

FORENSIC BOTANY AND AQUATIC PLANT ANALYSIS: EMERGING APPLICATIONS IN ENVIRONMENTAL CRIME INVESTIGATION

Dr Renu Devi^{1*}, Dr. Archana Khare², Dr. Kanika Chhikara³, Dr. Ganesh Datt Bhatt⁴, Dr Biju Sidharthan⁵, Zohra Muslimova⁶

¹Assistant Professor, Nims School of Forensic Sciences, Nims University, Rajasthan Jaipur, Rajasthan, renu.devi@nimsuniversity.edu ORCID ID: 0009-0002-2511-4197

²Assistant Professor, Pt. J. L. N. College Banda, 210001, Email ID: drarchanakhare07@gmail.com, ORCID ID-0009-0006-6155-2150

³Assistant Professor, Department of Forensic Science, School of Basic and Applied Sciences, Shree Guru Gobind Singh Tricentenary University, Haryana, kanika_sbas@sgtuniversity.org, ORCID ID:https://orcid.org/0009-0006-2728-7074

⁴Professor, College of Agriculture Sciences (COAS), Teerthanker Mahaveer University (TMU), 244001, Moradabad, India.ganeshdattbhatt@gmail.com, ORCID ID: https://orcid.org/0000-0001-5211-3849

⁵Scientist, Department of Plant Breeding and Genetics, College of Agriculture, Vellanikkara, Thrissur 680656, Kerala Agricultural University, biju.s@kau.in, ORCID ID: 0009-0008-9775-7670

⁶Associate Professor, Department of Crop Science/Plant Science, Institute of Physics Public Legal Entity, Ministry of Science and Education of the Republic of Azerbaijan, zohre.biologist@gmail.com, Orcid : 0009-0007-8131-9230

ABSTRACT:

Environmental crimes such as illegal industrial discharge, oil spills, mining contamination, eutrophication, and freshwater habitat destruction pose serious threats to ecological sustainability and biodiversity conservation. In recent years, forensic botany has emerged as a promising interdisciplinary field for investigating environmental disturbances through the analysis of plant-based evidence. This review critically examines the emerging applications of aquatic plant analysis in environmental crime investigation and ecological forensics. Aquatic plants function as effective bioindicators due to their ecological sensitivity, pollutant bioaccumulation capacity, and ability to preserve long-term environmental signatures associated with contamination events. The review highlights the forensic significance of aquatic macrophytes, algae, and other aquatic vegetation in detecting heavy metals, hydrocarbons, radionuclides, nutrients, and microplastics in aquatic ecosystems. Furthermore, the integration of emerging analytical technologies including environmental DNA (eDNA), DNA barcoding, metabolomics, stable isotope analysis, remote sensing, Geographic Information Systems (GIS), and artificial intelligence has significantly enhanced species identification, pollution source attribution, ecological reconstruction, and environmental monitoring. Despite substantial progress, challenges related to methodological standardization, environmental variability, and legal admissibility remain critical concerns. Overall, aquatic forensic botany represents a rapidly evolving and sustainable forensic approach with significant potential for strengthening environmental monitoring, ecological restoration, and environmental justice frameworks.

KEYWORDS: Forensic botany, Aquatic plants, Environmental forensics, Bioindicators, Environmental DNA (eDNA)

INTRODUCTION

Environmental crimes have emerged as an increasing global threat, with the severity of their effects on the environment, nature conservation, and health of the population. Illegal discharge of by-products from industries, dumping of toxic waste, destruction of natural habitats, illegal mining, contaminating water with pollutants, as well as exploitation of wild animals still continue to progress and worsen environmental degradation and ecological imbalance all over the world (Casali et al., 2022; Sharma, 2025). Environmental crimes can result in long-term impact on the environment, which can be hard to trace, track, and prove. The increasing complexity has resulted in the development of ecological and environmental forensics as emerging interdisciplinary scientific fields that combine forensic science, ecology, toxicology, environmental chemistry and criminology to investigate and reconstruct environment crimes and damage (Kumar et al., 2025). Environmental forensic investigations are not only directed at identification of contaminants and pollution sources, but also provide an understanding of ecological responses and environmental signatures to anthropogenic disturbances. In recent years, the use of biological indicators that can document environmental changes has become more significant in the context of aquatic and terrestrial ecosystems in forensic contexts.

Plants are among these biological indicators, since they closely interact with the environmental conditions in its surroundings, and have been proved to be valuable forensic tools. Forensic Botany is a specialized field of forensic science that involves using plant-derived evidence like pollen, spores, seeds, leaves, fibres, wood particles etc., and plant DNA to assist in criminal and environmental investigations (Uddin et al., 2024). Forensic botany was mainly used in the past for terrestrial applications such as crime scene reconstruction, geographic origin determination, estimating post mortem interval and linking suspects by botanical traces. The use of forensic botany in aquatic systems has greatly increased with developments in environmental sciences and technologies for ecological monitoring. Aquatic plants have emerged as a witness in environmental crime investigations, particularly as aquatic pollution events have become more common, wetlands are being destroyed, eutrophication is a growing problem, and contamination of freshwater resources becomes more common. Plants communities are sensitive to chemical pollution, nutrient enrichment, sediment

disturbance and anthropogenic stressors and are very dynamic in aquatic ecosystems (O'Hare et al., 2018). Therefore, aquatic plants are important ecological indicators which can be used for the detection of contamination, environmental reconstruction and ecological risk assessment.

Aquatic plants are crucial for the ecological role in the freshwater and marine ecosystem, such as regulation of nutrient cycling, sediment stabilization, enhancement of oxygen availability, and maintenance of the complexity of the aquatic ecosystem (Kurbatova & Yershov, 2020). They are very sensitive to environmental disturbances and exposure to pollutants because of their close contact with water and sediments. Aquatic macrophytes have high bioaccumulation potential and can be able to uptake and store heavy metals, hydrocarbons, pesticides, radionuclides, excess nutrients, etc. in their tissue for long periods of time. This property is useful to aquatic plants to record in a natural way, both spatial and temporal aspects of contamination and ecological change in the ecosystems. In addition, physiological and biochemical responses of aquatic vegetation can also show patterns of pollutant stress and degradation of the environment, further enhancing their value as forensics bioindicators. The precision and reliability of aquatic plant-based forensic investigations have also been improved by recent progress in molecular biology, environmental DNA (eDNA) analysis, metabolomics, stable isotope profiling, remote sensing, and artificial intelligence (AI). These technologies enable species identification, source identification of pollution, ecological monitoring and large-scale environmental surveillance, with greater analytical sensitivity and forensic authenticity.

Although the field of forensic botany and environmental forensics is a growing scientific interest, the utilization of aquatic plant analysis in environmental crime investigation is still scattered among several scientific disciplines. The existing literature is spread across forensic science, aquatic ecology, environmental toxicology and molecular biology research, which hinders the ability to build an integrated knowledge of aquatic forensic methodologies and applications. Furthermore, review literature that covers the integration of new technologies into aquatic forensic botany is limited. Thus, a multi-disciplinary approach to the analysis of aquatic plant evidence, forensic techniques, ecological uses and technological advancements is urgently required to ensure the scientific basis of environmental forensic investigations are further enhanced. The purpose of this review is to provide a comprehensive overview of the growing importance of forensic botany and aquatic plant analysis, emphasizing the recent developments in aquatic plant analysis, analytical methodology, aquatic forensic applications and future research directions in aquatic environmental forensics.

Research Objectives

- To evaluate the forensic applications of aquatic plants in environmental crime investigation and pollution assessment
- To analyze emerging molecular, biochemical, and geospatial techniques used in aquatic forensic botany
- To identify current challenges, research gaps, and future prospects in aquatic plant-based environmental forensics

METHODOLOGY

The comprehensive review was conducted following PRISMA 2020 guidelines to systematically evaluate the emerging role of forensic botany and aquatic plant analysis in environmental crime investigation. Relevant peer-reviewed literature published between 2000 and 2026 was retrieved from Scopus, Web of Science, PubMed, ScienceDirect, and Google Scholar using Boolean search combinations of terms including “forensic botany,” “aquatic plants,” “environmental forensics,” “bioindicators,” “eDNA,” and “environmental crime.” Studies focusing on aquatic plant-based forensic applications, pollution detection, molecular identification techniques, geospatial analysis, and ecological evidence were included, while non-peer-reviewed articles, unrelated terrestrial studies, and duplicate records were excluded. Retrieved articles were screened through title, abstract, and full-text assessment, followed by thematic synthesis and critical evaluation based on methodological quality, analytical approaches, forensic applicability, and emerging technological advancements in aquatic environmental forensics.

3. RESULTS

3.1 Foundations of Forensic Botany in Environmental Investigation

Forensic botany has become a growing sub-discipline of environmental forensics, and it is important that biological evidence is gathered for environmental forensics investigations of ecological crime, environmental monitoring and environmental pollution source attribution. Plant Forensics combines various disciplines such as plant sciences, ecology, molecular biology, and forensics techniques to examine plant-related evidence in the context of criminal or environmental-related activities (Uddin et al., 2024). While the field of forensic botany had traditionally been used for terrestrial investigations, developments in ecological sciences, environmental DNA (eDNA) and environmental datasets have led to the application of forensic botany in aquatic ecosystems and environmental crime investigations (Spencer, 2021). The importance of plant evidence in a forensic investigation is great as plants are a good indicator of time, environmental conditions, contamination, and habitat alteration. Botanical evidence can be used to determine spatial and temporal information for pollution events, ecosystem degradation and anthropogenic activities during environmental investigations to support ecological reconstruction and interpretation of legal evidence.

3.1.1 Plant-Based Trace Evidence

Plant remains, known as trace evidence, are one of the most significant elements of forensic botany, particularly because they can persist, are ecologically specific, and are sensitive to the environment. Pollen grains are known as very good forensic indicators, as their morphology, abundance and geographical distribution are very species specific and informative. Pollen analysis can help identify the source(s) of environmental contaminants, ecological disturbances, and the aquatics and terrestrial habitats of suspects or materials (Uddin et al., 2024). Likewise, the presence of seeds and plant fragments provide ecological data as they are not easily degraded by an environment and they are linked to the

local vegetation community. The morphology and dispersal patterns of seeds can assist investigators in determining the habitat disturbance, illegal dumping site and/or changes in aquatic ecosystems. Macroscopic botanical remains and plant fibers are also useful forensically in investigations of the environment. Fibrous materials from aquatic or wetland plants can be used to identify habitat destruction, sediment movement or contamination pathways. Algae is another important category of plant based forensic evidence since algal community is very sensitive to the changes in the aquatic systems like nutrient enrichment, eutrophication, toxic pollutants and physicochemical changes. Algal changes in composition and biomass can, therefore, be used as sensitive measures of water quality deterioration and contaminations of aquatic environments. Also, aquatic macrophytes have become more of focus in environmental forensics because of their stability, ability to accumulate pollutants and their potential to record environmental changes over long time periods (Lesiv et al., 2020). They are an important source of information about hydrology, contamination exposure, and ecological succession, and are valuable resources when investigating historical environmental disturbances and pollution events (Figure 1).

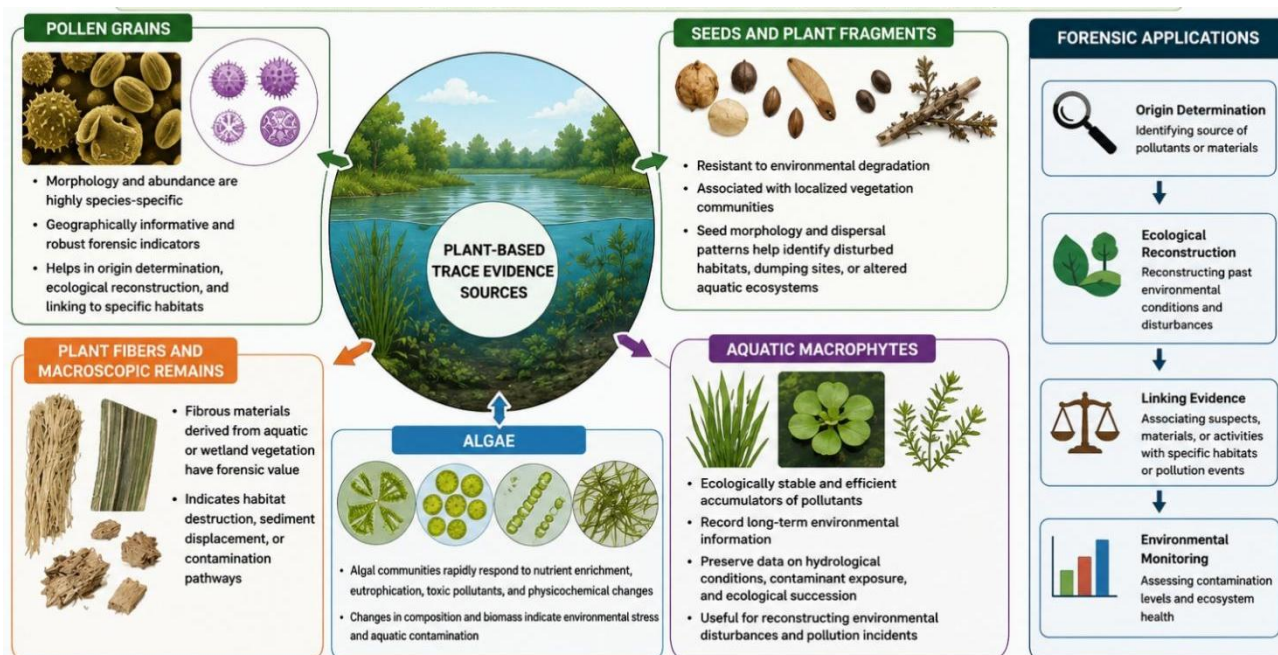


Figure 1. Plant-Based Trace Evidence and Forensic Applications in Environmental Botany

3.1.2 Ecological Signatures and Habitat Reconstruction

Plant communities are used as ecological signatures to be used for habitat reconstruction and for environmental crime analysis. Species in a water body can be associated with varying ecological conditions, contamination levels, availability of nutrients and anthropogenic disturbances. Changes in aquatic plant species composition can thus be used to detect environmental changes due to industrial effluent, mining operations, eutrophication or habitat loss. Plant assemblage environmental fingerprinting can be used to detect pollution sources, to create an ecological history and to determine the level of ecosystem degradation. Long-term assessment and interpretation of the environment are supported by stratigraphic and ecological signatures trapped in aquatic (pedogenic) vegetation and sediments (Nawrot et al., 2018). In modern environmental forensic investigations, the combination of ecological information and the molecular and geospatial tools have therefore improved the confidence in habitat reconstruction.

3.2 Aquatic Plants as Forensic Bioindicators

Due to the direct relationship with water, sediments and dissolved contaminants, aquatic plants are becoming well-known and are very useful as forensic bioindicators. They are ecologically sensitive and can accumulate pollutants, which makes them good bioindicators of environmental quality, pollutant levels and ecosystem disturbance. Aquatic vegetation can provide integrated long-term records of environmental exposure and ecological stress, which is not the case for conventional physicochemical monitoring methods that mostly provide short-term pollutant measurements. Hence, aquatic plants have been extensively used in environmental monitoring, environmental pollution assessment and ecologic risk evaluation (Polechońska & Klink, 2023).

3.2.1 Major Aquatic Plant Groups

Aquatic vegetation consists of several distinct types of vegetation which are emergent, floating, submerged, and algal. Emergent macrophytes grow up from the water and contribute to nutrient cycling, sediment stabilization and the trapping of pollutants. Species like *Phragmites australis* can be of special interest in environmental forensics as they can contain trace metals from both sediments and the atmosphere (Gacia et al., 2021). Floating aquatic plants (*Lemna* spp. and *Eichhornia crassipes*) grow rapidly and are efficient at absorbing pollutants and are good indicators of nutrient enrichment and chemical contamination. The level of dissolved contaminants and hydrologic changes are reflected by submerged vegetation (*Hydrilla verticillata*) and are continuously interacting with water columns and sediments. Algal

communities are also excellent ecological indicators because they are very sensitive to environmental stressors and pollution events with a quick physiological response.

3.2.2 Mechanisms of Bioaccumulation

The value of the aquatic plants in the forensics is highly dependent on the bioaccumulation of contaminants from the surrounding environment. Bioaccumulation refers to the physiological and biochemical uptake, transport, sequestration and retention of pollutants in plant tissue (Chugh et al., 2022). Aquatic plants are able to sorb heavy metals like Cd, Pb, Hg, Mn, As from the water and sediments, sometimes accumulating them at levels much higher than the environmental matrices (Petrov et al., 2023). Aquatic plants can withstand toxic substances and accumulate them within their body through various mechanisms such as ion exchange, chelation, compartmentalization, and antioxidant detoxification (Nnaji et al., 2023). Aquatic plants can also bind organic pollutants, radionuclides, pesticides, hydrocarbons and micro plastics, giving long-term information of contamination of the environment. The use of aquatic plants (*Lemna minor*) as bioindicators of emerging pollutants has been proven in recent studies, demonstrating measurable physiological and biochemical changes in the presence of microplastics (Rozman & Kalčíková, 2022).

3.2.3 Indicator Species in Pollution Detection

The aquatic plants showed high potential to be bioindicators for detecting environmental pollution, with several species being identified. *Lemna* species are common duckweed species and have been largely adopted for ecotoxicological studies due to their high sensitivity to pollutants, measurable physiological response to environmental stressors, and ability to grow quickly. *Lemna minor* has demonstrated special abilities to detect microplastic pollution and related oxidoreductive responses in aquatic ecosystems (Rozman & Kalčíková, 2022). Likewise *Eichhornia crassipes* (water hyacinth) is considered as one of the strongest emerging pollutants bio indicator due to its exceptional ability to absorb pollutants and tolerance to contaminated environment (De Laet et al., 2019). The species will concentrate organic contaminants, pharmaceuticals, heavy metals, and nutrients, which will help identify pollution sources and evaluations of aquatic remediation.

Significant bioaccumulation is also observed in submerged macrophytes like *Hydrilla verticillata*, especially in areas that are affected by mining and industrial activities. Emerging studies have shown that *Hydrilla verticillata* can be used for monitoring aquatic pollution (Wu et al., 2024) and aquatic ecological forensic studies in manganese mining affected river systems, where potentially toxic elements have been found to accumulate at higher levels. In wetland ecosystems, *Phragmites australis* is a dual bioindicator that provides information on both atmospheric and sediment-related trace metal pollution (Gacia et al., 2021). The species has a large root system and is very widespread, making it useful to give information on pollutant transport pathways, ecological disturbances, and long-term environmental contamination. Together, these are aquatic indicator species that enhanced the contribution of forensic botany to environmental crime investigation through the supply of scientifically sound biological evidence for the detection of pollution, reconstruction of an environment and environmental risk assessment (Table 1).

Table 1. Aquatic Plants as Forensic Bioindicators with Supporting References

Aquatic plant group/species	Forensic relevance	Target pollutants/indicators	Key application	References
<i>Lemna minor</i>	Sensitive bioindicator	Microplastics, oxidative stress	Emerging pollutant detection	Rozman & Kalčíková (2022)
<i>Eichhornia crassipes</i>	Strong pollutant accumulator	Heavy metals, organic pollutants, nutrients	Water pollution assessment	De Laet et al. (2019)
<i>Hydrilla verticillata</i>	Bioaccumulation indicator	Potentially toxic elements, mining pollutants	Contamination tracing	Wu et al. (2024)
<i>Phragmites australis</i>	Dual air-sediment indicator	Trace metals, sediment pollutants	Wetland forensic assessment	Gacia et al. (2021)
Algal communities	Rapid ecological stress indicator	Eutrophication, toxic pollutants	Aquatic ecosystem monitoring	Lesiv et al. (2020)

3.3 Applications in Environmental Crime Investigation

With the capacity to detect contamination, to reconstruct ecological disturbances and to find pollution sources, aquatic plants and forensic botanical tools are growing in significance for environmental crime investigations. Aquatic vegetation and sensor-based monitoring systems are extensively applied to toxicity mapping and chemical tracing to help identify the unpermitted discharge of contaminants into aquatic environments in the case of industrial discharge (Shi et al., 2022). Bioaccumulation patterns from plants can give long-term information on the presence of industrial contaminants, and can be used to determine contamination routes for forensic analysis.

Aquatic plants are good indicators of hydrocarbon contamination in investigations of oil spills and hydrocarbons because of the ability to acquire hydrocarbons and respond to their physiologic effects. Due to the analytical chemistry advances, the ability to detect hydrocarbon residues and vegetation stress biomarkers for oil pollution events has also increased considerably (Wise et al., 2023). Likewise, mining operations are a significant source of heavy metal contamination in aquatic environments, and such polluted plants as *Hydrilla verticillata* and *Spirogyra varians* serve as indicators of the levels of heavy metals contamination and/or exposure to heavy metals in aquatic environments (Wu et al., 2024). The ability of *Phragmites australis* to accumulate trace metals has also been shown to be useful in the identification of contamination in wetland sediments and atmosphere (Gacia et al., 2021).

Aquatic forensic investigations also help in the detection of illegal waste disposal and eutrophication by using nutrient signatures, algal bloom analysis and water quality assessment (Glova Végsoöová & Straka, 2025). These methods allow detection of where contamination is occurring and ecological degradation of the environment due to illegal dumping (Table 2). In addition, freshwater habitat destruction and ecocide investigations depend on the patterns of alteration in biodiversity, assessment of ecosystem disturbance and evaluation of ecological damage to quantify the level of damage to the environment and to take legal action against environmental crimes (Jer, 2019; Romaniuk et al., 2025).

Table 2. Applications of Aquatic Forensic Botany in Environmental Crime Investigation and Pollution Assessment

Environmental Crime Application	Forensic Approach	Key Indicators	Representative Species/Tools	Forensic Significance	References
Illegal Industrial Discharge Detection	Toxicity mapping and chemical tracing	Chemical pollutants, water toxicity, contaminant pathways	Sensor networks, aquatic macrophytes	Identifies unauthorized industrial contamination and pollution sources	Shi et al. (2022)
Oil Spill and Hydrocarbon Investigation	Hydrocarbon uptake analysis and stress biomarker assessment	Petroleum residues, vegetation stress responses	Aquatic plants, analytical chemistry techniques	Detects oil contamination and ecological impact	Wise et al. (2023)
Mining and Heavy Metal Contamination	Bioaccumulation and isotopic analysis	Heavy metals, toxic elements, metallophyte responses	Hydrilla verticillata, Spirogyra varians, Phragmites australis	Assesses mining-related pollution and trace metal contamination	Wu et al. (2024); Gacia et al. (2021); Punia (2021)
Illegal Waste Disposal and Eutrophication	Nutrient profiling and algal bloom forensics	Nutrient enrichment, eutrophication, water quality changes	Algal communities, aquatic vegetation	Identifies ecological degradation caused by illegal dumping	Glova Végsoöová & Straka (2025)
Freshwater Habitat Destruction and Ecocide	Ecological damage assessment	Biodiversity alteration, ecosystem disturbance	Aquatic biodiversity indicators	Evaluates environmental damage and supports legal investigations	Jer (2019); Romaniuk et al. (2025)

3.4 Emerging Analytical Technologies

In recent years, the field of aquatic forensic botany has been increasingly successful in environmental crimes investigation due to advances in molecular biology, geospatial sciences and computational analytics. The use of environmental DNA (eDNA) has been revolutionized as a tool to assess the presence of a species, shifts in biodiversity and environmental disturbances associated with pollution by collecting trace genetic material from water and sediment samples (Beng & Corlett, 2020). eDNA-based methods can be used for species identification, source tracking and degraded sample analysis, and provide enhanced ecological monitoring and forensics in aquatic ecosystems with contaminants.

The use of DNA barcoding and phylogenetic analysis has also improved forensic studies, providing accurate taxonomic identification and authentication of plant-derived materials. Standardized genetic markers are used to rapidly identify species in water, and to better validate the chain-of-evidence in environmental forensic investigations (DeSalle & Goldstein, 2019). Such molecular methods are especially valuable for differentiating between morphologically similar species and in determining the geographic source of biological specimens.

The metabolic and protein-based analysis of metabolites, proteins and biochemical pathways is an emerging tool to assess environmental stress to aquatic plants caused by pollutants. The stress-response biomarkers and pollutant-specific biochemical profiles provide detailed information on contaminant exposure and ecological toxicity (Chen & Gerszten, 2020). These techniques aid in the understanding of plant response to hydrocarbons, heavy metals, pesticides and emerging pollutants in aquatic environments.

Stable isotope analysis is also becoming a critical tool in environmental forensics as a method to determine geographic origin and pollution sources by isotopic signatures. Stable isotopes, along with chemometric analysis, can be used to reliably identify the sources of contamination and reconstruct environmental pathways (Wang et al., 2020). Furthermore, the use of remote sensing and Geographic Information Systems (GIS) has transformed the environmental monitoring of large areas by providing a means of assessing vegetation via satellite, spatial analysis and ecological mapping. These technologies provide tools for use in aquatic ecosystem long-term surveillance, habitat disturbance detection, and crime scene reconstruction (Almalki et al., 2022).

Artificial intelligence (AI) and machine learning are also revolutionizing ecological forensic investigations, allowing for automated species classification, predictive ecological modeling, and enhanced pattern recognition. Data from environmental measurements are analysed in high throughput and AI-driven analytical systems enhance data interpretation, contamination prediction and ecological risk assessment (Kühl et al., 2022). These developing analytical technologies greatly improve the accuracy, efficiency and interdisciplinary applicability of aquatic forensic botany for contemporary environmental crimes investigation.

3.5 Case Studies and Real-World Applications

The application of aquatic forensic botany in the field of environmental crime investigations has proven to be very valuable in freshwater, coastal and wetland environments. Aquatic plants and algal communities have been widely employed to evaluate pollution and contamination from industrial discharge, agricultural runoff and microplastic accumulation in freshwater pollution cases. Research conducted in freshwater ecosystems in Turkey emphasized the increasing effects of microplastic pollution on aquatic biodiversity and the role of aquatic vegetation and ecological indicators in monitoring and assessing pollution and the environment (Erdoğan, 2020). The same, aquatic macrophytes and algae are also employed to determine the accumulation of heavy metals and ecological disturbance due to mining and industrial pollution.

Toxic microalgae and phycotoxins have become key forensic markers in coastal and marine investigations for assessing marine pollution, eutrophication and harmful algal blooms. Toxic microalgae have been shown to be associated with anthropogenic pollution and environmental degradation, which has been shown in coastal studies in China, highlighting their importance in marine ecological monitoring and environmental forensic investigations (Liang et al., 2019). These investigations help determine where pollution is coming from and the potential ecological hazards to marine ecosystems.

As biodiversity loss and habitat degradation continue to rise, wetlands destruction and ecological restoration litigation have come into the spotlight worldwide (Table 3). In recent years, there has been a surge in using environmental litigation frameworks to seek ecological restoration and compensation for environmental harm using science and ecological assessment (Phelps et al., 2021). Environmental litigation has been a key means of promoting ecological restoration policies and biodiversity conservation in the context of environmental law in China (Rong, 2023). In addition, the use of remote sensing and GIS-based vegetation mapping has enhanced environmental crime investigations by providing extensive monitoring of habitat destruction, vegetation loss and ecological disturbances (Almalki et al., 2022). The incorporation of artificial intelligence and machine learning has additionally enhanced the capacity to predict ecological impacts, identify species and recognize environmental patterns in forensic investigations (Kühl et al., 2022).

Table 3. Case Studies and Real-World Applications of Aquatic Forensic Botany in Environmental Crime Investigation

Case	Region	Crime Type	Plant Evidence	Investigative Outcome
Freshwater microplastic contamination	Turkey	Freshwater pollution	Aquatic vegetation and ecological indicators	Detection of microplastic pollution and ecological degradation
Toxic algal bloom investigation	Coastal China	Marine pollution and eutrophication	Toxic microalgae and phycotoxins	Identification of pollution-associated harmful algal blooms
Wetland trace metal contamination	Ebro River, Spain	Industrial pollution	Phragmites australis	Assessment of sediment and atmospheric metal contamination
Habitat destruction and biodiversity loss	China	Wetland destruction/ecocide	Vegetation cover and biodiversity indicators	Ecological restoration through environmental litigation
Remote sensing vegetation monitoring	Arid and semi-arid regions	Ecological degradation	Satellite-based vegetation mapping	Large-scale environmental monitoring and habitat assessment

3.6 Strengths and Limitations of Aquatic Plant Forensics

Aquatic plant forensics has multiple scientific benefits in the context of environmental crime investigations as aquatic plants are a highly sensitive resource and are known to accumulate pollutants. Aquatic plants are sensitive to chemical pollution, nutrient enrichment and ecological disturbances, and are good bioindicator organisms for monitoring pollution and habitat loss. They bioaccumulate heavy metals, hydrocarbons, pesticides and microplastics, giving long-term records of the environment useful for the identification of pollution sources and the reconstruction of the environment. In addition, the investigations based on water plants are relatively inexpensive and environmentally friendly compared to complicated physicochemical monitoring systems.

Although these benefits are significant, a number of technical challenges prevent the widespread use of aquatic Forensic Botany. Plant growth, physiological reactions, and patterns of accumulation of contaminants may be affected by seasonal variability, which can lead to inconsistent analytical results and to interpretation challenges. The possibility of species misidentification, especially among morphologically similar aquatic species, can also affect the accuracy of the forensics. Also, hydrological changes, climate variability, sediment interactions and mixed sources of pollution may make contamination assessment and ecological interpretation complicated.

Other legal and evidentiary issues are also significant issues in environmental forensic investigations. Plant-based evidence may be admissible if analytical procedures are standardized, science is validated and reproducible. Chain of custody is critical for the reliability of the evidence starting with sample collection, preservation and analysis in the laboratory. Thus, more methodological standardization and validation are needed to enhance the legal acceptance and forensic utility of aquatic plant evidence to environmental litigation.

4. DISCUSSION

Environmental crimes are becoming increasingly complex and interdisciplinary forensic approaches are playing an important role linking the environmental disturbances with the anthropogenic activities. The characteristics of ecological sensitivity, pollutant accumulation and bioindicator potential of aquatic plants have made the field of aquatic forensic botany a promising science. Aquatic plant-based investigations have the advantage of providing long-term ecological records, with the ability to enhance environmental reconstruction and contamination source attribution (Rao et al., 2020), compared with conventional forensic technologies which are mostly physicochemical based. Aquatic vegetation in environmental forensics thus enhances the ecological crime investigation, biodiversity evaluation and environmental litigation processes.

The analytical precision and application of aquatic forensics has been greatly enhanced by recent technological advances. New molecular tools like metabolomics and proteomics can help pinpoint the biochemical signature and stress response to a particular pollutant in aquatic plants, improving the ability to detect ecological toxicity and contaminants exposure (Chen & Gerszten, 2020). In the same way, stable isotope analysis can be integrated with chemometric methods to enhance geographic origin tracing and pollution source attribution and provide more accurate forensic evidence in environmental monitoring and legal investigations (Wang et al., 2020). The analytical approaches offer useful information regarding contaminant pathways, environmental disturbances, and long-term environmental change.

Environmental forensic investigations have also been revolutionized by geospatial technologies, including remote sensing and Geographic Information Systems (GIS), which can provide a way to monitor vegetation from the orbit of Earth, to assess habitats, and to conduct large-scale ecological surveillance. Technologies such as remote sensing are especially beneficial in detecting wetland destruction, the loss of vegetation, and ecosystem degradation caused by industrial activities, illegal waste disposal, and other forms of environmental destruction that involve ecocide (Almalki et al., 2022). In addition, environmental forensic tools for aquatic systems support the assessment of water resources, mapping contamination and environment risk assessment (Brčeski & Vaseashta, 2021). The inclusion of artificial intelligence (AI) and machine learning (ML) in ecological forensics has also been boosted by automated species classification, environmental pattern recognition, and high throughput environmental data analysis (Kühl et al., 2022).

There is growing use of scientifically sound ecological evidence in environmental lawsuits and ecological restoration policies for tackling biodiversity loss and environmental degradation. Research has pointed to the increasing importance environmental liability litigation plays in the restoration of damaged ecosystems and the development of environmental accountability mechanisms (Phelps et al., 2021). Ecological restoration practices have shown that scientific evidence plays a crucial role in environmental law-based biodiversity conservation and environmental governance in China (Rong, 2023). Moreover, it is still needed to improve the legal culture and the enforcement of criminal law in the field of environmental protection and sustainable development (Handayani & Hardiyanti, 2025).

Although tremendous strides have been made, certain barriers still prevent the widespread use of aquatic forensic botany. Environmental, analytical, species misidentification, and forensic validation limitations can impact the reliability of the evidence and its admissibility in court. Additionally, there is a need for more collaboration between ecologists, forensic scientists, molecular biologists, legal professionals, and environmental policymakers. Future studies should therefore aim to establish standardised methodologies, to increase ecological databases, to introduce analytical systems with artificial intelligence and to optimize molecular forensic techniques, in order to increase the scientific robustness and legal application of aquatic plant-based forensic investigations.

CONCLUSION

By combining ecological science with forensic analysis and cutting-edge environmental monitoring technologies, aquatic forensic botany has become a valuable interdisciplinary practice for investigating environmental crime. The ecological sensitivity, pollutant bioaccumulation ability, and the preservation of long-term environmental signatures of pollutant and habitat disturbance are characteristics of aquatic plants that make them good forensic bioindicators. This review focuses on the role of aquatic vegetation as a tool for identifying the illegal discharge of industries, oil spills, contamination from mining operations, eutrophication, biodiversity loss and environmental damage from ecocide. Analytical innovations such as environmental DNA (eDNA), DNA barcoding, metabolomics, stable isotope analysis, remote sensing, Geographic Information Systems (GIS) and artificial intelligence have greatly enhanced species identification, pollution source identification, ecological reconstruction, and environmental surveillance on a large scale. *Lemna minor*, *Eichhornia crassipes*, *Hydrilla verticillata* and *Phragmites australis* are example of indicator species with high potential for environmental monitoring and forensic assessment. However, these gains have been counteracted by difficulties with environmental variation, lack of standardized methodologies, difficulties in species identification, and

legal admissibility. In summary, methodological standardization, interdisciplinary cooperation and the implementation of molecular and AI-based technologies will be the focus of future research to enhance the scientific credibility and legal acceptance of aquatic plants-based forensic research for sustainable environmental protection and ecological justice.

REFERENCES

1. Almalki, R., Khaki, M., Saco, P. M., & Rodriguez, J. F. (2022). Monitoring and mapping vegetation cover changes in arid and semi-arid areas using remote sensing technology: A review. *Remote Sensing*, 14(20), 5143.
2. Beng, K. C., & Corlett, R. T. (2020). Applications of environmental DNA (eDNA) in ecology and conservation: opportunities, challenges and prospects. *Biodiversity and conservation*, 29(7), 2089-2121.
3. Brčeski, I., & Vaseashta, A. (2021). Environmental forensic tools for water resources. In *Water Safety, Security and Sustainability: Threat Detection and Mitigation* (pp. 333-370). Cham: Springer International Publishing.
4. Casali, M. B., Travaini, G. V., Di Francesco, C. V., & Genovese, U. R. (2022, January). Environment, Environmental Crimes, Environmental Forensic Medicine, Environmental Risk Management and Environmental Criminology. In *Healthcare* (Vol. 10, No. 2, p. 263). MDPI.
5. Chen, Z. Z., & Gerszten, R. E. (2020). Metabolomics and proteomics in type 2 diabetes. *Circulation research*, 126(11), 1613-1627.
6. Chugh, M., Kumar, L., Bhardwaj, D., & Bharadvaja, N. (2022). Bioaccumulation and detoxification of heavy metals: an insight into the mechanism. In *Development in wastewater treatment research and processes* (pp. 243-264). Elsevier.
7. De Laet, C., Matringe, T., Petit, E., & Grison, C. (2019). *Eichhornia crassipes*: a powerful bio-indicator for water pollution by emerging pollutants. *Scientific reports*, 9(1), 7326.
8. DeSalle, R., & Goldstein, P. (2019). Review and interpretation of trends in DNA barcoding. *Frontiers in ecology and evolution*, 7, 302.
9. Erdoğan, Ş. (2020). Microplastic pollution in freshwater ecosystems: A case study from Turkey. *SU URUNLERI DERGISI*, 37(3).
10. Gacia, E., Soto, D. X., Roig, R., & Catalan, J. (2021). *Phragmites australis* as a dual indicator (air and sediment) of trace metal pollution in wetlands—the key case of Flix reservoir (Ebro River). *Science of the Total Environment*, 765, 142789.
11. Glova Végsőová, O., & Straka, M. (2025). Illegal Waste Dumps and Water Quality: Environmental and Logistical Challenges for Sustainable Development—A Case Study of the Ružín Reservoir (Slovakia). *Environments*, 12(8), 251.
12. Handayani, E., & Hardiyanti, M. (2025). Forging a legal culture: criminal law enforcement in environmental protection amidst the sustainable development era. *Clío. Revista de Historia, Ciencias Humanas y Pensamiento Crítico.*, (10), 249-281.
13. Jer, S. B. (2019). Ecocide or environmental self-destruction?. *Environmental Ethics*, 41(3), 237-247.
14. Kühl, N., Schemmer, M., Goutier, M., & Satzger, G. (2022). Artificial intelligence and machine learning. *Electronic Markets*, 32(4), 2235-2244.
15. Kumar, A., Patle, C. R., Tomar, S., Yadav, M. M., & Sharma, G. (2025). Ecological Crime Scene Investigation. In *Introducing the Synergy Between Forensic Science and Environmental Analysis* (pp. 121-145). Singapore: Springer Nature Singapore.
16. Kurbatova, S. A., & Yershov, I. Y. (2020). The importance of aquatic plants in maintaining zooplankton diversity and abundance: An experimental approach. *Regulatory Mechanisms in Biosystems*, 11(4).
17. Lesiv, M. S., Polishchuk, A. I., & Antonyak, H. L. (2020). Aquatic macrophytes: ecological features and functions. *Біологічні студії/Studia Biologica*, 14(2), 79-94.
18. LIANG, Y. B., LI, D. M., YAO, J. Y., JIN, W., GONG, C. B., & LIU, R. Y. (2019). Progresses in investigation and research on phycotoxins and toxic microalgae in the coastal waters of China. *Oceanologia et Limnologia Sinica*, 50(3), 511-524.
19. Nawrot, R., Scarponi, D., Azzarone, M., Dexter, T. A., Kusnerik, K. M., Wittmer, J. M., ... & Kowalewski, M. (2018). Stratigraphic signatures of mass extinctions: ecological and sedimentary determinants. *Proceedings of the Royal Society B: Biological Sciences*, 285(1886).
20. Nnaji, N. D., Onyeaka, H., Miri, T., & Ugwa, C. (2023). Bioaccumulation for heavy metal removal: a review. *SN Applied Sciences*, 5(5), 125.
21. O'Hare, M. T., Aguiar, F. C., Asaeda, T., Bakker, E. S., Chambers, P. A., Clayton, J. S., ... & Wood, K. A. (2018). Plants in aquatic ecosystems: current trends and future directions. *Hydrobiologia*, 812(1), 1-11.
22. Petrov, D. S., Korotaeva, A. E., Pashkevich, M. A., & Chukaeva, M. A. (2023). Assessment of heavy metal accumulation potential of aquatic plants for bioindication and bioremediation of aquatic environment. *Environmental Monitoring and Assessment*, 195(1), 122.
23. Phelps, J., Aravind, S., Cheyne, S., Dabrowski Pedrini, I., Fajrini, R., Jones, C. A., ... & Webb, E. L. (2021). Environmental liability litigation could remedy biodiversity loss. *Conservation Letters*, 14(6), e12821.
24. Polechońska, L., & Klink, A. (2023). Macrophytes as passive bioindicators of trace element pollution in the aquatic environment. *Wiley Interdisciplinary Reviews: Water*, 10(2), e1630.
25. Punia, A. (2021). Role of temperature, wind, and precipitation in heavy metal contamination at copper mines: a review. *Environmental Science and Pollution Research*, 28(4), 4056-4072.
26. Rao, P. K., Tharmavaram, M., & Pandey, G. (2020). Conventional technologies in forensic science. *Technology in forensic science: sampling, analysis, data and regulations*, 17-34.

27. Romaniuk, M., Lypnytska, Y., Demianchuk, T., Herasymenko, O., & Husak, A. P. (2025). Legal Principles and Methodological Approaches to Organizing Pre-Trial Investigation of Environmental Criminal Offenses. *Grassroots Journal of Natural Resources*, 8(2).
28. Rong, Z. (2023). Using Environmental Litigation to Advance Ecological Restoration under the Convention on Biological Diversity in China. *Chinese Journal of Environmental Law*, 7(1), 100-130.
29. Rozman, U., & Kalčíková, G. (2022). The response of duckweed *Lemna minor* to microplastics and its potential use as a bioindicator of microplastic pollution. *Plants*, 11(21), 2953.
30. Sharma, J. K. (2025). Ecological and environmental crimes: a threat to sustainable development. In *Transnational Unconventional Organized Crime: A National and Global Security Concern: Volume I: Thematic Perspectives* (pp. 55-88). Cham: Springer Nature Switzerland.
31. Shi, B., Catsamas, S., Deletic, B., Wang, M., Bach, P. M., Lintern, A., ... & McCarthy, D. T. (2022). Illicit discharge detection in stormwater drains using an Arduino-based low-cost sensor network. *Water Science and Technology*, 85(5), 1372-1383.
32. Spencer, M. A. (2021). Forensic botany: time to embrace natural history collections, large scale environmental data and environmental DNA. *Emerging Topics in Life Sciences*, 5(3), 475-485.
33. Uddin, M. K., Moni, S. Y., Islam, M. S., Rahman, M. M., Sultana, N., & Islam, M. R. (2024). Forensic Botany: The Growing Discipline Revolutionizing Plant Science and Criminal Investigations. *International Journal of Forensic Expert Alliance*, 1(1), 46-52.
34. Ulybina, L. Y., & Harbuz, M. V. (2025). Peculiarities of plant-based meat substitutes classification in the course of forensic commodity examination. *Bulletin of Kharkiv National University of Internal Affairs*, 108(1 (Part 1)), 404-415.
35. Wang, J., Chen, T., Zhang, W., Zhao, Y., Yang, S., & Chen, A. (2020). Tracing the geographical origin of rice by stable isotopic analyses combined with chemometrics. *Food chemistry*, 313, 126093.
36. Wise, S. A., Rodgers, R. P., Reddy, C. M., Nelson, R. K., Kujawinski, E. B., Wade, T. L., ... & Liu, Z. (2023). Advances in chemical analysis of oil spills since the deepwater horizon disaster. *Critical Reviews in Analytical Chemistry*, 53(8), 1638-1697.
37. Wu, D., Zhang, Z., & Wang, Z. (2024). Impact of manganese mining on potentially toxic elements pollution and bioaccumulation in *Spirogyra varians* and *Hydrilla verticillata* in the Xiaojiang River. *Environmental Geochemistry and Health*, 46(10), 381.