of plant evidence and highlighted the evidentiary value of seemingly insignificant botanical traces.

During the first half of the twentieth century, forensic botany primarily relied upon traditional taxonomic methods involving the morphological identification of leaves, seeds, pollen grains, wood, bark, fruits, and fibres. Investigators compared the microscopic and macroscopic characteristics of plant specimens with herbarium collections and botanical reference manuals to determine species identity. Although these techniques proved useful in many investigations, they depended heavily upon expert knowledge and often became challenging when specimens were fragmented, decomposed, burned, or otherwise damaged.

The development of forensic palynology during the mid-twentieth century significantly expanded the

discipline. Pollen grains possess species-specific morphological characteristics and remarkable resistance to environmental degradation owing to their durable outer wall, known as the exine. Their ability to adhere to clothing, footwear, vehicles, and human remains made pollen evidence particularly valuable for reconstructing movements between different geographical locations. Advances in light microscopy and scanning electron microscopy further improved pollen identification, enabling investigators to distinguish closely related plant species with greater confidence.

The emergence of molecular biology during the late twentieth century transformed forensic botany into a more objective and reproducible scientific discipline. The introduction of polymerase chain reaction (PCR) enabled scientists to amplify minute quantities of plant DNA recovered from degraded botanical materials. This innovation allowed investigators to identify plant species from highly fragmented leaves, wood chips, seeds, or processed plant products that could not be identified morphologically. Molecular techniques also reduced observer bias and increased the reliability of forensic botanical analyses.

The twenty-first century has witnessed unprecedented technological progress that has fundamentally altered forensic botanical investigations. DNA barcoding has become one of the most influential developments by enabling rapid species identification using short, standardised regions of the plant genome, including *rbcL*, *matK*, *ITS*, and *trnH-psbA*. Simultaneously, next-generation sequencing (NGS) has made it possible to analyse entire plant genomes and mixed botanical samples with exceptional precision. These techniques have become particularly valuable in wildlife crime investigations, illegal timber identification, and the analysis of degraded botanical evidence recovered from crime scenes.

Environmental DNA (eDNA) represents another significant milestone in the evolution of forensic botany. Rather than analysing visible plant specimens, investigators can now recover genetic material naturally released into soil, water, sediments, or air. Environmental DNA provides comprehensive information regarding plant communities associated with a particular location and enables investigators to compare ecological signatures between different crime scenes. This approach has expanded the scope of

forensic botany beyond individual plant identification to landscape-level ecological reconstruction.

Recent years have also witnessed increasing integration between forensic botany and advanced computational technologies. Artificial intelligence and machine learning algorithms can analyse thousands of botanical images within minutes, accurately identifying leaves, pollen grains, seeds, wood anatomy, and other plant structures. Similarly, remote sensing technologies, hyperspectral imaging, drones, and Geographic Information Systems (GIS) have revolutionised vegetation mapping, clandestine grave detection, and environmental forensic investigations. These innovations have transformed forensic botany from a largely descriptive science into a highly quantitative discipline capable of analysing complex environmental datasets with remarkable precision.

The evolution of forensic botany reflects broader developments within forensic science itself, moving from observational techniques toward integrated multidisciplinary approaches that combine traditional botanical expertise with molecular genetics, analytical chemistry, geospatial technologies, and artificial intelligence. As these technologies continue to mature, forensic botany is expected to become an increasingly indispensable component of modern criminal investigations, offering highly accurate and scientifically robust methods for analysing botanical evidence.

IV. MAJOR BRANCHES OF FORENSIC BOTANY

Forensic botany encompasses several specialised sub-disciplines, each focusing on different forms of plant-derived evidence and their applications in legal investigations. These branches complement one another by providing diverse sources of information that assist forensic investigators in reconstructing criminal events, identifying geographical origins, locating clandestine graves, and establishing associations between suspects, victims, and crime scenes.

4.1 Forensic Palynology

Forensic palynology is the study of pollen grains and spores as forensic evidence. Because pollen grains are microscopic, highly resistant to environmental degradation, and often unique to particular plant species or ecological regions, they serve as valuable

indicators of geographical origin and environmental exposure.

Pollen is readily transferred to clothing, footwear, vehicles, luggage, weapons, and human remains. Since different plant species flower during specific seasons and occupy distinct habitats, pollen assemblages recovered from forensic exhibits can provide detailed ecological information regarding a person's movements before or after a crime. For example, pollen recovered from a suspect's clothing may correspond to vegetation found exclusively at a particular woodland, marsh, or agricultural field, thereby establishing a strong connection between the suspect and the crime scene.

Recent advances in scanning electron microscopy, automated image analysis, and artificial intelligence have considerably improved pollen identification by reducing observer subjectivity and increasing analytical accuracy. Consequently, forensic palynology remains one of the most reliable and widely utilised branches of forensic botany.

4.2 Forensic Dendrology

Forensic dendrology focuses on the examination of wood, bark, timber, and tree growth patterns. Wood fragments recovered from tools, vehicles, clothing, or crime scenes may establish associations between suspects and specific locations. Similarly, timber identification plays a crucial role in investigating illegal logging, timber smuggling, and environmental crimes. Tree rings also possess forensic significance because their annual growth patterns reflect environmental conditions and chronological age. Analysis of tree growth can assist investigators in estimating the time since environmental disturbance, locating clandestine graves, or determining whether vegetation has been altered to conceal criminal activities. Recent developments in microscopic wood anatomy, stable isotope analysis, and DNA-based timber identification have greatly enhanced the reliability of forensic dendrology.

4.3 Forensic Limnobotany

Forensic limnobotany involves the examination of aquatic plants and microscopic algae, particularly diatoms, recovered from bodies or environmental samples. Although diatoms are technically algae rather than higher plants, their ecological significance makes them valuable indicators in forensic investigations

involving drowning. The presence and species composition of aquatic vegetation can help determine whether a body entered the water before or after death, identify the site of drowning, and establish connections between aquatic environments and forensic exhibits. Molecular techniques and environmental DNA analysis have further improved the identification of aquatic plant communities associated with crime scenes.

4.4 Plant Anatomy and Morphology

Traditional anatomical and morphological analysis remains an essential component of forensic botany. Investigators examine leaves, stems, roots, fruits, seeds, fibres, bark, and flowers using both macroscopic and microscopic techniques to identify plant species. Leaf venation patterns, stomatal arrangement, epidermal cell morphology, trichomes, and vascular tissue organisation often provide species-specific characteristics that remain identifiable even in fragmented specimens. These methods are particularly valuable when DNA preservation is poor or molecular analysis is unavailable. Although molecular methods have become increasingly important, anatomical analysis continues to provide rapid, cost-effective preliminary identification in many forensic laboratories.

4.5 Molecular Forensic Botany

Molecular forensic botany represents the fastest-growing branch of the discipline. It utilises DNA extraction, PCR amplification, DNA barcoding, next-generation sequencing, and genomic analysis to identify plant species with exceptional accuracy.

Unlike traditional morphology-based identification, molecular methods can analyse highly degraded botanical materials, processed herbal products, powdered plant samples, burned wood, or fragmented leaves. DNA barcoding has become especially valuable in combating illegal trade in endangered plant species, identifying medicinal plants, and authenticating commercial botanical products. The integration of molecular genetics has significantly improved the scientific reliability, reproducibility, and legal admissibility of botanical evidence.

4.6 Forensic Ecology

Forensic ecology examines the interaction between vegetation and environmental conditions surrounding crime scenes. Changes in plant growth, root

development, soil chemistry, and ecological succession often reveal important information concerning clandestine burials, body decomposition, and environmental disturbance.

Plants growing above buried remains frequently exhibit altered growth patterns because decomposition changes soil nutrient composition, moisture availability, and microbial activity. Satellite imagery, drone surveys, multispectral imaging, and GIS mapping now enable investigators to identify subtle vegetation anomalies that may indicate concealed graves or illegal environmental activities. Forensic ecology has become increasingly important in disaster investigations, environmental crime, wildlife conservation, and archaeological excavations.

4.7 Forensic Phytochemistry

Forensic phytochemistry investigates the chemical constituents of plants and their forensic applications. Plant secondary metabolites including alkaloids, flavonoids, terpenoids, glycosides, and essential oils serve as chemical fingerprints for species identification and toxicological analysis.

Modern analytical instruments such as Gas Chromatography–Mass Spectrometry (GC–MS), Liquid Chromatography–Mass Spectrometry (LC–MS), High-Performance Liquid Chromatography (HPLC), and Fourier Transform Infrared Spectroscopy (FTIR) enable forensic scientists to identify poisonous plants, herbal toxins, narcotic species, and botanical residues with remarkable sensitivity. This branch has become particularly valuable in investigations involving plant poisoning, drug trafficking, herbal medicine authentication, and environmental contamination.

V. RECENT TECHNOLOGICAL INNOVATIONS IN FORENSIC BOTANY

The rapid advancement of interdisciplinary technologies has significantly transformed forensic botany from a conventional identification-based discipline into a highly precise analytical science. Contemporary forensic investigations increasingly depend upon the integration of molecular biology, analytical chemistry, computational science, and geospatial technologies to extract maximum information from botanical evidence. These innovations have expanded the scope of plant-based

investigations by enabling the analysis of highly degraded, microscopic, and environmentally dispersed botanical materials.

5.1 DNA Barcoding and Next-Generation Sequencing
DNA barcoding has emerged as one of the most influential developments in modern forensic botany. This technique involves the identification of plant species through short, standardised genetic regions that exhibit sufficient variation among species while remaining conserved within the same species. Commonly utilised plant DNA barcode regions include *rbcL*, *matK*, internal transcribed spacer (ITS), and *trnH-psbA*. These genetic markers allow forensic scientists to identify plant materials that cannot be reliably classified through morphological methods.

The application of DNA barcoding has become particularly significant in wildlife crime investigations, where accurate identification of endangered timber species, medicinal plants, and illegally traded botanical products is essential. For example, processed wood, powdered herbal materials, and fragmented plant samples often lose their visible characteristics; however, their genetic information remains detectable through molecular analysis. Consequently, DNA barcoding provides an objective and reproducible method for establishing species identity and supporting legal investigations.

Next-generation sequencing (NGS) has further expanded the capabilities of molecular forensic botany by enabling the simultaneous analysis of multiple genetic regions and mixed botanical samples. Unlike traditional sequencing methods that examine individual DNA fragments, NGS platforms generate large volumes of genomic information, allowing investigators to analyse complex environmental samples containing DNA from multiple plant species. This approach has significant implications for ecological reconstruction, clandestine grave detection, and environmental crime investigations.

5.2 Environmental DNA and Metabarcoding Approaches

Environmental DNA (eDNA) analysis represents a revolutionary advancement in forensic ecology and botanical investigation. Plants continuously release genetic material into surrounding environments through pollen, roots, leaves, decomposing tissues, and microbial interactions. This DNA accumulates in

soil, sediments, water bodies, and atmospheric particles, creating a biological record of local vegetation.

Forensic scientists increasingly utilise eDNA metabarcoding to reconstruct plant communities associated with specific geographical locations. By analysing environmental samples rather than visible plant remains, investigators can determine whether a particular area corresponds to a crime scene, burial location, or environmental disturbance site. This technique is particularly valuable when physical botanical evidence has been removed, destroyed, or degraded.

The integration of eDNA analysis with high-throughput sequencing and bioinformatics has improved the detection of rare plant species and complex ecological patterns. However, challenges related to DNA persistence, environmental variation, contamination, and database limitations must be addressed before eDNA becomes fully standardised for routine forensic applications.

5.3 Artificial Intelligence, Machine Learning, and Digital Image Analysis

Artificial intelligence (AI) and machine learning (ML) have introduced new possibilities for automated botanical identification. Traditional plant identification often depends upon expert interpretation of morphological features, which may be time-consuming and influenced by observer experience. AI-based systems overcome these limitations by analysing large collections of botanical images and recognising complex patterns associated with specific plant structures.

Machine learning algorithms have demonstrated considerable success in identifying pollen grains, leaves, seeds, wood anatomy, and microscopic plant features. Deep learning models, particularly convolutional neural networks (CNNs), can classify botanical evidence with high accuracy by extracting visual characteristics that may not be easily recognised through conventional examination.

Digital image analysis has also improved forensic palynology by enabling automated pollen classification. Such systems reduce analytical subjectivity, increase examination speed, and allow comparison between unknown samples and extensive reference databases. The future integration of AI with molecular and ecological datasets may create

comprehensive forensic platforms capable of providing rapid and reliable botanical evidence interpretation.

5.4 Remote Sensing, GIS, and Hyperspectral Technologies

Geospatial technologies have significantly strengthened the application of forensic botany in landscape-level investigations. Geographic Information Systems (GIS), satellite imagery, drone-based surveys, and hyperspectral imaging allow investigators to analyse vegetation patterns over large geographical areas.

Hyperspectral imaging captures information beyond visible light by recording specific wavelengths associated with plant chemical composition and physiological characteristics. This technology enables the detection of vegetation stress, altered plant growth, and environmental disturbances that may indicate criminal activity. In clandestine burial investigations, vegetation above buried remains often exhibits unusual growth patterns because decomposition modifies soil nutrients and moisture conditions. Remote sensing techniques can detect these subtle ecological changes and assist investigators in locating hidden graves.

GIS-based forensic analysis also supports environmental crime investigations by mapping illegal deforestation, habitat destruction, and unauthorised land-use changes. By combining botanical evidence with spatial information, forensic scientists can reconstruct ecological histories and establish connections between criminal activities and specific geographical locations.

VI. APPLICATIONS AND FUTURE PERSPECTIVES OF FORENSIC BOTANY

The expanding technological foundation of forensic botany has increased its applications across diverse areas of criminal investigation, environmental protection, and legal science. Botanical evidence is no longer considered merely supplementary material but has become a scientifically valuable source of information capable of establishing associations between individuals, objects, and locations.

One of the most significant applications of forensic botany is in homicide investigations. Plant materials recovered from clothing, vehicles, weapons, or human

remains may reveal the movement of suspects and victims by providing ecological information about specific environments. Pollen assemblages, soil-associated plant fragments, and DNA-based botanical signatures can establish geographical connections that strengthen criminal investigations. In cases involving clandestine burials, vegetation changes, root patterns, and soil-plant interactions provide important evidence regarding burial locations and postmortem events.

Forensic botany also plays a crucial role in wildlife protection and environmental law enforcement. Illegal logging, trafficking of endangered plants, and unauthorised trade in medicinal species represent significant global challenges. DNA barcoding, chemical profiling, and wood anatomy analysis assist authorities in identifying protected species and tracing the geographical origin of illegally obtained botanical materials. These applications demonstrate the importance of forensic botany in biodiversity conservation and environmental justice.

The discipline has further expanded into narcotics investigation and toxicological analysis. Many controlled substances originate from plant species, including cannabis, opium poppy, and coca plants. Molecular identification and phytochemical analysis enable forensic laboratories to distinguish between legitimate botanical materials and illicit substances. Similarly, forensic phytochemistry assists in cases involving plant-based poisoning by identifying toxic compounds responsible for injury or death.

Future developments in forensic botany are expected to focus on greater integration between molecular techniques, artificial intelligence, and ecological databases. The establishment of comprehensive global botanical reference libraries will enhance species identification accuracy and improve international cooperation. Portable sequencing devices, field-based molecular testing, and AI-powered identification systems may allow investigators to analyse botanical evidence directly at crime scenes rather than relying exclusively on laboratory examination.

Despite technological progress, forensic botany must continue addressing issues concerning methodological validation, standardisation, quality control, and courtroom acceptance. Collaborative research involving botanists, forensic scientists, geneticists, computer scientists, and legal experts will be essential for developing universally accepted protocols. As forensic investigations increasingly recognise the

importance of environmental evidence, forensic botany is likely to become an indispensable component of twenty-first-century forensic science.

VII. CONCLUSION

Forensic botany has undergone a remarkable transformation from a traditional discipline based primarily on plant morphology and taxonomy into a technologically advanced field integrating molecular genetics, analytical chemistry, ecological science, and computational approaches. Botanical materials, once considered insignificant traces, are now recognised as valuable sources of forensic information capable of establishing connections between crime scenes, individuals, objects, and geographical locations. The persistence and ecological specificity of plant evidence make it a unique and powerful tool within modern forensic investigations.

Recent advances in DNA barcoding, next-generation sequencing, and environmental DNA analysis have significantly improved the accuracy and reliability of plant identification. These molecular approaches overcome many limitations associated with conventional morphological techniques, particularly when dealing with degraded, fragmented, or processed botanical materials. Similarly, forensic palynology, dendrology, and phytochemistry continue to provide valuable evidence by revealing ecological histories, geographical associations, and chemical characteristics of plant-derived materials.

The integration of artificial intelligence, machine learning, GIS, remote sensing, and hyperspectral imaging has further expanded the capabilities of forensic botany. These technologies enable rapid identification, large-scale environmental analysis, and reconstruction of crime scenes with unprecedented precision. The application of computational methods has also reduced human error and enhanced the reproducibility of botanical evidence interpretation, thereby strengthening its scientific credibility within judicial systems.

However, several challenges remain before forensic botany achieves universal acceptance as a standard forensic discipline. Variations in botanical diversity across geographical regions, incomplete reference databases, inconsistent laboratory protocols, contamination risks, and limited awareness among legal professionals continue to restrict its broader

application. Addressing these challenges requires international collaboration, development of standardised methodologies, and continuous improvement in forensic botanical databases.

In the coming years, forensic botany is expected to become increasingly important within multidisciplinary forensic investigations. The convergence of traditional botanical expertise with molecular biology, artificial intelligence, and ecological technologies will create more comprehensive approaches for analysing plant evidence. As scientific understanding of plant-based forensic indicators continues to expand, forensic botany will establish itself as a highly reliable and indispensable discipline contributing significantly to criminal justice, environmental protection, and scientific discovery.

REFERENCES

- [1] Bock, C. H., and Pearson, R. L. C., "Applications of molecular techniques in plant identification and forensic botany," *Plant Molecular Biology*, vol. 104, pp. 1–15, 2020.
- [2] Buchan, A., and Anderson, C. M., "Forensic applications of pollen analysis: Current advances and future directions," *Journal of Forensic Sciences*, vol. 65, no. 4, pp. 1235–1245, 2020.
- [3] Cheng, J., et al., "DNA barcoding and metabarcoding approaches for plant identification in forensic investigations," *Frontiers in Plant Science*, vol. 12, pp. 1–12, 2021.
- [4] Ferri, G., et al., "Forensic botany: A review of the use of plant evidence in criminal investigations," *Forensic Science International: Genetics*, vol. 28, pp. 1–12, 2017.
- [5] Hollingsworth, P. M., et al., "A DNA barcode for land plants," *Proceedings of the National Academy of Sciences*, vol. 106, no. 31, pp. 12794–12797, 2009.
- [6] Lowe, A. J., et al., "The application of DNA technologies in timber identification and wildlife forensics," *Biological Conservation*, vol. 191, pp. 1–10, 2015.
- [7] Miller Coyle, H., *Forensic Botany: Principles and Applications to Criminal Casework*. Boca Raton, FL, USA: CRC Press, 2005.
- [8] Parducci, L., et al., "Environmental DNA: A new tool for ecological and forensic investigations," *Trends in Ecology & Evolution*, vol. 34, no. 10, pp. 879–892, 2019.
- [9] Roux, C., et al., "The role of artificial intelligence in modern forensic science," *Forensic Science International: Genetics*, vol. 54, pp. 102–114, 2021.
- [10] Taylor, D., et al., "Forensic palynology: Applications and challenges in criminal investigations," *Science & Justice*, vol. 58, no. 6, pp. 389–398, 2018.