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Year: 2026

Nature as Witness: Environmental Forensics and Scientific Responses to Ecological Crime

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Abstract

Environmental crimes are grave threats to the ecosystem, biodiversity, public health and sustainable development and require strong scientific methods to investigate and prevent. Environmental forensics has become an interdisciplinary science that brings together chemistry, biology, geology, toxicology, molecular science and geospatial technologies to determine sources, characterize and track environmental contaminants, and provide legally defensible evidence. This review addresses the concept of the "Nature as Witness" focusing on the natural elements that include soil, water, air, sediments, vegetation and wildlife, which maintain physical, chemical and biological evidence of disturbances to the environment. The paper addresses pollution investigations, illegal mining, investigations of wildlife crime, oil spills, and plastic contamination investigations, as they relate to environmental crime scene investigation and evidence collection, as well as some of the analytical processes used, such as chemical fingerprinting, stable isotope analysis, environmental DNA, chromatography, spectroscopy, and remote sensing. It also emphasises on legal, regulatory and scientific problems in the Indian scenario and discusses new technologies like Artificial Intelligence, IoT-based monitoring, portable forensic instruments and climate forensics. The review highlights that the adoption of cutting-edge scientific approaches alongside good environmental governance measures can reinforce environmental justice, enhance environmental criminal investigations, and facilitate sustainable natural resource conservation.

[1] ISBN No.- 978-93-7640-081-2

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Keywords; Environmental forensics; Ecological crime; Environmental evidence; Chemical fingerprinting; Environmental justice

1 Introduction

The term "Nature as Witness" indicates that humans are leaving behind physical, chemical, and biological signatures of their presence in the environment that are persistent. Scientists can trace the contamination and ecological disturbance in soil, water, air, sediments, vegetation, and wildlife, and use this to determine what happened in the past, long after it has taken place. These natural records, unlike human testimony, are free of prejudice and measurable, and therefore are invaluable forensic evidence. Environmental forensics uses these natural signatures to determine the source, source time, and extent of the environmental damage, and, in a sense, allows nature to be an objective witness during a criminal investigation.[2]

Environmental forensics is an emerging interdisciplinary science that uses chemistry, biology, geology, toxicology, ecology, and geospatial science to elucidate the sources, transport, and effects of environmental contamination. The discipline has grown in significance in criminal investigations, where environmental evidence is subjected to scientific analysis to establish linkages between such evidence and illegal activity. Environmental forensic investigations combine systematic field sampling, laboratory analyses and data interpretation to offer scientifically sound evidence to help support regulatory actions and criminal prosecution.[3]

Ecological crime refers to a wide variety of acts that have a detrimental impact on ecosystems and on biodiversity and public health. They can be broadly grouped into industrial pollution, illegal disposal of hazardous waste, wildlife poaching and trafficking, illegal mining and logging, oil spills, and surface and ground water contamination. These crimes frequently involve

[2] M. Lewis et al., “The forensic potential of environmental DNA (eDNA) in freshwater wildlife crime investigations: From research to application,” Sci. Justice, vol. 64, pp. 443–454, 2024, doi: https://doi.org/10.1016/j.scijus.2024.06.003.

[3] G. A. Toranzos and R. J. Cano, “Definitions and Historical Perspectives in Environmental Forensics,” Microbiol Spectr., vol. 6, no. 2, pp. 1–7, 2018, doi: doi:10.1128/microbiolspec.EMF-0016-2018.

intricate criminal networks and cross-border operations, and are likely to cause long-term environmental harm.[4]

Science plays a key role in the quest for environmental justice because it is objective and defensible in a legal sense as evidence of environmental harm. Chemical fingerprinting, stable isotope analysis, environmental DNA (eDNA), chromatographic and spectrometric techniques, and remote sensing technologies are all advanced analytical methods that can be used to precisely identify pollution sources, trace contaminant pathways and estimate ecological impacts. Therefore, environmental forensics can be used as a tool in environmental science and criminal investigation, which can enhance the capability of law enforcement and ensure protection of the ecosystem, accountability and sustainable management of natural resources.[5]

2 Environmental Crime Scene Investigation and Types of Environmental Evidence

Environmental crime scenes vary widely from traditional crime scenes in many aspects, as the evidence can be spread out over a vast area and can be altered over time by biological activity, hydrological processes, weather conditions, or human activity. As a result, it is necessary to adopt a multi-disciplinary approach for environmental crime scene investigation, combining forensic science, environmental chemistry, ecology, geology and geospatial technologies. The primary goal is to scientifically and legally defensibly identify, collect, preserve and analyze environmental evidence to determine the source, extent and time of ecological harm.[6]

A. Characteristics and Documentation of Environmental Crime Scenes

An environmental crime scene could be a contaminated land, river, industrial facility, forest, mining site, coastal area or wildlife habitat. Investigators perform systematic site evaluations to determine potential contamination sources, exposed areas and possible contaminant migration pathways. Photographs, field notes, geologic positioning systems (GPS), and mapping

[4] H. S. Bakhtiar, B. Waluyo, B. Harefa, A. L. Ibrahim, S. T. Wahyudi, and R. D. Agustanti, Utilisation of Forensic Evidence in the Disclosure of Environmental Damage. Atlantis Press SARL, 2025. doi: https://doi.org/10.2991/978-2-38476-356-6_22.

[5] S. U. Wali, N. B. Alias, I. U. Kaoje, S. Ibrahim, and A. B. Usman, "Forensic Hydrochemistry for Environmental Crime Investigation: A PRISMA-Based Systematic Review of Isotopic and Geochemical Fingerprinting Techniques," Glob. J. Earth Sci. Eng., pp. 131–152, 2025, doi: https://doi.org/10.15377/2409-5710.2025.12.8.

[6] T. Vj, P. Rv, K. Ks, K. Jt, and P. Aa, "Forensic Science Analysis as an Emerging New Dimension of Environmental Issues," J. Forensic Sci. Crim. Investig., vol. 17, no. 2, pp. 1–7, 2023, doi: 10.19080/JFSCI.2023.17.555960.

techniques help to accurately document the spatial association of evidence and suspected criminal activity.[7]

B. Environmental Evidence: Identification, Collection, and Preservation

Environmental evidence includes soil, water/sediment, air samples, plants, animal tissues, pollutants, microorganisms, and industrial wastes. Every evidence type will give significant clues as to the source, transport, persistence and effects of the contaminant. Sample sizes must be representative of conditions at a site to assure that the samples collected are representative of conditions at the site. Investigators use sterile equipment, proper containers and controlled storage procedures to reduce contamination and retain the physical, chemical and biological integrity of samples until analyzed in the lab during collection.[8]

C. Chain of Custody and Quality Assurance

An unbroken chain of custody is essential for establishing the credibility of environmental forensic evidence by documenting the handling of evidence from collection through transportation to the laboratory for analysis and storage. Analytical errors and cross-contamination are minimized by using standardized sampling procedures, quality checks in the field, decontamination of equipment, duplicate sampling, and strict quality assurance and quality control (QA/QC) procedures. These measures help to maintain environmental evidence that is reliable, reproducible, and legally admissible in environmental investigations and court cases.[9]

3 Analytical Techniques in Environmental Forensics

Environmental forensics is a branch of science that uses sophisticated analytical methods to identify sources of environmental contamination, characterize environmental pollutants, reconstruct environmental contamination pathways and link ecological damage causally to criminal activity. These approaches combine analytical chemistry, molecular biology, geospatial science and computation to provide solid evidence for environmental investigations. The choice

[7] A. Pivato, C. Gwinett, and G. Varghese, "Environmental Forensics," Detritus, vol. 12, 2020, doi: https://doi.org/10.31025/2611-4135/2020.14021.

[8] S. J. Cooke et al., "Environmental evidence in action: on the science and practice of evidence synthesis and evidence-based decision-making," Environ. Evid., vol. 12, no. 10, pp. 1–10, 2023, doi: https://doi.org/10.1186/s13750-023-00302-5.

[9] S. Bruzzese et al., "Examining the adoption of PEFC chain of custody certification in the Italian forest-based industry: An empirical study on motivations and impacts," For. Policy Econ., vol. 170, p. 103385, 2025, doi: https://doi.org/10.1016/j.forpol.2024.103385.

of technique will rely on the type of environmental sample, the nature of the contaminant and the purpose of the forensic examination.[10]

i. **Chemical fingerprinting:** Identifies the chemical makeup of pollution, e.g., petroleum hydrocarbons, industrial chemicals, and hazardous waste, that allows source identification and distinguishing between multiple pollution sources.
ii. **Stable isotope analysis:** Track the origin, route and environmental transformation processes of contaminants by measuring the natural variations in their isotopic ratios (e.g., carbon, nitrogen, sulfur, oxygen and lead isotopes).
iii. **DNA and environmental DNA (eDNA):** Identifies organisms in water, soil or sediments via genetic detection to identify species, monitor biodiversity, investigate wildlife crime and assess ecosystem disturbance.
iv. **Microbial forensics:** Compares the microbial community composition and genetic markers to assess pollution events, sewage pollution, bioremediation processes and environmental source attribution.
v. **Heavy metal and trace element analysis:** Measures toxic metals and elemental markers of industrial pollution and mining operations, and polluted soils with the world's most sensitive analytical tools.
vi. **Chromatographic techniques (GC-MS and LC-MS):** Separation, identification & quantification of complex organic contaminants such as pesticides, petroleum products, pharmaceuticals & persistent organic pollutants.
vii. **Inductively Coupled Plasma Mass Spectrometry (ICP-MS):** Determines trace metals and isotopic compositions with very high precision at very low concentrations.
viii. **Spectroscopic methods:** FTIR, Raman spectroscopy and X-ray fluorescence (XRF) are techniques that can rapidly and quickly characterize chemical compounds, minerals, polymers, and industrial residues with minimal sample preparation.
ix. **Remote sensing, GIS, drones, and satellite imagery:** Enables large-scale monitoring of illegal mining, deforestation, oil spills, land degradation and pollutant dispersion, as well as spatial analysis and crime scene documentation.
x. **Artificial intelligence and machine learning:** Analyse and understand large environmental datasets, identify abnormal pollution patterns, forecast pollution trends,

[10] D. Baragano, G. Ratie, C. Sierra, V. Chrastný, M. Komarek, and J. R. Gallego, "Multiple pollution sources unravelled by environmental forensics techniques and multivariate statistics," J. Hazard. Mater., vol. 424, 2022, doi: https://doi.org/10.1016/j.jhazmat.2021.127413.

automate interpretation of images, enhance environmental monitoring and decision-making.

Table 4: Performance metrics and forensic applicability of analytical techniques for emerging contaminants[11].

Method	Scope of Application	Forensic Role	Key Limitations
GC–MS	Volatile & semi-volatile organics (pesticides, hydrocarbons)	Confirmatory identification; chemical Fingerprinting	Extensive sample prep; cost; limited non-volatile coverage
LC–MS/MS	Polar & non-volatile ECs (pharmaceuticals, PFAS)	Gold-standard trace detection; legal defensibility	Matrix effects; ion suppression
FTIR	Microplastic polymer Identification	Rapid screening; material Classification	Low sensitivity; poor nanoplastic detection
Remote Sensing & GIS	Hotspot detection; transport pathway analysis	Contextual & spatial forensic support	No chemical specificity
ICP–MS/sp-ICP– MS	Metals, elemental tracers, tagged MPs/NPs	Elemental fingerprinting; particle sizing	No molecular structure information

4 Applications of Environmental Forensics in Ecological Crime Investigation

Environmental forensics has emerged as an invaluable aid to ecological crime investigation, and offers scientific evidence for the identification of pollution sources and the reconstruction of environmental incidents, and linkage of illegal activity with environmental damage. Environmental forensic investigations, which combine chemical, biological, molecular, and

[11] G. N. Prabhadevi, M. S. A. Samad, A. Jayadev, D. I. Nair, G. M. Thomas, and G. Prasad, "Unveiling Hidden Pollutants: An Environmental Forensics Approach to Water Contamination," Forensic Sci., vol. 6, no. 12, pp. 1–17, 2026, doi: https://doi.org/10.3390/forensicsci6010012.

geospatial analyses, assist law enforcement, regulatory and judicial agencies in identifying offenders, determining environmental effects, and improving environmental accountability.

i. **Illegal hazardous waste dumping:** Chemical fingerprinting and trace element analyses can help investigators determine the origin and composition of hazardous wastes as well as their disposal history, helping to determine which industry or individual disposed of what.
ii. **Oil spill source identification:** Identification of the source of spilled petroleum from a number of potential sources and liability for damage to the environment is achieved using hydrocarbon fingerprinting, biomarker analysis and stable isotope techniques.
iii. **Water and groundwater contamination:** Chemical contaminants, nutrient, heavy metal and isotopic signature analyses determine the sources of pollution, migration pathways and affected water resources.
iv. **Air pollution investigations:** To identify emission sources, measure pollutant concentrations and assess conformity to environmental regulation, atmospheric sampling and chemical characterization are used.
v. **Illegal mining and industrial pollution:** Unauthorized mining, industrial discharges, and contamination of surrounding ecosystems are detected by heavy metal profiling and mineralogical analysis, and by remote sensing.
vi. **Wildlife trafficking and poaching:** DNA profiling, environmental DNA (eDNA) and isotope analysis aid in species identification, geographic origin identification and illegal wildlife product traceability.
vii. **Illegal logging:** The natural authentication of timber species and geographic provenance is possible using genetic markers, wood anatomy, dendrochronology and stable isotope analysis to identify illegally harvested wood.
viii. **Soil contamination:** The geochemical characterization, pollutant fingerprinting and microbial analyses assess contamination from industrial waste, petroleum spills, pesticides and mining operations.
ix. **Marine pollution:** Environmental forensics employs water, sediment and biological sample analyses to investigate oil spills and chemical discharges, as well as ballast water contamination and heavy metal accumulation.
x. **Plastic pollution investigations:** Polymer characterization, additive analysis, and microplastic identification techniques can trace the source, transport, and environmental fate of plastic debris, aiding in pollution source attribution and environmental management.

5 Legal, Regulatory, and Scientific Challenges in Environmental Forensics

While scientific progress is essential for the success of environmental forensics in the field of ecological crime, it is also equally important that the legal structure and regulations be robust and that multidisciplinary collaboration be present. Environmental investigations in India are becoming more complex due to rapid industrialization, urbanization, unregulated extraction of natural resources and transboundary environmental problems. Despite its recognition, environmental forensic science is confronted by a number of legal, regulatory and scientific issues such as collecting, interpreting and adducing environmental evidence in judicial proceedings.[12]

A. Legal Challenges

Environmental forensic evidence is admissible in Indian courts if it satisfies the scientific validity, documentation, and continuity of the chain of custody as per the Indian Evidence Act, 1872 (as amended by the Bharatiya Sakshya Adhiniyam, 2023) and criminal law procedures. Environmental evidence needs to be gathered in a standardized way and backed up by accredited laboratory analyses to be able to withstand judicial scrutiny. India has also ratified various international environmental treaties, such as the Basel Convention, Convention on Biological Diversity (CBD), Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) and the Ramsar Convention, to further cooperation efforts for combating the illegal movement of waste, wildlife crime and ecosystem conservation.[13]

B. Regulatory Challenges

India has already come up with a comprehensive environmental regulatory regime through Environment (Protection) Act, 1986, Water (Prevention and Control of Pollution) Act, 1974, Air (Prevention and Control of Pollution) Act, 1981, Wild Life (Protection) Act, 1972 and Biological Diversity Act, 2002. The Central and State Pollution Control Boards and Forest Departments and other regulatory bodies are primarily responsible for enforcement. However, given resource constraints, limited monitoring efforts, and jurisdictional issues, illegal harvesting, dumping of

[12] S. Sundar, “Challenges in Implementing Environmental Laws and Policies in India,” Curr. World Environ., vol. 18, no. 3, 2023, doi: https://dx.doi.org/10.12944/CWE.18.3.27.

[13] K. Roy, S. Fatima, S. R. Chaudhary, S. Sonal, A. Mishra, and S. Chanda, “Forensic Environmental Science and Legal Admissibility: Bridging the Gap Between Data and Justice,” Int. J. Environ. Sci., vol. 11, no. 12, pp. 546–563, 2025.

hazardous waste, industrial pollution and trans-border poaching of wildlife and hazardous materials are still serious concerns.

C. **Scientific Challenges**

Environmental conditions can be heterogeneous, evidence can be lost or degraded, and variations in seasonal conditions can make it challenging to differentiate natural contamination from anthropogenic ones. Climate change adds to the forensics challenge and further complicates hydrodynamic changes, sediment transport and pollutant distribution. Science is credible only if it takes into account ethical issues like transparency, impartiality, environmental care and responsible interpretation of data. Steps towards addressing these challenges involve close interdisciplinary collaboration between forensic scientists, environmental scientists, ecologists, chemists, geologists, regulatory authorities and the police to make sure that the investigations are scientifically sound and a meaningful environmental justice in India is realized.[14]

6 Emerging Trends, Future Perspectives

The field of environmental forensics is an emerging discipline that is merging with digital technologies, sophisticated analytical techniques, and data analysis, all of which are improving the detection, investigation, and prevention of environmental offenses. India's rising industrialization, urbanization, changing environmental conditions due to climate change and the rising awareness of biodiversity loss have fast tracked the demand for innovative forensic methodologies. New technology is helping investigators to track changing environmental conditions in real-time, enhance evidence gathering and create scientifically sound information to assist regulatory enforcement and judicial deliberation. The developments are likely to enhance India's ability to deal with sophisticated environmental crimes and sustainable use of the natural resources.[15]

The use of automated sensor networks for real-time environmental monitoring is revolutionizing the way that environmental surveillance is conducted by continuously monitoring air quality, water quality, meteorological conditions, and industrial emissions. Combined with the Internet of Things (IoT), these sensors can be used to monitor the environment remotely, detect pollution

[14] R. C. Guevara, V. M. V. Sir, J. A. Reategui, A. C. Revilla, and D. B. B. Timaná, “Challenges and Improvements in the Environmental Prosecution of Environmental Crimes in the Specialized Prosecutor’s Office of Chachapoyas,” J. Educ. Soc. Res., vol. 15, no. 3, pp. 261–276, 2025, doi: https://doi.org/10.36941/jesr-2025-0058.

[15] G. K. Sharma and D. A. R. Rawat, “EMERGING TRENDS AND DEVELOPMENTS IN FORENSIC SCIENCES: A CONTEMPORARY ANALYSIS,” CINEFORUM, vol. 64, no. 3, pp. 276–292, 2024.

incidents early, and transmit environmental information to regulatory authorities quickly. These systems are increasingly being used to monitor rivers, industrial areas, and urban areas in India, to enhance environmental compliance and emergency response.[16]

In recent years, a number of portable analytical tools, such as handheld X-ray fluorescence (XRF) analyzers, portable Raman and Fouriertransform infrared (FTIR) spectrometers and field DNA analysis devices, have become available to investigators for rapid on-site screening of environmental material. These technologies minimise lab delays and assist in timely decision making in environmental crime investigations.[17]

Artificial Intelligence (AI), machine learning, and big data analytics are becoming effective tools for the environmental forensics field. AI can analyze vast amounts of environmental, geospatial, and satellite data to detect irregular pollution levels, map illegal mining and deforestation practices, forecast contaminant spread, and aid in predictive environmental crime analysis. Likewise climate forensics is becoming more relevant in the identification of anthropogenic environmental damage from climate-induced environmental damage, by combining meteorological, hydrological and geochemical evidence.

The standardization of forensic sampling protocols, laboratory analytical procedures, quality assurance frameworks, and data interpretation is expected to drive the advancement of environmental forensics in India in the future. Accreditation of environmental forensic laboratories, fostering interdisciplinary research, combining remote sensing with molecular forensic, and improving cooperation between scientific institutions, regulatory agencies and the legal system will increase the reliability of environmental evidence. Ongoing investment in cutting-edge technologies and trained human resources will continue to help position environmental forensics as a key and important scientific tool in the protection of ecosystems, environmental justice, and to meet new ecological challenges.

7 Conclusion

Environmental forensics has revolutionized the science of ecological crime. It is the science that supplies scientifically sound techniques for pollution source identification, environmental crime

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[16] D. A. Ashok, S. K. Dattaram, A. R. M. R, and M. N. Vishe, "Environmental Crimes in India: A Comprehensive Review," Int. J. LATEST Technol. Eng. Manag. Appl. Sci., vol. XIV, no. Viii, pp. 924–928, 2025, doi: https://doi.org/10.51583/IJLTEMAS.2025.1408000119.

[17] G. N. Prabhadevi, M. S. A. Samad, A. Jayadev, D. I. Nair, G. M. Thomas, and G. Prasad, "Unveiling Hidden Pollutants: An Environmental Forensics Approach to Water Contamination," Forensic Sci., vol. 6, no. 12, pp. 1–17, 2026, doi: https://doi.org/10.3390/forensicsci6010012.

reconstruction and linkage of illegal activities to environmental damage. Through the fusion of environmental science and forensic investigation, the discipline provides objective tools and matrices from the environment, such as soil, water, air, sediments, vegetation, and biological materials, as sources and recorders of evidence. Rapid progress in chemical, molecular, isotopic, spectroscopic and geospatial technologies has greatly improved the precision and acceptability of environmental evidence in courts of law. In India, environmental forensics is increasingly playing a significant role in the resolution of issues related to environmental pollution caused by industries, illegal mining activities, wildlife crime, hazardous waste disposal and other recent environmental issues. But, enhancing its lab infrastructure, harmonizing forensic protocols, coordinating between the regulatory agencies and encouraging interdisciplinary collaboration are key to ensure maximum utilization. The use of emerging technologies, such as artificial intelligence, Internet of Things (IoT) based monitoring systems, portable analytical tools, and climate forensics, is also anticipated to provide further enhancements to environmental monitoring and crime detection. Ongoing investment in research, capacity building and scientific innovation will improve governance of the environment, facilitate evidence-informed decision making and lead to more sustainable protection of ecosystems, biodiversity and public health in the long-term. In the end, environmental forensics is a testament to the idea that nature itself can stand as a witness and help to ensure accountability and environmental justice and sustainable resource management.

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[3] S. Bakhtiar, B. Waluyo, B. Harefa, A. L. Ibrahim, S. T. Wahyudi, and R. D. Agustanti, Utilisation of Forensic Evidence in the Disclosure of Environmental Damage. Atlantis Press SARL, 2025. doi: https://doi.org/10.2991/978-2-38476-356-6_22.

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