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SCIENTIFIC EVIDENCE IN ENVIRONMENTAL LAW: FORENSIC INNOVATIONS AND LEGAL IMPLICATIONS

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Abstract: *An emerging area of the criminal justice system is environmental forensics, which is used to gather evidence and address crimes involving the environment. Since pollution cases are rising more quickly in India due to the country's fast industrialization, environmental forensics is becoming essential for identifying the cause of pollution and other environmental crimes as well as for mitigating them. The study will discuss significant nations' usage of environmental forensics methods and how India can apply them to address its rising pollution levels. The potential application of emerging environmental forensics techniques in India to gather evidence and address pollution will be examined along with recommendations for a path to strengthen the current laws in India.*

Keywords: *Environmental Protection Agency (EPA), Gas chromatography- mass spectrometry (GC-MS), Geographic Information Systems (GIS), Chemical fingerprinting(CF), CODIS (Combined DNA Index System), volatile organic compounds (VOCs)*

INTRODUCTION

India's fast urbanisation and industrialisation have led to a rise in environmental crimes including groundwater poisoning, unlawful garbage disposal, and air pollution. Despite India's numerous environmental laws, such as the "Environment Protection Act (1986)", "Biomedical Waste Management Rules (2016)", "The Air (Prevention and Control of Pollution) Act (1981)", and "The Water (Prevention and Control of Pollution) Act (1974)" the India's environmental crime rate is continuously rising. There are many reasons contributing to such increase in environment crimes like absence of infrastructure, resources, and coordination between the judiciary and the regulator. Thus, such loopholes prevent such violations from being effectively addressed. Therefore, the advanced forensic technologies are required because standard surveillance techniques have not been able to determine the origin and severity of these acts. In this regard, environmental forensics can play a crucial role in locating the pollution source and locating the contaminants through the integration of numerous scientific, technological, and legal domains. Environmental forensics is a scientific method that combines geology, hydrogeology, chemistry, biology and forensic science to identify the source, age, or pathway of environmental toxins. The developed countries like United States and the European Union have also developed advanced forensic techniques that allow them to develop exhaustive data globally with robust legal and technological backing. Therefore, the capacity building, international cooperation, and advanced forensic technologies are crucial for effective application of environmental forensics in India. India must develop a strong framework with advanced forensic techniques for dealing with environmental crimes by adopting the best international practices, which will increase accountability and promote the sustainable development.

EMERGING TECHNOLOGIES OF ENVIRONMENTAL FORENSICS

In an era when environmental pollution and environmental crimes are increasing, the environmental forensics is an emerging area of science and technology to identify the sources and origins of environmental contamination. Numerous methods and technology in this area are opening up new possibilities for the effective detection, tracking, and prosecution of environmental infractions. These technologies include Environmental DNA (eDNA) analysis, Microbial Forensics, Artificial Intelligence (AI), High-Resolution Mass Spectrometry (HRMS), and other new methods of bio toxin detection. These techniques are classified as follows:

A. Chemical Techniques

That includes chemical fingerprinting which includes the analysis of polychlorinated

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biphenyls (PCBs), dioxin congener, petroleum hydrocarbons, and stable isotopes. Inductively coupled plasma-mass spectrometry (ICP-MS), gas chromatography, and X-ray fluorescence (XRF) are also the examples of analytical methods. Compound-specific isotope analysis (CSIA), dendrochronology, and sediment core analysis are further environmental tracking methods. Studies of biodegradation and bio indicators are biological and eco-toxicological techniques. Air dispersion modelling, groundwater modelling, remote sensing, and GIS are other geographical and modelling techniques. High Resolution Mass Spectrometry (HRMS) is an advanced analytical technic measuring environmental contaminants at trace levels with a high accuracy and sensitive.[1] The method was developed to identify and quantify pollutants using their mass-charge ratio, accurate to complex mixtures typically found in polluted environment. Particularly about the hazardous chemicals, industrial effluents, pesticides, and medications that are likely to be released into soil and water bodies, HRMS offers a great deal of potential to address environmental pollution in India. For example, public health issues are being increasing day by day with Yamuna and Ganga rivers' contamination by industrial chemicals, pesticides, and pharmaceuticals. India might better monitor and enforce water quality requirements by using HRMS to determine the precise types and quantities of pollutants present in these bodies of water.[2]

B. Biological Techniques

An emerging technique called DNA analysis can identify genetic material released by environmental organisms with less work, expense, and risk to professionals.[3] With this technology, scientists can detect the presence of species in an ecosystem without direct observation or collection of organisms, mainly used for biodiversity monitoring and precisely to detect rare, endangered, and even invasive species and follow up on the pollution effects on ecosystems. eDNA analysis could prove a very effective tool for monitoring water bodies in India, including application for detecting pollutants or assessing aquatic ecosystem health.[4] For example, eDNA can be used to assess the biodiversity of sensitive places subject to oil spills, industrial pollution, and agricultural runoff, such as the coral reefs in the Andaman and Nicobar Islands or the mangrove forest in the Sundarbans. The eDNA may be able to identify the genetic material of species that are potentially impacted by pollution, which would allow for the identification of the source of the pollution and the potential ecological effects. On the other hand, eDNA could also be applied to wildlife conservation wherein the presence of an endangered species, such as the Ganga River dolphin, the Indian rhinoceros, could be tracked. In addition, it could also be used to detect the presence of invasive species such as in water bodies, a growing problem in India attributed to climate change and the movement of goods through waterways. Also, the technology can help to understand how pollution like oil or chemical runoff affects marine life and which species are affected by contaminants. Similarly, the Microbial forensics is the study of microbial community found in the contaminated environment to trace the source of pollution.[5] Commonly, microorganisms like bacteria, fungi, and viruses can be very specific to environments and the presence can indicate the source of contamination. Forensic experts are, therefore, able to trace pollution back to its source by analysing the microbial populations in water, soil or air when there is little chemical or physical evidence.[6] Tracking pollution from water bodies, industrial effluents, and agricultural runoff can easily be detected by microbial forensics. For instance, if severely contaminated Indian rivers like the Yamuna are sampled, microbiological forensics can assist in

[1] B Cook, "High-Resolution Mass Spectrometry: Instruments and Technology" *Lab Manager Magazine* (February 2, 2024) <https://www.labmanager.com/high-resolution-mass-spectrometry-instruments-and-technology-31733> accessed February 13, 2025

[2] Hernandez F, "Current Use of High-Resolution Mass Spectrometry in the Environmental Sciences" (2012) 403 Anal Bioanal Chem.

[3] Zeshan Umar Shah and Saltanat Parveen, "Pesticides Pollution and Risk Assessment of River Ganga: A Review" (2021) 7 Heliyon <https://doi.org/10.1016/j.heliyon.2021.e07726> accessed 13 February 2025

[4] Philip Francis Thomsen and Eske Willerslev, "Environmental DNA – An Emerging Tool in Conservation for Monitoring Past and Present Biodiversity" (2015) 183 Biological Conservation

[5] Sangwan P and others, "Molecular Approaches in Soil Microbial Analysis: Forensic Perspective – Biosciences Biotechnology Research Asia" 20 Biosciences Biotechnology Research Asia 367

[6] A. Gouello and others, "Analysis of Microbial Communities: An Emerging Tool in Forensic Sciences" (2021) 12 Diagnostics <https://pmc.ncbi.nlm.nih.gov/articles/PMC8774847/> accessed 11 February 2025

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identifying the sources of pollution from untreated sewage or agricultural runoff. It is possible to identify the locations of specific bacteria found in sewage, such as industrial discharge points or municipal garbage. Furthermore, in industrial areas such as Gujarat's Vapi, microbiological forensics may be able to detect the precise type of organic or chemical waste that is being dumped into waterways. Additionally, oil spills are crucial to the examination of microbiological forensics. By using microorganisms that may be engaged in oil degradation, hints regarding the cause and duration of a spill might be found.

C. Geospatical and Remote Sensing Techniques

GIS and remote sensing are Geospatial technologies which are essential in conducting the environmental forensics. Pollution source mapping is used to identify the reasons of spread of pollution overtime by using GIS while remote sensing encompasses the use of satellite imagery to observe environmental changes.[7] Particularly effective for large scale environmental change tracking, deforestation, land degradation, illegal mining, etc. However, the remote sensing and GIS could be used to monitor large areas of land, forest or water bodies for pollutant or illegal activities.[8] For instance, the Sunderbans, Kaziranga or the Western Ghats are areas, where deforestation and illegal logging is common, the data from remote sensing can be used to monitor land-use changes and deforestation in near real-time. For mapping pollution sources like effluent discharges and their movement over time the GIS could be used in better environmental regulation enforcement. Furthermore, remote sensing data could be introduced in environmental monitoring networks in India to monitor pollutants in the environment. For instance, India's National Remote Sensing Centre (NRSC) can use satellite images to monitor the air quality, water quality, and greenhouse gas emissions on the national level to offer important data for forensic investigations.[9] India may need to use historical maps, aerial photography, and industrial and regulatory data[10] to identify pollution, enhance wildlife conservation, and manage natural resources responsibly to address the growing environmental problems the nation confronts.

D. Physical techniques

These techniques entail tracing contaminants by analysing the physical characteristics of materials, soils, sediments, and geological formations. For example, soil and sediment analysis uses physical and chemical characteristics to identify pollutants such as petroleum, herbicides, and heavy metals in soils and sediments. Analysing minerals and their compositions are another way that mineralogical study helps us understand the origins and patterns of environmental contaminants.[11]

GLOBAL PERSPECTIVES ON TACKLING THE POLLUTION CRIME THROUGH ENVIRONMENTAL FORENSICS: LEGAL AND TECHNOLOGICAL

Environmental forensics, being a recent development in the area of science and research, countries across the world are developing and introducing new techniques to tackle pollution related crimes.

A. United States

The United States is generally considered a global leader in the field of environmental forensic science. For several decades agencies like the EPA, with the help of the Department of Justice, have been using sophisticated chemical and physical analysis techniques to identify, trace and bring to justice environmental criminals. Pollution source fingerprinting capabilities through the application of gas chromatography-mass spectrometry (GCMS), stable isotope ratio analysis and hydrocarbon fingerprinting. Furthermore, the US routinely performs multidisciplinary forensic investigations in complex environmental litigation, integrating ecologic, legal, and toxicologic expertise. United

[7] S Schmedes and B Budowle , 'Microbial Forensics' [2019] Encyclopedia of Microbiology

[8] Life GF, "Remote Sensing and Geographic Information Systems (GIS)" (*GIS For Life*, January 5, 2023) <https://gisforlife.com/remote-sensing-and-geographic-information-systems-gis/> accessed February 11, 2025

[9] 'NRSC' (*NRSC website*) <https://www.nrsc.gov.in/> accessed February 11, 2025

[10] Toranzos GA, Cano RJ., "Definitions and Historical Perspectives in Environmental Forensics" (2018) 6(2) Microbiol Spectr <https://doi.org/10.1128/microbiolspec.emf-0016-2018> accessed 12 February 2025

[11] Pavel LV and Gavrilescu M, "Overview of ex situ Decontamination techniques for soil cleanup" (2008) 7 Environmental Engineering and Management Journal 815

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States, the Environmental Protection Agency (EPA) uses chemical fingerprinting in forensics. Chemical fingerprinting analyses the chemical makeup of environmental contaminants, including their source, kind, molecular batch, and pathway, to identify and track their origins. The idea behind it is that every substance, including oil, pesticides, heavy metals, and industrial chemicals, has distinct "fingerprints"—that is, chemical signatures—based on their molecular structure, isotopic composition, chemical additives, and other distinctive characteristics. These fingerprints can be used to track down the source, type, and occasionally even the duration of pollution.[12] Along with it, geographic mapping technique is also used. Geographic mapping is employed to examine and assess the spatial distribution of pollutants or sources of pollution within a certain region. The USA has been integrating its advanced environmental forensics techniques within the legal and regulatory frameworks.[13] The EPA uses the latest in forensic methods to pursue and address environmental crimes, especially through the Superfund program. Under the EPA the Superfund Program serves as a fundamental American initiative to address hazardous waste sites that no longer have responsible parties for management.[14] The "Comprehensive Environmental Response Compensation Liability Act (CERCLA)" operates under the name Superfund Program as an agency started through official legislation in 1980.[15]

The infamous Love Canal case (1978) in the United States was a hazardous chemical leak that affected the health of homeowners and schoolchildren due to a chemical waste site beneath residences and educational institutions.[16] The GC-MS equipment detects organic chemicals within chemical mixtures and calculates their exact concentrations.[17] The widespread applications of this method include identifying pesticides and VOCs as well as hydrocarbons. Researchers employed GC-MS to determine benzene and dioxins concentrations in earth and water substances. The United States Superfund program was created as a foundation for cleaning hazardous sites because of the evacuation of the area.[18] This program serves to cleanse sites burdened with toxic contamination from heavy metals together with industrial chemicals and hazardous waste products. The Superfund Program works to find and establish priority lists for hazardous waste sites needing remediation work.[19] Similarly, the National Priorities List contains these hazardous sites based on the extent of contamination together with risks to both human health and environmental safety. Environmental forensics along with site assessments enable the identification of contamination scope. An important aspect of US environmental law enforcement is the National Enforcement Investigations Centre (NEIC) comprised of scientists that apply environmental forensics to detect environmental violations.[20]

B. United Kingdom

Environmental forensics in the UK is framed within a strong environmental regulatory system. Forensic evidence is also used by

[12] Saba T and Ph.D., "Using Environmental Forensics to Determine Liability for Environmental Contamination" (*Exponent*, September 9, 2022) <https://www.exponent.com/article/using-environmental-forensics-determine-liability-environmental-contamination> accessed April 8, 2025

[13] "The Role of Advanced Environmental Forensics in Addressing Emerging Contaminants" (Antea Group) <https://us.anteagroup.com/news-events/blog/the-role-of-advanced-environmental-forensics-in-addressing-emerging-contaminants> accessed February 13, 2025

[14] 'Collection of Methods' (*US EPA*, April 8, 2014) <https://www.epa.gov/measurements-modeling/collection-methods> accessed February 11, 2025

[15] "Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and Federal Facilities" (*US EPA*, August 20, 2013) <https://www.epa.gov/enforcement/comprehensive-environmental-response-compensation-and-liability-act-cercla-and-federal> accessed February 13, 2025

[16] USA EPA, 'The Love Canal Tragedy' (*US EPA*) <https://www.epa.gov/archive/epa/aboutepa/love-canal-tragedy.html> accessed February 13, 2025

[17] Jyoti Bashyal, "Gas Chromatography-Mass Spectrometry (GC-MS)" (*Sagar Aryal*, February 12, 2023) <https://scienceinfo.com/gas-chromatography-mass-spectrometry-gc-ms/> accessed February 13, 2025

[18] The Editors of Encyclopaedia Britannica, "Love Canal | Environmental Disaster, Toxic Waste & Health Effects | Britannica" (*Encyclopaedia Britannica*, 20 July 1998) <www.britannica.com/place/Love-Canal> accessed 9 February 2025.

[19] 'Superfund: CERCLA Overview' (*US EPA*, September 9, 2015) <https://www.epa.gov/superfund/superfund-cercla-overview> accessed February 11, 2025

[20] 'National Enforcement Investigations Center (NEIC)' (*US EPA*, May 3, 2013) <https://www.epa.gov/enforcement/national-enforcement-investigations-center-neic> accessed February 11, 2025

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agencies such as the Environment Agency (EA) when prosecuting illegal waste dumping, water contamination and breaches of air quality legislation. Isotopic fingerprinting, elemental analysis, or DNA-based tracking of microbial communities have been used to ascribe blame for pollution events. Environmental forensics underpins enforcement under the Environmental Protection Act 1990 and several EU-derived regulations that continue to carry weight in post-Brexit Britain. The Environmental Protection Act (1990)[21] and the Environment Act (2021)[22] add further impetus to UK legislation, through which a legal framework is created in which environmental forensics is integrated. Britain has different specialized forensic units that use isotope analysis, remote sensing, and chemical fingerprinting to find traces of pollutants and assign liability for environmental crimes.[23] In UK law, the use of forensic science in relation to pollution in criminal investigations is explicitly outlined allowing such evidence to be collected and presented in court. Environmental forensics are also used by the Environment Agency to investigate contamination caused by landfills, illegal dumping of waste and industrial activities.[24]

C. European Union

Drawing on its action against pollution crime, the European Union (EU) has emerged as a front runner in this field with the incorporation of environmental forensic which includes the collection and application of analysis to identify, trace, and assign sources of environmental contamination. Instead, this method supports law enforcement and judicial systems by providing them with reliable evidence to prosecute environmental offenders. Changes to this directive in recent time worked to further bolster enforcement by broadening the range of offenses and harsher penalties. In addition, environmental forensics can substantiate cross-border investigations that are crucial in a region characterized by shared ecosystems and transboundary pollution challenges. The EU is a global leader in environmental crime and shows how to effectively combat environmental crime with a combination of science and policy. The Forensic science is included in EU environmental liability frameworks, which differ from other legal systems. The EU's Environmental Liability Directive (2004/35/EC) requires to hold business liable for environmental damage and implementing forensic techniques for the tracing of environmental sources of pollution.[25] This extensive use of remote sensing and GIS technologies for monitoring air and water quality, for observation of industrial emissions, and for assessing environmental damage is made by the EU. In fact, satellite-based monitoring can be used to monitor illegal deforestation and degradation of land in real time to intervene. Forensic damage assessment and stable isotope analysis by EU's regulatory agencies[26] also help establishing the exact sources of pollution and the amount of environmental degradation.

D. Australia

Environmental forensics have been successfully used in Australia to fight pollution from oil spills, mining, agriculture, and industrial activities. The country's federal and state environmental protection agencies pick up the tab, with forensic labs already in use, like the New South Wales Environment Protection Authority (NSW EPA), to analyse chemical pollutants and trace their origins.[27] Commonly applied in this field are fingerprinting techniques like trace metal analysis and sediment fingerprinting, as well as isotope ratio analysis. It promotes capacity building and inter-agency collaboration to ensure forensic evidence enables regulatory action and support in court. Australia has been forward-looking in including environmental forensics in its regulatory approach.[28] Chemical fingerprinting, toxicology, and satellite imagery are taken as tools under the Environmental Protection Act

[21] Environmental Protection Act 1990
[22] Environment Act 2021
[23] 'Future of Forensic Science in the United Kingdom', *Advances in Forensic Human Identification* (CRC Press 2014) <https://doi.org/10.1201/b16509-24> accessed February 13, 2025
[24] Liu Y, Kong F and Santibanez Gonzalez EDR, "Dumping, Waste Management and Ecological Security: Evidence from England" (2017) 167 Journal of Cleaner Production 1425
[25] Directive 2004/35/EC of the European Parliament and of the Council of 21 April 2004 on environmental liability with regard to the prevention and remedying of environmental damage [2004] OJ L143/56.
[26] Meier-Augenstein W, *Stable Isotope Forensics: Methods and Forensic Applications of Stable Isotope Analysis* (John Wiley & Sons 2017)
[27] "The Environmental Detectives Solving Ecological Crimes" (*Western Sydney University*, November 26, 2024) <https://www.westernsydney.edu.au/future-makers/issue-eight/the-environmental-detectives-solving-ecological-crimes?utm_source=chatgpt.com> accessed April 8, 2025
[28] *Ibid*

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(1994)[29] and other regulations at state level to track pollutants resulting from industrial sources as well as hazardous waste. Australia has also developed significant advances in satellite remote sensing for monitoring deforestation, water quality, changing land use, for example in the Great Barrier Reef area.[30] Additionally, the "National Pollutant Inventory (NPI)" requires emissions reporting in detail and the use of forensic techniques is in place to ensure that the appropriate laws are adhered to.[31]

E. Japan

Japan has adopted environmental forensics within this highly organization and scientific approach to the problem of pollution control. Together with research institutions under the Ministry of the Environment, it investigates soil and groundwater contamination, marine debris, and air quality violations in the industrial pollution. Tools like dioxin fingerprinting, DNA barcoding for illegal waste tracking and rocket chromatography are popular Big Bang forensics tools. Japan's forensic work has been especially evident in dealing with contamination from past industrial activities like mercury and PCB pollution. Its principle of using scientific knowledge in developing environmental policies provides a template for how to reconcile economic advancement and ecological health.

Japan has a very sophisticated approach when it comes to environmental forensics and this is partially achieved by laws including various pollution control laws, which directs the use of these advanced methods of forensics.[32] Microbial forensics is used by Japan to determine the source of pollutants in soil and water, especially in the case of industrial pollution. The country has harnessed the use of chemical fingerprinting and gas chromatography for environmental investigations, hence consequently is among one of the best in pollution sources' identification.[33] Moreover, Japan's Environmental Impact Assessment (EIA) framework demands the use of environmental forensics of industrial projects in large scale [34]. India has not accepted microbial forensics or shifted to sophisticated technologies for investigations such as gas chromatography in its environmental laws. Tracking the nation's pollution sources has also proven difficult because there is no required methodology for Environmental Impact Assessment that incorporates forensic examination.

F. Sweden

Sweden is a global leader in sustainability and environmental policy, and practices environmental forensics within a robust regulatory and scientific framework. The Swedish Environmental Protection Agency cooperates with forensic laboratories and academic institutions to identify pollution sources, especially in lakes, forests, and facilities — and actively seeks to understand the causes of pollution. This detection includes using methods like compound-specific isotope analysis and pollutant degradation profiling to trace them back and track sources of contamination, according to Sweden. Sweden uses environmental forensics for long-term ecological assessments, in Arctic and sub-Arctic areas impacted by transboundary pollution. Sweden's use of scientific data in its regulatory processes exemplifies evidence-based environmental management. Sweden is on the forefront of using life cycle assessments (LCA) in forensic investigations to monitor the amount of pollution from industry.[35] Assessment of the environmental impact of business operations is regulated in the Swedish Environmental Code and forensic tools are used for control of pollution sources and compliance.[36] The industrial emissions are traced in Sweden by chemical fingerprinting,

[29] Environmental Protection Act 1994 (Qld)

[30] 'Putting Satellite Data into Decisions' (*Geoscience Australia*, June 18, 2024) <https://www.ga.gov.au/scientific-topics/dea/about/putting-satellite-data-into-decisions> accessed February 13, 2025

[31] "About the NPI" (*DCCEEW*) <https://www.dcceew.gov.au/environment/protection/npi/about> accessed February 11, 2025

[32] Intelligence GL, "Understanding Environmental Regulations and Compliance Obligations in Japan" (*Generis Global Legal Services*, November 19, 2024) <https://generisonline.com/understanding-environmental-regulations-and-compliance-obligations-in-japan/> accessed February 13, 2025

[33] Sato M and others, "Monitoring Environmental Sustainability in Japan: An ESGAP Assessment" (2024) 19 Sustainability Science 539

[34] *Ibid*

[35] 'Advancing Life Cycle Assessment to Foster Sustainable Innovation' *Chalmers University of Technology* (October 14, 2024) <https://www.chalmers.se/en/current/news/slc-advancing-life-cycle-assessment-to-foster-sustainable-innovation/> accessed February 13, 2025

[36] Thollander P and others, "A Review of Industrial Energy and Climate Policies in Japan and Sweden with Emphasis towards SMEs" (2015) 50 Renewable and Sustainable Energy Reviews 504

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toxicological analysis to prosecute environmental crimes.[37]

G. Italy

Since 1980s Italy has increasingly used environmental forensics in its battle against pollution crime, particularly in those areas most affected by industrial contamination and illegal waste disposal carried out by criminal organizations such as the Camorra. Environmental forensics is the application of scientific techniques—chemical fingerprinting, isotope analysis, geospatial mapping, etc.—to tracing pollutants back to their sources, and thus making those sources accountable for legal consequences and remediation efforts. The Italian authorities, in some cases working with international organisations such as INTERPOL and Europol, have utilised these tools to investigate environmental crimes more effectively and prosecute polluters. Documented successes include the application of forensic geochemistry to trace toxic waste illegally dumped in the Campania region, leading to landmark court decisions and greater public awareness, among others.[38]

In the example of Seveso Dioxin Crisis, Italy (1976), a chemical factory explosion caused toxic pollution of air by releasing dioxins. The research team employed the method of air dispersion models to determine the distribution pattern of dioxins while identifying danger zones based on their dispersion. It led to the passing of the "European Seveso Directive" for tackling and preventing major accidents from hazardous substances in future.[39]

ENVIRONMENTAL FORENSICS IN INDIA

Environmental forensics is in nascent stages in India, still awareness and implementation to large extent is needed. The barriers like traditional infrastructures, regulatory backing, and know-how affect its implementation on a grand scale hinders in adoption of any new technology. In India the improper waste disposal, industrial operations, and agricultural practices are the main causes of pollution crimes. Determining the precise location of the pollution source is essential for both enforcing environmental regulations and holding criminals accountable for their actions. In India, technical, administrative and infrastructural limitations makes it difficult to ascertain the exact location of pollution. India faces technical glitches like disconnected environmental monitoring, lack of real-time data, and limited access to advanced forensic technologies. Most sectors, notably small and medium businesses, continue to run without adequate waste management systems and regularly release effluents clandestinely, preventing source tracking. Moreover, the overlap of jurisdictions among the regulatory authorities (CPCB, SPCBs, local authorities) results in poor coordination and poor compliance enforcement. While unregulated urban expansion, informal industrial clusters, and lack of investment in scientific research continue to undermine the capacity for source-specific inquiries. Consequently, rather than being held genuinely accountable, responses to pollution are usually ambiguous and more mitigating.[40]

There are definite advantages of using innovative environmental forensics in India that could base the responsible detection, tracing, and prosecution of pollution crimes on scientific precision. Using tools such as chemical fingerprinting, isotope analysis, and GIS-based spatial mapping, authorities can pinpoint the precise types of pollutants, discern between natural and anthropogenic contamination as well as collect evidence that will withstand legal scrutiny. These reforms would enhance regulatory enforcement, bolster environmental governance, and enhance accountability across industries and polluters. It would also enable better policy decisions and targeted remediation measures, particularly in critically polluted areas such as the Ganga basin or industrial belts. In summary, advanced environmental forensics could transform India from a reactive pollution control regime to a proactive and evidence-based environmental management regime.

[37] Anna Björklund, "Life Cycle Assessment as an Analytical Tool in Strategic Environmental Assessment. Lessons Learned from a Case Study on Municipal Energy Planning in Sweden" (2012) 32 Environmental Impact Assessment Review <https://doi.org/10.1016/j.eiar.2011.04.001> accessed 11 February 2025

[38] Cori L, "Risk Communication in Highly Polluted Sites in Italy: Three Case Studies" (2007) 18 Epidemiology S127

[39] Eskenazi B, "The Seveso Accident: A Look at 40 Years of Health Research and Beyond" (2018) 121 Environment international <https://doi.org/10.1016/j.envint.2018.08.051> accessed 11 February 2025

[40] Pujari PR and Deshpande V, "Source Apportionment Of Groundwater Pollution Around Landfill Site In Nagpur, India" (2005) 111 Environmental Monitoring and Assessment 43

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The technique of geographic mapping is employed to examine and assess the spatial distribution of pollutants or sources of pollution within a certain region. With use of spatial data and geographical information systems (GIS) environmental toxics are investigated, monitored, and analysed.[41] GIS helps visualize, analyse, and interpret spatial data that is aiding environmental forensics for pollution and different environmental crime. By combining data based on location with information regarding features that may impact the environment, the GIS helps investigators pinpoint sources of pollution, monitor the distribution of pollutants, and evaluate not only the flow of environmental pollutants but their evolution with time and consequence within the surroundings. GIS may be better applied to map illegal waste dumping, correlate industrial emissions with ambient air or water quality data, and simulate dispersal of pollutants over time, using topography, hydrology, and wind patterns as layers. This geospatial approach can assist authorities in prioritizing areas around pollution sources to investigate, enhance the ability to build strong legal cases, and improve overall decision-making related to remediation planning. GIS, when integrated with remote sensing and GPS data, and chemical analyses, can be a forensically powerful tool in combating environmental crime.[42] It helps to link a particular contaminant to pollution to identify the source.[43]

But India is still far from being able to use these methods in every instance of pollution this is because of India's large and varied topography, which includes many rural areas, crowded cities, and expansive agricultural zones. Developing a one-size-fits-all solution is challenging since pollution can vary greatly based on local factors. Advanced methods necessitate specialized equipment, trained staff, and laboratories. Many places lack these amenities, particularly rural or isolated ones. Several logistical, financial, legal, and technical obstacles prevent such methods from being widely used in all pollution cases in India. By extending the application of these cutting-edge techniques, India would be able to detect polluting organizations and enforce laws more effectively.

A. Leading environmental cases in India

1. Bhopal gas tragedy

Methyl isocyanate (MIC) gas escaped from the Union Carbide factory in the Bhopal Gas Tragedy case (1984), one of the greatest industrial disasters in history, resulting in hundreds of thousands of people being exposed to hazardous fumes and thousands of deaths. As forensic models, soil and water contamination analyses, as well as retrospective air dispersion modelling, were employed. Reconstructing the magnitude and impact of pollution was challenging due to the lack of pre-disaster data. Access to the material was additionally hampered by inadequate record-keeping and restricted availability of sophisticated forensic techniques at the time. High-resolution satellite imagery, historical monitoring data, and immediately deployed real-time air quality monitoring equipment could have helped manage the problem more rapidly.

2. Mumbai oil spill case

The Mumbai Oil Spill of 2011[44], caused by the collision of two ships off the Mumbai coastline necessitated a complex forensic investigation of the source, assessment of the environmental impact and identifying the responsible parties. Like other notorious incidents internationally, this spill also made use of numerous forensic methodologies. Oil fingerprinting is one of the most helpful forensic techniques that are used for investigating oil spills to find out where the spilled oil came from.[45] The Mumbai spill was fingerprinted, but for the forensic process there were great challenges. The chemical signature was made more complex by the release of the oil

[41] "2016 International Conference on Computational Science and Computational Intelligence (CSCI)" (IEEE 2016) <https://doi.org/10.1109/csci40581.2016> accessed April 8, 2025

[42] Moharir K and Pande C, "Introduction to Remote Sensing and GIS Application in Forest Conservation and Planning," *Advances in Geographical and Environmental Sciences* (Springer Nature Singapore 2025) <https://doi.org/10.1007/978-981-96-1733-3_1> accessed April 8, 2025

[43] Russell H. Plumb, "Fingerprint Analysis of Contaminant Data: A Forensic Tool for Evaluating Environmental Contamination" [2004] Environmental Protection Agency <https://www.epa.gov/remedytech/fingerprint-analysis-contaminant-data-forensic-tool-evaluating-environmental> accessed 13 February 2025.

[44] Reshma Jathar, 'Mumbai oil spill: threat to marine life, coast' (*Down To Earth*, 27 August 2010) <www.downtoearth.org.in/environment/mumbai-oil-spill-threat-to-marine-life-coast--1841> accessed 8 February 2025.

[45] Zhendi Wang, 'Analytical developments for oil spill fingerprinting' (2007) 7(2) Environmental Forensics <https://doi.org/10.1080/15275920600667104> accessed 9 February 2025

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in the spill, which consisted of crude oil plus other petroleum products. Combined with the weathering process of chemical change of oil, due to evaporation and microbial degradation of the chemical composition of the oil over time, the analysis became even more complicated. Moreover, samples from the responsible vessels and nearby refineries for laboratory comparisons were not readily available for identification. The usefulness of techniques like remote sensing was constrained by weather, since satellites were stationary, and had cloud cover with high winds that prevent seeing from them or from aircraft. Finally, chemical analysis focuses at the surface level of oil contamination and do not monitor deep areas around the oceans, where there could be significant damage[46].

These cases show the improper forensic technique used due to lack of fundings and poor infrastructure.

B. Best Forensic Technologies From Different Countries which India Can Adopt

Appropriate environmental techniques are required to be used for a better source location. Satellite imagery and geospatial mapping can be used to identify illicit activities that result from pollution offenses, including illicit mining or deforestation, and make sure the authorities promptly take the appropriate action.[47] The issue of inappropriate disposal of hazardous waste, such as chemical and e-waste, is becoming more prevalent in Indian cities. With the advent of new methods, such as chemical fingerprinting and microbiological forensics, hazardous waste disposal and the like may be traceable. Through the analysis of waste materials' chemical composition or microbial populations, forensic scientists can also establish a connection between pollutants and their sources, which can be a crucial component of an inquiry. Below mentioned are some of the foreign techniques which can be used in India:

1. Germany:

Countries like Germany has developed strong systems for managing hazardous waste and have forensic instruments in place to stop illicit disposal. Germany has highly stringent rules around the disposal of e-waste.[48] India can use these methods to pinpoint pollution sources and stop unnecessary hazardous waste disposal. Widespread harm to the environment is caused by illicit mining and careless pesticide use. To link pollutants associated with these activities to unlawful mining operations or unsustainable farming practices, geochemical analysis and stable isotope ratio analysis are employed.[49] This enables authorities to identify the source of pollution, target actions, and ensure that those responsible are held accountable. Germany also utilizes wood DNA analysis to verify timber that has been unlawfully taken.[50] This technique can be used to detect the species such as the Ganga River dolphin or Indian rhinoceros, which are present in Kaziranga National Park and the Sundarbans, which are protected areas[51].

2. Brazil:

Advanced forensic techniques are used in nations like Brazil can be used to combat illicit mining and logging which results in air pollution. Brazil uses geochemical isotope analysis to determine the origin of timber that has been illegally logged in the Amazon.[52]

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[46] Maharashtra Pollution Control Board, *Report on Oil Spill in Arabian Sea* (2010).

[47] David B Olawade, "Artificial intelligence in environmental monitoring: Advancements, challenges, and future directions" (2024) 12 Hygiene and Environmental Health Advances <https://doi.org/10.1016/j.heha.2024.100114> accessed 7 February 2025

[48] Taniya Banerjee, Ammu P Nair and Smitha M.S, "Hazardous waste management: lessons from developed countries" [2023] Waste Management and Resource Recycling in the Developing World <https://doi.org/10.1016/B978-0-323-90463-6.00001-4> accessed 7 February 2025

[49] Zeshan Arshad, Kyung-Hoon Shin and Jin Hur, "Utilization and applications of stable isotope analysis for wastewater treatment systems: A review" (2025) 264(1) Environmental Research <https://www.sciencedirect.com/science/article/abs/pii/S0013935124022540> accessed 10 February 2025

[50] 'Wildlife forensics - Leibniz Institute for Zoo and Wildlife Research' (Home - Leibniz Institute for Zoo and Wildlife Research) <www.izw-berlin.de/en/wildlife-forensics.html> accessed 11 February 2025.

[51] Ashish Sahu and others, "Environmental DNA (eDNA): Powerful technique for biodiversity conservation" (2023) 71 Journal for Nature Conservation <https://www.sciencedirect.com/science/article/abs/pii/S1617138122001984> accessed 6 February 2025

[52] Fernanda Wenzel, "Brazil researchers boost timber traceability with new chemical analysis" (*Mongabay Environmental News*, 4 November 2024) <https://news.mongabay.com/2024/11/brazil-researchers-boost-timber-traceability-with-new-chemical-analysis/> accessed 31 January 2025.

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3. Australia:

Similarly, Australia engages in illicit mining using the stable isotope technique.[53] India can also adopt the similar technologies to check the pollution crimes especially in Jharkhand, Chhattisgarh where the illegal mining is rampant.

4. United States:

Oil spills and marine pollution are two of India's biggest environmental issues, especially when it comes to its long coastline. Cities like Mumbai, for instance, are vulnerable to oil spills from pipelines, offshore platforms, and commercial ships. By using environmental forensics and chemical analysis of the pollutants, the source of marine pollution can be found. Norway and the US are two examples of nations that use forensic technologies to look into oil spills and marine contamination. Chemical fingerprints are used by the US "National Oceanic and Atmospheric Administration (NOAA)" to identify the source of an oil spill by connecting it to a specific ship or offshore rig.[54] It also helps with clean-up efforts and the punishment of those involved. If India used similar forensic methods, it might better respond to crimes involving marine pollution and hold those responsible for oil spills in the Bay of Bengal and Arabian Sea accountable.[55]

5. South Africa:

Many of the diverse species found in India are illegally hunted, poached, or destroyed. Poaching is one of the major reasons for chemical intoxication of rivers. The techniques of the environmental forensics are used to solve crimes involving wildlife, including monitoring endangered species, identifying poachers, and protecting species' habitats. One such technique is eDNA analysis, which enables researchers to identify genetic material from soil or water samples. To combat animal crimes, nations like South Africa have been able to make considerable use of forensic technologies. In South Africa, rhino poaching is frequently tracked down via DNA analysis, which makes it simple for law enforcement to link a pulled rhino to a specific person or gang.[56] Thus, India could adopt this technology to enhance efforts to safeguard animals in areas where habitat loss and poaching are common.

Therefore, the use of environmental forensics is particularly helpful for tracing the sources of pollution, identifying those sources, and prosecuting those who commit these crimes. India still lags many developed nations in the application of cutting-edge technologies for the investigation of pollution crimes, despite of some progress in the developed procedures of forensic tools like chemical analysis and pollution monitoring.

CHALLENGES ASSOCIATED WITH ENVIRONMENTAL FORENSICS IN INDIA

Environmental forensics' growth in India is hampered by several variables, including social structures, economic conditions, legal restrictions, technological limitations, political considerations, and operational difficulties. To address these issues, a thorough understanding of their scope and the use of data in conjunction with particular technical elements are required:

A. *Lack of Awareness:*

Most individuals within India's vast population live at risk from environmental threats even though few people take part in environmental crime solutions. The Lancet's 2020 report discovered 2.3 million people died annually from environmental degradation within India[57]. Environmental forensics awareness together with pollution control measures remain low throughout rural territories and across different

[53] Erik B Melchiorre, "Stable isotope and geochemical evidence for genesis of secondary copper deposits at Girilambone, New South Wales, Australia" (2022) 86(4) Mineralogical Magazine <https://www.cambridge.org/core/journals/mineralogical-magazine/article/stable-isotope-and-geochemical-evidence-for-genesis-of-secondary-copper-deposits-at-girilambone-new-south-wales-australia/> accessed 6 February 2025

[54] 'Fingerprinting Oil' (*response.restoration.noaa.gov*) <https://response.restoration.noaa.gov/oil-and-chemical-spills/oil-spills/resources/fingerprinting-oil.html> accessed February 13, 2025

[55] B Purohit and others, "Marine oil spill clean-up: A review on technologies with recent trends and challenges" (2024) 80 Regional Studies in Marine Science <https://www.sciencedirect.com/science/article/abs/pii/S2352485524005097> accessed 6 February 2025

[56] 'About the African Wildlife Forensics Network' (*African Wildlife Forensics Network*) <https://africanwildlifeforensics.org/en/about> accessed 7 February 2025.

[57] Watts N, 'The 2020 Report of The Lancet Countdown on Health and Climate Change: Responding to Converging Crises' (2021) 397 The Lancet

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population groups while environmental crime statistics continue to rise alarmingly. Poorer or vulnerable groups are frequently disproportionately impacted by environmental crimes, such as the unlawful disposal of industrial waste, deforestation, and water contamination. Due to their high cost, environmental forensics instruments may not be available in India's rural or underdeveloped areas. In general, these disenfranchised communities lack the political-economic clout, resources, and expertise necessary to solve such problems.

B. *Legal Challenges:*

The Environment (Protection) Act, 1986, the Water (Prevention and Control of Pollution) Act, 1974, the Air (Prevention and Control of Pollution) Act, 1981, and the Hazardous Waste Management Rules are among the key laws that guide the overarching framework of environmental protection. But none of these explicitly require forensic science to investigate environmental crimes or evaluate liability. As a result, there is insufficient legal clarity surrounding the admittance and standards of forensic evidence. Furthermore, enforcement authorities including Central and State Pollution Control Boards often do not have the technical infrastructure or trained manpower to carry out detailed forensic studies. Legal spearheads like the NGT and environmental courts have forward momentum, including through the need for scientific bases in environmental petitions, however forensic data's use remains erratic. Besides, lack of standardized procedures for collection, preservation and analysis of environmental samples reduces the weight of evidence presented in our courts. Moreover, criminal laws should have specific provisions on environmental crimes and the contribution of forensic evidence should be emphasised in investigation and trial of such crimes. A more proactive approach towards corporate accountability should be adopted whereby mandatory environmental audits for highly pollutant industries should be a mandate. Companies should be audited with forensic techniques to assure companies' compliance with their environmental standards as well as identification of potential violations prior to these violations' causing severe harm. Moreover, cases relating to complex environmental forensic evidence should be taken up by environmental courts in India. To achieve this, judges, legal professionals, and law enforcement officers would need to be trained to recognize and assess forensic data. This would occur when environmental disputes would be subjected to the legal application of forensic science.

C. *Economic Challenges*

The environmental protection sector in India receives 1.5% of its Gross Domestic Product while China invests 3%.[58]The implementation of advanced environmental forensics demands extensive capital expenditure on facilities with accompanying employment of qualified personnel. The expansion of environmental forensics in India encounters several obstacles that arise from various factors like social structures, low economic investment, legal & political constraints, technical limitations, and operational challenges.

D. *Infrastructure Challenges*

The fundamental technological for environmental forensics investigation in India is still outdated. Environmental sample identification through complex compounds requires updated equipment such as "Fourier-transform infrared spectroscopy (FTIR)" and "Gas Chromatography-Time of Flight Mass Spectrometry (GC-TOF-MS)" which most pollution control boards currently lack. [59] The monitoring of real-time air and water quality exists only in few urban centres throughout the country. There are two armatures of forensic infrastructure in India – CFSLs controlled by "Directorate of Forensic Science Services (DFSS)" and SFSLs[60] with certain specialised facilities like DNA profiling, toxicology, cyber forensics and ballistics analysis. Despite its challenges—such as a lack of staff, outdated technology, and no database for managing evidence—they are making every effort to settle both civil and criminal cases. However, the United States has a well-established forensic framework, with the FBI laboratory at the head and support from a network of additional federal, state, and municipal authorized forensic labs. Processes for evidence processing, interoperability, and integration of data

[58] World Bank, World Development Indicators: Environmental Protection Expenditures (2025) <https://data.worldbank.org> accessed 11 February 2025.

[59] Collins Nana Andoh, "Fourier Transform Infrared Spectroscopy: An Analytical Technique for Microplastic Identification and Quantification" (2024) 136 Infrared Physics & Technology

[60] 'Regulation of Forensic Laboratories' (2024) <https://pib.gov.in/PressReleasePage.aspx?PRID=2077952> accessed February 11, 2025

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between agencies are made more efficient by utilizing advanced technologies such as CODIS and NIBIN (National Integrated Ballistic Information Network) in criminal investigations.[61]

SUGGESTIONS

A. Strengthen Policy and Institutional Framework

Institutionally, India must establish dedicated environmental forensic cells within the Central and State Pollution Control Boards, the Ministry of Environment, Forest and Climate Change (MoEFCC) and even implement them in the judiciary. These cells need to be populated by trained environmental scientists, forensic experts, legal advisors, and data analysts. With established centralized and regional forensic laboratories with modern analytical capabilities, such as chemical fingerprinting, isotopic analysis, and DNA-based microbial source tracking, accurate identification of contamination sources and polluters could be undertaken. Policy reforms must also address access to forensic and other materials to maintain transparency and public trust in environmental governance. Environmental forensics can be integrated in EIA protocols and pollution audits making monitoring proactive instead of responsive. The better investigation and enforcement of pollution control measures can be adopted to perform pollution detection through creating dedicated Environmental Forensic Units at the central and state levels.

B. Strengthen Legal Enforcement and Accountability

Strict implementation of pollution control measures require legal reforms. Strong deterrent will be provided by introducing more severe sanctions for industrial polluters as well as fast track prosecution of environmental crimes. To produce the forensic evidence in court, the protocols for evidence collection, preservation and archive of custody should be standardized. Data bank for such evidence should be ensured to be stored securely, tamper proof with help of latest block chain technology. Industries ought to be categorized based on the pollution they produce. Regular independent third-party audits and monitoring is necessary for such industries on the basis of the categorisation. The government must support and protect activists and whistle-blowers who report such acts.

C. Invest in Advanced Forensic Technologies In FSLs Both Centre as well as State

It is important to upgrade forensic technology for enhancing pollution crime investigations. Each state's labs must be state-of-the-art, equipped with cutting-edge instruments like High-Resolution Mass Spectrometry (HRMS), Inductively Coupled Plasma Mass Spectrometry (ICP-MS), and GC-MS to precisely identify and track waste. Mobile environmental forensic units should be created in order to look into onsite contamination at pollution hot spots. Using IoT-based sensors and remote sensing technology to continuously track the quality of the air, water, and soil will aid in the growth of real-time monitoring networks.

Additionally, the integration of GIS for showing environmental infractions will improve monitoring capabilities. Analysis of crude oil and BTEX (benzene, toluene, ethyl benzene, and xylene) as isotopes is a key tool to address the origin, transport pathway and degradation processes of hydrocarbons. Carbon (δ13C), hydrogen (δD) and sulphur isotopes have developed into well-established isotope analysis in the USA and there is a ample of research using advanced technologies. The method is extensively use for oil field exploration, reservoir characterization and environmental forensics, where its uses include oil spill identification and tracking the contamination sources.

Isotope analysis has been used within regulations of the U.S. Environmental Protection Agency (EPA), especially monitoring BTEX in groundwater and air pollution studies.[62] On the other hand, India is galloping to its isotope analysis capacity which is being off stead by leading research institutions like NGRI and IITs. The principal emphasis is on new petroleum basins and depositional environments. All these studies use the technique called compound specific isotope analysis (CSIA) for BTEX that is still in an emerging stage in India but gaining momentum in the context of groundwater contamination and air quality studies in urban areas. Unlike the USA, India's application of

[61] 'CODIS Archive' (*Law Enforcement*, June 3, 2022) <https://le.fbi.gov/science-and-lab/biometrics-and-fingerprints/codis-2> accessed February 11, 2025

[62] RP Philp, J Allen and T Kuder, "The Use of the Isotopic Composition of Individual Compounds for Correlating Spilled Oils and Refined Products in the Environment with Suspected Sources" (2002) 3 Environmental Forensics 341

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isotope analysis is not as much driven by regulation as technology and environmental concerns further develop.[63] India needs a robust National Environmental Forensics Lab Network with facilities that include GC-MS systems together with isotopic analysis technology and air dispersion modelling capacity. The government should pass new regulations which assign legality to industries through forensic evidence for pollution responsibilities.

D. Use of AI

Similarly, India can use advance technology like Artificial Intelligence in environmental forensics technologies that can be very helpful in collecting large volumes of environmental data from many sources, including satellite imaging, pollution sensors, and sensor monitoring stations. With AI's help, the India can improve its capacity to track environmental infractions and anticipate pollution trends. AI for instance, can analyse data from air quality sensors, weather patterns, and satellite imagery to forecast pollution levels and identify pollution hot spots in cities like Delhi and Mumbai where air quality has become a public health concern. So, the CPCB could use AI to gauge where immediate action is needed to prevent the industrial contaminants are high or areas where waste is disposed of illegally in the river. AI empowered systems could help in analysing satellite imagery to detect places of deforestation or illegal mining, especially the area of concern like Western Ghats or Sundarbans. An example of usage of AI in the real-life scenario of India is the use of AI for monitoring air pollution through the National Air Quality Index (AQI).[64] AI can analyse historical data patterns to make better predictions of the air quality and assist authorities to enforce some strong regulations and inform the public immediately. In addition to this, AI can become useful in the legal front by identifying the levels of pollution and its correlation to the observed health impacts in those regions, thus strengthening the evidence of enforcing and legal procedures.

Environmental forensics in India may become much more effective at identifying and analysing pollution with the use of artificial intelligence (AI)-powered methods. Artificial intelligence (AI)-powered predictive modelling can analyse massive datasets from environmental sensors, satellite photos, and pollution reports to forecast pollutant behaviour and identify potential sources to stop them from wreaking havoc. Artificial intelligence (AI)-powered image recognition technologies[65] can be harnessed for processing and analysing satellite imagery or aerial footage for illegal dumping detection or real-time monitoring of environmental degradation. The use of these AI driven techniques would help make the forensic investigations in India more efficient, faster, and more accurate, with environmental violations can be identified faster while the regulations can be more effectively enforced. India's capabilities in environmental forensics would be significantly strengthened by incorporating a range of cutting-edge and distinctive technology employed in this field worldwide. For instance, airborne laser scanning (LiDAR), which is frequently used in Europe to map environmental damage and find pollutants in remote places[66], can be used to monitor hazardous waste spills, illegal mining, and deforestation in India. By combining these methods with GIS for spatial analysis, India can improve its capacity to identify, track down, and manage environmental infractions, by providing a comprehensive approach to pollution monitoring and environmental forensics.

E. Leverage International Collaboration and Knowledge Exchange

The collaboration of Indian Government (Directorate of Forensic Science Services, Ministry of Home Affairs) with international organisations such as the United Nations Environment Programme (UNEP) and the US-Environmental Protection Agency (EPA) would be beneficial for India. Adopting best global practices and partnership with best organisations working in the field of

[63] India EU Water Partnership, 'Handbook for Stable Isotope Data Interpretation in India' (Jochen Wenninger 2020

[64] Kuldeep Singh Rautela and Manish Kumar Goyal, "Transforming Air Pollution Management in India with AI and Machine Learning Technologies" (2024) 14 Scientific Reports

[65] "AI Cameras – Their Significance and Applications in Embedded Vision" (*TechNexion*, January 21, 2025) <https://www.technexion.com/resources/ai-cameras-their-significance-and-applications-in-embedded-vision/> accessed 11 February, 2025

[66] Cosgrove C and others, "Using the Full Potential of Airborne Laser Scanning (Aerial LiDAR) in Wildlife Research" (2024) 48 The Wildlife Society <https://doi.org/10.1002/wsb.1532> accessed 11 February, 2025

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environmental forensics will be of immense help to India. The country will further enhance its expertise in participation of international research project in transboundary pollution and emerging forensic technologies. But improved India's monitoring and investigation capability can adopt successful models from Germany and Japan.

F. Establishment of Environmental Forensics Database

India should develop a centralized database for environmental forensics that contains information on contaminants, their chemical fingerprints, and their possible origins. This database includes, among other things, reference information on typical industrial contaminants, pollutant dispersion models, and past pollution incidents. Forensic specialists will be able to quickly identify contaminants at a crime scene and trace them back to known sources thanks to this database. To identify trends and forecast the pollution trend, machine learning algorithms can be applied to the database.

CONCLUSION

The area of environmental forensics is expanding in India and has the potential to secure environmental justice and eradicate environmental crimes, especially pollution-related ones. Although environmental laws and technology have evolved in India, the country still lags behind wealthy countries in the use of sophisticated forensic instruments, forensic investigative methods, and the successful integration of forensic evidence in court cases. To detect and trace pollutants, nations like the US and EU have built very sophisticated frameworks based on high-tech modern technologies like DNA fingerprinting, Stable Isotope Analysis, High-Resolution Mass Spectrometry, and so forth. The legal system must adapt to recognize the credibility and admissibility of scientific evidence in environmental matters, and it is imperative to close the technical gap for innovative rather than technological reasons. India may thus conform with worldwide environmental norms, learn from global best practices, and work on a more cohesive and thorough path of environmental forensics. This not only strengthen our legal framework and enhancing our current ability to handle pollution crimes but also encourage sustainable growth for healthier, cleaner mother earth for coming generations.