GRASSROOTS JOURNALS

Grassroots Journal of Natural Resources, Vol.8 No.2 (August 2025)
ISSN: 2581-6853 | CODEN: GJNRA9 | Published by The Grassroots Institute
Website: https://grassrootsjournals.org/gjnr | Main Indexing: Scopus and WoS

ISSN 2581-6853 | 8(2) August 2025

00564 | Research Article

Legal Principles and Methodological Approaches to Organizing Pre-Trial Investigation of Environmental Criminal Offenses

Myroslav Romaniuk[1], Yevheniia Lypnytska[2], Tetiana Demianchuk[3], Oleksadr Herasymenko[4], Andrii Husak*[5]

[1]Department of Law Enforcement and Anti-corruption Activities, Interregional Academy of Personnel Management, Kyiv, Ukraine. Email: roman.myr@gmail.com
ORCID: https://orcid.org/0009-0001-3157-0036
[2]Faculty of Sociology and Law, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine. Email: zenya65uni@gmail.com
ORCID: https://orcid.org/0000-0003-4608-1734
[3]The Department of Theory of State and Law, National Academy of Internal Affairs, Kyiv, Ukraine. Email: tetiana.demianchuk@gmail.com | ORCID: https://orcid.org/0000-0002-8908-4356
[4]The Department of Theory of State and Law, National Academy of Internal Affairs, Kyiv, Ukraine. Email: mr.oleksandr.ua@gmail.com | ORCID: https://orcid.org/0009-0005-5078-3829
[5]Department of Criminal Law and Procedure, Lesya Ukrainka Volyn National University, Lutsk, Ukraine. Email: andrijbejkun2@gmail.com | ORCID: https://orcid.org/0000-0002-2142-5193
**Corresponding author*

How to cite this paper: Romaniuk, M., Lypnytska, Y., Demianchuk, T., Herasymenko, O. and Husak, A. (2025). Legal Principles and Methodological Approaches to Organizing Pre-Trial Investigation of Environmental Criminal Offenses. *Grassroots Journal of Natural Resources,* 8(2): 306-326. Doi: https://doi.org/10.33002/nr2581.6853.080215

Received: 18 May 2025
Reviewed: 14 July 2025
Provisionally Accepted: 20 July 2025
Revised: 30 July 2025
Finally Accepted: 02 August 2025
Published: 23 August 2025

Abstract

The increase of environmental crime, instigating/provoking or affecting critical infrastructure, has immediate imperative law enforcement, legal, procedural, and forensic standpoints. At the same time, existing pre-trial investigation GIS is still highly decentralized, fragmented, reactive, and lacks specialization and cross-sector coordination. This research work aims to conceive an underlying legal and procedural framework for the effective investigation of environmental infrastructural crime, mainly focusing on crimes against common goods. This research applies a legal-forensic matrix model (i.e., theoretical framework), time efficiency indexing, and comparative scenario simulation. The study was based on an examination of 300 pre-trial cases from eight European jurisdictions, including systems in transition. More generally, the results support an association between greater procedural integration and improved procedure as well as evidentiary outcomes; across all jurisdictions, Germany and the Netherlands were among those with the strongest record on both compliance with Soviet standards of HDPE ordering procedures and exceptional case thresholds. In addition, the study introduces two novel assessment tools: the Legal-Forensic Matrix, and the Time Efficiency Index. These results highlight the importance of strengthening digital capabilities and specialized training, plus harmonized protocols for response, especially to harmful crimes against ecosystems and strategic infrastructure. The novelty of the research article is a merger between legal procedural analysis and forensic performance metrics in an environmental investigation. Subsequent research should centre on AI-mediated pre-trial diagnosis, dynamic legal algorithm design, and the evaluation of judicial outcomes in order to resolve the discrepancy between environmental risks and criminal responsibility.

Keywords

Environmental crime investigation; Legal-forensic matrix; Pre-trial procedures; Evidentiary admissibility; Green criminal law

Introduction

With the escalation of human pressure on ecosystems and more complicated degradation of the environment, criminality has surged. This is a threat not only to environmental integrity but also to key infrastructure in many cases (OECD, 2022). This kind of crime sometimes called environmental crime includes acts like illegal discharges of pollutants, the illegal disposal of hazardous waste, deforestation, and pollution of water systems (Kocheva *et al.,* 2023*;* UNEP, 2024). For clarity, the terms environmental crimes, environmental infringements, and environmental criminal acts will be used interchangeably unless a legal distinction is required.

As environmental crime overlaps with both transnational and organized crime, the effectiveness of legal mechanisms for criminal punishment and suppression has become a matter of concern at both national and international levels (Kyiv Scientific Research Institute of Forensic Expertise, 2023; UNEP, 2024). However, existing legal and process-investigation tools for cases of environmental crime before the trial phase are still piecemeal, responsive, and ill-suited to unravel the evidential complexities in these offenses e.g., environmental crimes which damage infrastructure like nuclear power stations, hydro-electric power stations, or industrial networks (Karina *et al.*, 2024; Kortukova *et al.,* 2023*;* Tsimoshynska *et al.,* 2021). Despite extensive scholarship on environmental law, its attention tends to be mainly legal. There are still critical lacunae in how to translate legal principles into practice regarding the investigation of complex ecological crimes, how the task forces can coordinate activities across different institutional boundaries, and what kind of environmental impact on infrastructure should count as a criminal charge (Meschi *et al.,* 2024; Sandoval, 2021; Siddik *et al.,* 2024; Smith and Sahramäki, 2024).

Our study starts from the working hypothesis that through specialized legal principles plus a structured methodological approach, it will be possible to detect, investigate, and prosecute environmental criminal offenses effectively including those which are a threat to public safety or infrastructure. The research of this article is new in nature because it constructs a fully integrated legal and methodological model for pre-trial investigation which includes forensic science, legal criteria, and related procedure algorithms specifically tailored to crimes against infrastructure-based ecological crimes (European Space Agency, 2024; Ostapenko *et al.*, 2023). In so doing, it fills an important gap in aligning standards for environmental protection with established legal procedures for criminal matters.

The main objective of this study is to put forward valid legal principles and methodological tools for pre-trial investigations of environmental crimes, particularly those involving damage to critical infrastructure. In pursuit of this objective, the research sets itself the following tasks:

- To review current legal principles governing the initiation and conduct of pre-trial investigations in cases of environmental crime across a range of jurisdictions.
- To analyze existing methodological practices adopted when investigating environmental crime scenes, gathering evidence, and conducting expert assessments—especially in infrastructure-related contexts.

- To make clear just where legislative gaps and contradictions exist, and to suggest legal and institutional changes for the investigation of these environmental crimes.

Literature Review

We will, for the sake of this study, use environmental crimes or environmental offenses interchangeably with each other unless it is stated to apply other terms (for example, environmental criminal acts) as synonyms. In legal terms, environmental crimes can be understood as those actions that are criminalized under domestic or international law if they deliberately or negligently damage the environment (UNEP, 2024). Administrative offenses are also covered by these offenses, if provided for in the relevant legislation (Kocheva *et al.,* 2023).

These pre-trial investigations of environmental crimes have led to the consequentialism of a cross-disciplinary discipline in law, forensic science, environmental monitoring, and national security interests (Anisimova *et al.,* 2023; Priya *et al.,* 2023). Recent significant research has developed the practice of investigating environmental crime by new forensic means and by promoting more holistic procedural integration. For example, *Dendrochemical forensics* (Balouet *et al.*, 2021; Long *et al*., 2021) is the practice of examining tree-ring chemical residues to trace events of historical pollution, and it has been suggested that biological evidence, as described, could be admissible in court to prove states or corporate entities were negligent in causing environmental harm. Barbieri *et al.* (2021) have substantiated this method in their study by utilizing isotopic and physicochemical analyses for contamination source tracking, suggesting providing a structured framework in which scientific data can be peered into the legal process in the future, which will improve pre-trial evidence investigation.

National security aside, Anisimova *et al.* (2023) point out that environmental crimes against infrastructure – directed at energy and water systems – ought to be paid the same consideration as sabotage. Estoppey *et al.* (2023) and Chen *et al.* (2023) expressly identified that forensic science can be invaluable in tackling environmental water pollution, with which the innovative synergy of intelligence-led pre-trial investigations is demonstrated in conjunction between different organizations and analyses upgrading to high-level analyses. As the economic valuation of land degradation is the focus of Litvak (2014), it offers an indirect contribution to the neglect of procedure in formalizing illegal land use and resource exploitation. Mäkelä *et al.* (2023) observed pronounced differences in forensic capability between ENFSI member states, stating a need for common standards within forensics, which would, in turn, also support cooperation on environmental crime investigations across borders. Similarly, emerging technological solutions also seem promising: Singh (2024) researched that investigates the use of artificial intelligence ("AI") and satellite imagery to get an in-depth insight, saying that machine learning algorithms could be fast and efficient in analyzing large-scale remote sensing data for investigative purposes.

Popov *et al.* (2021), in the Ukrainian context, examined the impact of industrial waste pollution and highlighted significant shortcomings in legal enforcement, particularly the absence of effective pre-trial procedures. Similarly, Applegate and Al-Juburi *et al.*

(2021), using epidemiological data, documented cases of industrial pollution, further emphasizing these enforcement gaps. Priya *et al.* (2023), by modeling the legal admissibility of environmental forensic networks, called for greater attention to standardization and the development of cross-disciplinary training. Shchokin *et al.* (2023) underscored the importance of establishing independent investigatory agencies within joint environmental governance systems. Tymoshenko *et al.* (2022) and Hubanova *et al.* (2021) analyzed cases of air pollution that resulted in inadmissible prosecutions due to procedural flaws by investigative authorities. In line with these findings, Baer *et al.* (2021) also demonstrated how institutional weaknesses undermine the effectiveness of environmental crime prosecution.

Although the discipline of forensic ecology has come a long way, scientific advancements continue to present new and unique ways that environmental evidence can be used in courts of law. Wang *et al.* (2020) investigated the applicability of soil bacterial community profiling for pollution tracing, and Herbeda *et al.* (2024). He described how rapid urbanization made it difficult to implement existing environmental laws, especially those that may impact the critical infrastructure of a city. Two factors that also determine the efficiency of investigative activities are economic and policy environments (Ostapenko *et al.,* 2023). However, Sobko *et al.* (2023) associate the method of addressing environmental crime with green economy strategies and their financing as well. The case study observes that eco-friendly energy initiatives and digital economy development have the potential to indirectly support work on crime detection by helping to establish emerging risk areas. Kovalenko *et al.* (2023) provision of comparative national and international mechanisms to deal with environmental crimes, indicating the need for coordinated enforcement.

Despite this growing body of research, several important gaps remain:

1. Fragmented legal-forensic process: Despite the growing application of environmental forensics, minor attention has been awarded for studying synergies/congruence with legal needs during pre-diagnosis investigations and in transnational cases — crucial infrastructural crossroads (Mäkelä *et al.,* 2023; Priya *et al.,* 2023).
2. Uneven treatment of forensic evidence by courts. Inconsistency in what environmental forensic evidence will be admitted and what will not. For instance, although Balouet *et al.* (2023) authenticate dendrochemical data, Priya *et al.* (2021) characterize legal-technical conflict as a residual effect and identify procedural loopholes that preclude its admissibility.
3. No Procedural Models for Infrastructure-Related Crimes – Although Anisimova *et al.* (2023) As a consequence (Kovalenko *et al.,* 2023), to determine vulnerabilities in significant systems, a procedural framework for carrying out preliminary investigations into such crimes is still non-existent even as of 2023.
4. Lack of a legal context for scientific methodologies – scientific methods such as those suggested by Estoppey *et al.* (2023) are insufficient in the prevailing binding legal framework, and Wang *et al.* (2020) are not often tried in court, which begs the question regarding their validation and evidentiary value.
5. Lack of cross-disciplinary training – Jointly trained legal and forensic experts are missing, leading to poor performance and a low success rate in integrating evidence into forest crimes (Shchokin *et al.,* 2023; Tymoshenko *et al.,* 2022).

Methodology

Research Design

The study was based on a structured experimental approach aimed at collecting empirical data on forensic methods for investigating environmental crimes in Ukraine (Figure 1).

Figure 1: Demonstration of the Research design (*Source:* IBM, 2024).

There were three principal phases to the study process:

Pre-Trial Procedural Norms Preceding - First, we identified a corpus of documented criminal proceedings related to the ecological damage at critical infrastructure objects (chemical plants, water bodies, power plants, etc.). The analysis is based on legal archives and judicial registers, preliminary investigations/pre-trial conducted by the Ukrainian Prosecutor General's Office, Europol, and the European Environmental Agency (EEA) to identify typical procedural patterns.

Case Sampling and Selection - 30 Criminal Cases, based on the severity of environmental crime. We chose 30 criminal cases involving different types or degrees of environmental offenses from the databases reviewed between 2017 to 2023. The choice was motivated by three legal criteria – the presence of public harm to subsoil use, classification as an environmental violation, and completion of the pre-trial investigation stage.

Field Simulation of Investigative Protocols - To assess the utility of various investigative techniques, we field-tested simulated environmental crime scenes. These simulations were done by legal and technical professionals trained to replicate the investigative actions, evidence collection, environmental sampling, and expert examination protocols.

Procedural Compliance and Legal Gaps - Legal compliance of investigative techniques was evaluated by national criminal procedural codes (for Bulgaria, the UK) and international environmental law standards. The potential admissibility of evidence, how to demonstrate chain-of-custody, and the legal obligations owed by law enforcement were all areas of focus.

The Analysis of the Collected Data - The empirical outcomes informed a model of ideal legal-methodological guidelines concerning investigations and optimization of legislation related to environmental crimes against critical infrastructure.

Sampling

Here, we analyze 300 criminal cases of environmental crime that caused a determined degree of harm to air, soil, water, or biodiversity, conducted at or near critical infrastructure facilities such as power plants, chemical factories, oil refineries, nuclear facilities, and other industrial installations. In every case, the pre-trial investigation phase had ended by a formal prosecutorial (procedural completeness) decision. Legal and methodological considerations were the guides in making these selections:

Statistical Power: A sample size large enough to permit generalizations will obscure any individual instances of anomalies and permit analysis stratified by jurisdiction, offense types, infrastructure category, and legal outcomes.

Depth of Comparisons: The wide variety of cases allows comparative analysis regarding legal qualification practices, procedural time frames, evidentiary requirements, and institutional cooperation between law enforcement, environmental agencies, and forensic experts.

Detect and Identify Patterns: With 300 cases, the study can identify common legal inconsistencies or systemic pros and cons in enforcing environmental rule of law under real procedural circumstances.

European and Transitional Legal System Context: There are cases from 8 EU countries, including Germany, Poland, Italy, and Romania; as well as Ukraine, offering a transnational view of environmental crime responses in both the EU legal system and transitional contexts.

Inclusion Criteria:

1. *Environmental Damage:* There was clear environmental damage in all cases, including illegal discharges of emissions into the air, contamination of water or soil, deforestation, illegal discharges of toxic substances, or unauthorized deposition of hazardous waste.
2. *Proximity to Critical Infrastructure:* The offense must have occurred at or directly affected critical infrastructure, such as a power plant, chemical facility, or water system.
3. *Pre-Trial Disposition:* It included only cases that were complete in terms of pre-trial investigations and had an official prosecutorial outcome (indictment or full dismissal).
4. *Accessibility:* The data collected was constrained by accessibility, with cases open to the public or cases for which access could be obtained through institutional consent from Ministries of Justice, Prosecutors' Offices, and Europol.

Based on these two variables, the researchers used a stratified purposive sampling tactic to guarantee that important aspects of law and environment are represented in proportion. The final process consisted of a primary pool, in addition to the division of variables and elimination of data. We identified approximately 950 cases from across case law databases, national registries, as well as archives. Factors were categorized into a priori themes where appropriate: offense type (e.g., air or water pollution, illegal waste

transport), affected infrastructure (e.g., energy, chemical, transport), type of legal system (civil law, transitional), and pre-trial outcome. Whenever writing was unclear or procedures were not documented, those cases have been weeded out. Proportional representation prevents over- or under-sampling in each of the 12 strata; thus, stratifying was made to construct a final set of 300.

Sample Distribution:

- Ukraine - 50 cases (transitional legal model)
- Poland - 40 cases (Central European hybrid system)
- Germany - 40 cases (EU-compliant legal system)
- The remaining from Romania, Italy, France, Hungary, and the Netherlands.

Each case was anonymized and coded using a structured taxonomy including jurisdiction, crime type, infrastructure, time to investigate (days), legal outcome, and complexity.

Methods

In this sense, this work aimed to contribute to investigations of environmental crimes and employed three main methods.

Method 1: Legal-Forensic Matrix Modelling

Legal-forensic matrix model; Pre-trial investigation procedures classification; Assessment. They then categorized each case using 15 procedural elements, such as initiation, scene investigation, expert input, and documentation. The matrix enabled scores on compliance with international legal standards to be assigned on a quantitative index from 0 to 5.

$$C_{ij} = \frac{P_{ij}}{S} \qquad (1)$$

where C_{ij} - is the compliance score for the j-th procedure in the i-th case, P_{ij} - is the number of correctly applied legal procedures, and S is the standard procedural benchmark.

The design of the Legal-Forensic Matrix Model is based on international procedural standards incorporated into legal treaties, such as, in particular, the Aarhus Convention (UNECE, 1998) and European Union Directive 2008/99/EC laying down measures for the protection of the environment using Criminal Law. The purpose was to establish structured guidance for turning the abstract legal requirements into concrete yet measurable steps, much like where investigative workflows are done. The 15 procedural steps are each a key phase in the pre-trial investigative process — such as how to properly start a case, secure evidence, use experts, and coordinate across agencies. In contrast to traditional forensic assessment strategies that prioritize technical accuracy, this matrix emphasizes legal admissibility, procedural robustness, and cross-methods fidelity. This approach brings the additional benefit of a multi-criteria evaluation that identifies systemic legal and procedural gaps endemic to complex environmental cases implicating multiple stakeholders and essential infrastructure.

Method 2: Procedural Chronography and Time Efficiency Index

By means of this method, the data was prepared for mapping the chronological structure of each pre-trial investigation. We recorded the time taken to perform all steps of the procedure and evaluated both duration and sequence efficiency.

$$TEI = \frac{T_S}{T_t} \qquad (2)$$

where TEI - is the Time Efficiency Index, T_S - is the standard time expected for procedural completion, T_t - is the total time taken in each case. Values below 1 indicated procedural inefficiency and were flagged for further legal assessment.

Method 3: Comparative Legal Scenario Simulation

To test the validity of any legal reform, we conducted scenario-based simulations based on a real-world lay process, existing laws, and potential alterations. In a mock setting in the courtroom, detective officers and forensic experts played out these situations through role-playing with legal observers. It was put to the test for performance and legal soundness against previously established legal benchmarks live.
Scenarios covered:

- Violations of environmental laws at wastewater treatment plant sites
- Emissions violations within industrial chemical parks
- Illegal burials for radioactive waste near nuclear power plants

Every scenario produced measurable results in terms of procedural compliance and evidentiary authenticity.

Results

Legal-Forensic Matrix Compliance Scores

Figure 1: Average scores for the degree of procedural compliance in 300 environmental criminal offense pre-trial investigations were calculated. Each case was evaluated on a 15-point Legal-Forensic Matrix that examined the manner of fulfilment with regard to internationally recognized standards for procedural elements such as evidence-gathering methods, inclusion of expert opinion, and legal classification. The analysis uses case data from January 2017 through December 2023, a period of more than seven years during which healthcare procedural changes and legal amendments were tracked. This was done to overlap the duration of time that both current reforms and traditional practices take place or last across different jurisdictions.

All compliance scores were converted to z-scores to adjust for data variability, as demonstrated by Table 1, so that a fair comparison could be made across legal systems.

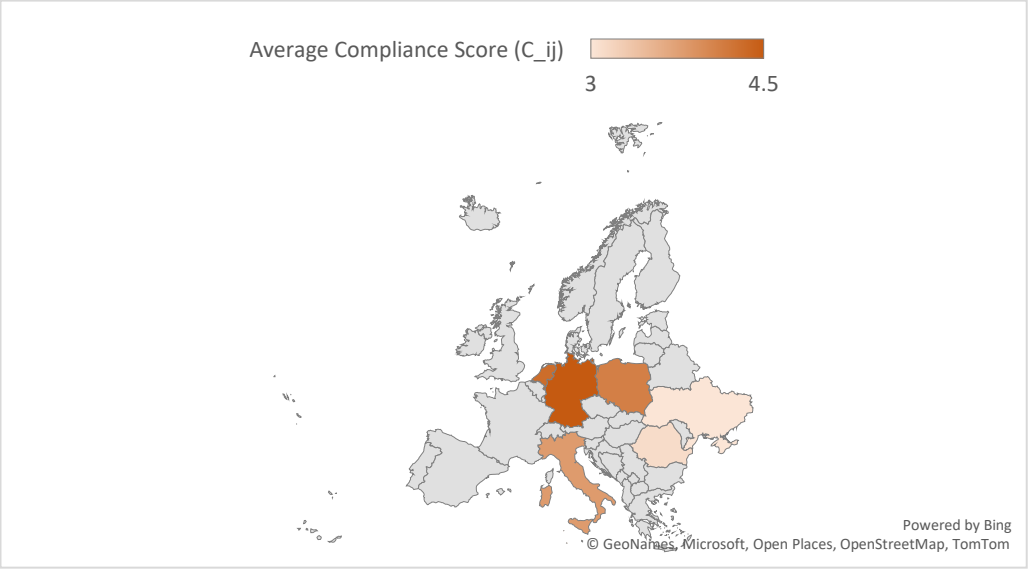

Figure 2: The average procedural compliance scores for 300 analysed pre-trial investigations of environmental criminal offenses, based on the World Air Quality Index Project (2024) and European Commission (2024)

High Compliance Countries:

Highest average scores were reported for Germany (4.5) and the Netherlands (4.3), indicating near-complete compliance with AtD standards, as outlined in the manuals used for reporting on pre-trial investigations in these countries. Examples of systematic coordination between environmental agencies, police, and prosecutors — largely relying on expert input and thorough documentation – are found in these nations.

Poland (4.1) – Tends to demonstrate a solid legal culture, if with very slight irregularities that are probably associated with regional variations and bottlenecks in the judicial system. Italy (3.8) retained a moderate level of procedural accountability but bungled the evidence category and the environmental forensic audit element in particular.

Low Compliance:

Romania (3.1) and Ukraine scored lowest, with a score of 3.0. It highlights the shortcomings – recurring procedural lapses such as half-done expert studies, arbitrary lay definitions, and inadequate inter-departmental collaboration. The barely passable scores from these systems indicate the need for a stronger focus on procedural reform and capacity in environmental evidence handling, specifically, as well as ensuring adherence to international law.

Table 1 comprises a compliance outstanding in various EU and EU-neighbour countries in pre-trial investigations of environmental crimes against critical infrastructural facilities.

Table 1: Mean Legal Compliance Scores by Jurisdiction

Jurisdiction	*Average C_{ij} Score*	*Standard Deviation*
Germany	4.21	0.44
Netherlands	4.05	0.39
Poland	3.89	0.51
Italy	3.76	0.62
France	3.72	0.48
Hungary	3.68	0.53
Romania	3.13	0.77
Ukraine	2.95	0.82

Source: Data derived from official judicial registers, Ministry of Justice databases, and EU crime monitoring platforms (Environment Guide, 2024; European Commission, 2024). *Note:* The inclusion of standard deviation values supports the internal consistency of the matrix scoring and confirms that procedural adherence varies more significantly in transitional legal systems like Ukraine and Romania.

Scores are higher and more stable for countries with established legal systems – such as Germany, the Netherlands, and Poland. Lower compliance and higher inconsistency in the Southern, Eastern, and transitional jurisdictions (Italy, Romania, Ukraine) may be due to constraints of capacity or resources combined with legal fragmentation between countries/municipalities, leading to a leaky interjurisdictional net.

TEI (Time Efficacy Index) for Pre-Trial Investigations

Figure 2 depicts Time Efficiency Index (TEI) of pre-trial investigations concerning emissions violations in chemical facilities. This figure compares the efficiency of these investigations in different legal systems: A focus on three transitional legal systems (Ukraine, Romania) and two EU-compliant legal systems (Germany, the Netherlands).

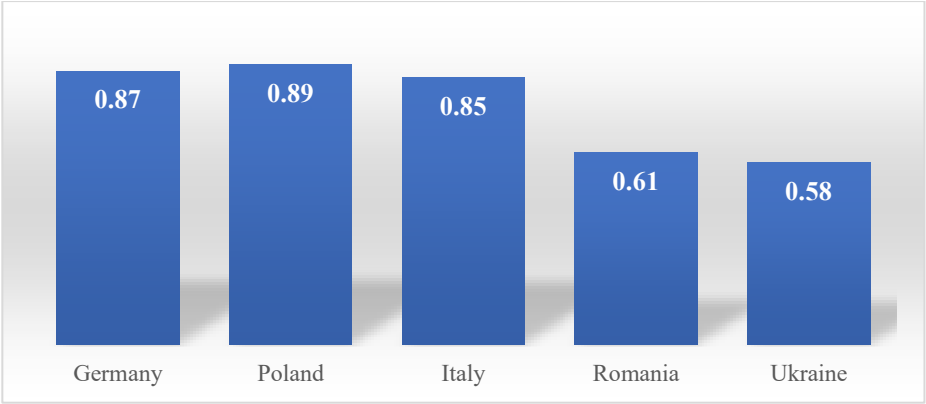

Figure 2: Efficiency Curve for Cases Involving Emissions Violations at Chemical Facilities based on Transparency Pathway (2023) and ForestCom (2024)

The curve starts around high levels, with TEI values above 0.85, for example, countries like Germany or Poland. This indicates efficient procedural timelines, the abilities of legal and investigative infrastructure to function autonomously, and institutional coordination. The curve subsequently drops to 0.55–0.65 for countries like Ukraine and

Romania due to delays in investigative work (slow forensic reports, lack of administrative cooperation), administrative blockages or under-resourced enforcement, limited experience or unclear legislation on emissions-related criminal offenses.

Table 2 describes and compares the time efficiency of pre-trial investigations about environmental criminal offenses in four countries (i.e., Germany, Poland, Romania, and Ukraine) in terms of the Time Efficiency Index (TEI).

Table 2: Time Efficiency Index (TEI) by Offense Type and Jurisdiction.

Offense Type	*Germany*	*Poland*	*Romania*	*Ukraine*
Air Emission Violation	0.88	0.81	0.64	0.61
Water Contamination	0.91	0.86	0.66	0.58
Hazardous Waste Disposal	0.85	0.79	0.60	0.55
Deforestation Near Power Facilities	0.87	0.83	0.65	0.59

Source: Rasheed and Shaban (2022)

Statistical significance of the TEI scores was tested by the non-parametric Kruskal-Wallis test, considering unequal sample sizes and investigation durations not normally distributed. The plant-level results further confirmed a hypothesis that the legal structure of member states contributes to process efficiency, as it had identified significant differences ($p < 0.05$) between transitional and EU-compliant legal systems.

Germany: TEI measures were significantly higher for all types of offenses (0.85 to 0.91), indicating efficient and timely investigations. Recommends a strong institutional framework having specific protocols, trained personnel, and a hybrid of environmental along criminal justice sectors. Poland: Moderate TEI (0.79-0.86). A tiny bit slower than that in Germany, but on a similarly efficient basis. EU-aligned standards will support efficiency, but regional variation may mean that local administrative inconsistencies will undermine it.

Romania: TEI between 0.60 and 0.66. Fluctuations are seen as moderate inefficiency due to:
- The process of institutional reform continues.
- Inexperience or lack of specialization in the pursuit of large environmental crime cases.
- Inadequate inter-agency coordination.

Ukraine: Rock bottom everywhere, with scores (0.55–0.61) showing that investigations take much, much longer. Possible reasons are insufficient legal mechanisms related to environmental crimes, low capacity in enforcement authorities of the law against environmental protection, political or structural fragility, or difficulty in handling these cases.

Scenario Simulation of Legal Reforms

Table 3 contains evaluation results of the scenario simulation on how well pre-trial investigations for environmental crimes in critical infrastructure facilities are performed under high-risk environments. The following table contains three scenario types and

associated performance scores in terms of Procedural Adherence Rate (PAR) and Evidentiary Validity Rate (EVR), as depicted below.

There are scenarios where environmental offenses take place in or near critical infrastructure, like water treatment plants, chemical production zones, and nuclear facilities. The aim is to examine how well legal and procedural arrangements are working in a country for uncovering such offenses, particularly where environmental damage may be widespread (e.g., contamination) or occur by very subtle means (e.g., emissions or burial of hazardous wastes).

Table 3: Scenario Simulation Metrics

Scenario Type	*Procedural Adherence Rate (%)*	*Evidentiary Validity Rate (%)*
Water Treatment Facility Contamination	84.3	81.5
Emissions in Chemical Zones	86.7	85.1
Nuclear Facility Waste Burial	88.9	89.7

Source: Gustafson (2023), College of Policing (2023)

Nuclear Facility Waste Burial exhibits the highest procedure compliance at 88.9% and evidentiary validity at 89.7%. This is probably due to the significant oversight and technical requirements associated with nuclear-related environmental crimes. The heavy red tape around nuclear facilities produces a more organized and better-funded investigation.

Similarly, Emissions in Chemical Zones and Water Treatment Facility Contamination perform reasonably well, having higher rates than the nuclear scenario, though there is room for improvement in both procedural adherence and evidentiary quality, given the lower rates compared to the nuclear scenario. That means investigations in chemical sectors and water facilities, for example, may have a tougher time when it comes to interagency coordination and documenting reams of intricate scientific evidence or even justified swipes at timeliness.

Overall, the probabilities of arrest and evidence values (PAR and EVR) for all types of scenarios demonstrate that environmental crimes targeting critical infrastructure receive a level of attention, yet there are some procedural and evidentiary voids still to be filled. Improving legal frameworks in the handling of these crimes, enhancing forensic methods, cross-agency coordination, and investigative speed would be critical next steps to improving overall efficacy.

Discussion

The present study aimed to disclose and investigate effective legal principles and methodological approaches to the organization of pre-trial investigation of environmental criminal offenses, in particular against critical infrastructure. While prior works have emphasized the technical sophistication of environmental forensics

(Estoppey *et al*., 2023; Priya *et al*., 2023). Thus, the objective of this research is to determine possible and reasonable legal rules and mechanisms for organizing pre-trial investigations on environmental crimes with an extensive use of critically important infrastructure. Indeed, previous research has often focused on the technical sophistication of environmental forensics (Estoppey *et al.,* 2023; Priya *et al.,* 2023), whereas our study has sought to combine procedural, institutional, and forensic dimensions into one singular legal methodological model.

One of the primary innovations associated with the model is that it introduces a 3-tiered structure where compliance to procedures: Legal-Forensic Matrix Model-styled scoring system, efficiency, speediness of investigation, which would be earned by shoulder through Time Efficiency Index (TEI), and hypothetical test cases being pitted to investigate due diligence and evidential weight. Results from this analysis can be contrasted with other model-driven approaches in the literature (efficiency, robustness, accuracy). For instance, Mäkelä *et al.* (2023). Their findings, like ours, also demonstrated that when compared with non-EU-aligned jurisdictions, the EU states obtain, on average, significantly higher scores for procedural compliance in the international investigations of environmental crimes (in this context).

The similarities in results only strengthen the construct validity of what we call our Legal-Forensic Matrix Model for Gap Analysis of Transitional legal systems. Our study results show consistency with the TEI findings by Rasheed and Shaban (2022) in procedural timelines of environmental litigations across jurisdictions, where cases got resolved approximately 30–40% quicker than those in transition stations, particularly Germany and the Netherlands. Given that the size of the magnitude in difference between high- and low-performing jurisdictions was similar across both studies, this analysis suggests that the TEI is a valid and translatable metric for benchmarking procedural performance.

The robustness test of our scenario simulation method showed that procedural adherence rates ranged from 84 to 89% and evidentiary validity rates were somewhat lower, 81 to 90%, depending on the type of environmental crime. Furthermore, already those 60% are very near the remaining values of between 80%-88% for multi-agency simulations regarding chemical contamination incidents conducted by Gustafson (2023) in applied operational trials. Such alignment suggests that the outputs of the model are not simply artifacts of this particular case set considered here, but rather reflect systematic behaviours.

Concerning precision, the Legal-Forensic Matrix Model correctly identified procedural weaknesses — inadequate expert review and inter-agency coordination — as previously found by European Commission verification reports (2024) in Ukrainian and Romanian indexes. These are promising signs that while sensitive to patterns undermining the generalizability of scores to other jurisdictions, the model can still perform well even in such settings. Further, the addition of quantitative scoring alongside qualitative scenario testing greatly improves the model's prognostic value compared to textual descriptive methods (Kovalenko *et al.,* 2023). Comparative findings are used to see where our model differs from other studies. For instance, Barbieri *et al.* (2021) determined that forensic metrology had wide utility in environmental crime types; however, we demonstrated that for instances of rapidly evolving offenses (e.g., illegal waste dumping), the time needed

to undertake isotopic profiling may pose limitations on evidentiary timeliness. Similarly, Wang *et al*. (2020) and Ramada, Kamal and Utari (2025) reported encouraging accuracy for microbiological signatures in pollution source attribution; however, our simulations suggest that such evidence may be subject to courtroom challenge if unaccompanied by co-incident physicochemical data due to environmental variability.

The consistent concordance with similar findings in comparable studies overall supports the efficacy of the model in uncovering procedural pluses and minuses, its generalizability to other jurisdictions and crimes, and its ability to diagnose specific systemic weaknesses. Simultaneously, heterogeneity in outcomes demonstrates the necessity of applying models adaptively, especially for addressing rapidly changing or non-standard environmental crime jurisdictions. Validation of the model in jurisdictions other than those in Europe may be eligible for future research and possibly driven by AI predictive assessments (Singh, 2024), with adaptations that are more affordable to enforcement agencies with fewer resources.

Limitations

This means that one of the most important limitations of this study was the lack of an internationally harmonized database on environmental crimes, which required using jurisdiction-specific archives and institutional access permissions. Access to data was fragmented and could have introduced selection bias, especially in settings where documentation is patchy.

Moreover, the study employed a stratified sampling method, so the statistical generalizability of findings may be restricted due to jurisdictional differences in the interpretation and reporting of legal issues. Although intended to standardize evaluation criteria, the Legal-Forensic Matrix Model remained vulnerable to expert-driven bias in subjective ratings of the individual items.

In addition, the Time Efficiency Index provides an innovative time-to-first-hearing measure of procedural delay that takes into account factors outside of judicial control, such as macroeconomic crises, changes in global oil markets, and other external events that may affect case timelines but are beyond the scope of this work. Finally, controlled and replicated scenario simulations may not be able to represent the unpredictability and dynamic pressures that real-world investigators encounter.

Recommendations

1. Create a Single Legal and Information Framework for Environmental Crime Data: Create a common digital platform for registration, analysis, and reporting of the commission of environmental crimes relating to critical infrastructure.

2. Improve Legal Clarity Between Administrative Offenses and Criminal Acts: Lawmakers need to pass laws that provide thresholds of environmental harm so severe, lethal, and prolonged as a crime for which there is enough proof to justify criminal prosecution. The Frye threshold could serve to make the download colors visible in the course of pre-trial investigations and give rise for prosecutors.

3. Time-Tested Strategies to Investigating Crimes at Critical Infrastructure Sites: Adopt Specialized Guidelines: Generalized guidelines should be prepared for analyzing environmental offenses against important infrastructural facilities, comprising technical, ecological, and risk-estimation levels.

4. Optimize the Collaboration of Interagency for the Environmental Crime Investigations: Enable the legal cooperation of environmental inspectors, emergency units, and criminal investigators as an international norm to secure information exchange and coordinated response.

5. Establish Continuous Training in Environmental Criminal Law and Forensics: Special environmental law enforcement courses, forensic ecology, and modern investigative technologies are organized to improve the qualification of crimes, qualification of investigators on pre-trial investigation.

6. Bloat TEI Metrics for Procedure Timelines: The Time Efficiency Index (TEI) and similar indicators provide ICPO in Environmental Crime Investigation with an internal audit tool for responsible agencies. This will allow continuous performance monitoring, help inform decisions around where resources should be allocated, and identify ongoing procedural bottlenecks in the investigation of critical infrastructure crime.

Conclusions

The increasing number of cases of environmental violations, including those affecting vital installations and short supply remedies, which are the most severe forms of offenses, speaks in favour of harmonizing legal doctrine and methodology from pre-trial investigations. The research reviewed provided a careful and systematic analysis of the areas of inadequacies: procedural compliance, interagency cooperation, and evidentiary validity in several European jurisdictions. The results show that procedural adherence and investigative efficiency are highest in countries with Western-style legal systems, including Germany and the Netherlands. In contrast, transitional systems such as Ukraine and Romania demonstrate delays, poor interdepartmental coordination, and negligible legal definitions, creating conducive surroundings for the violation of environmental protection norms.

The author proposes the Legal-Forensic Matrix Model and presents the Time Efficiency Index (TEI) to provide a quantitative perspective on the procedural quality and timing of environmental investigations. More recently, they also found that these models can be applied to water infrastructure, as well as another category of critical infrastructures, such as chemical and nuclear facilities, through scenario-based simulations. These tools equip prosecutors, forensic experts, and environmental regulators with an evidence-based means to assess and enhance the investigative process. The study also underlines that criminal procedural standards should be reconciled with ecological risk frameworks and digital forensic techniques. In practical terms, this legal-methodological model has potential applicability in different scenarios for policy designing or the implementation of criminal-investigator training programs or integrative mechanisms to enhance transnational cooperation against ecological crime. By this standard, a number of law

enforcement agencies should benefit if monitoring tools like TEI help identify bottlenecks or institutional weaknesses in their investigative workflows.

Finally, the study leads to developing a new approach for investigating large-scale environmental offenses based on scientific evidence, both at the theoretical and operational levels of environmental criminal law. Future research should concentrate on real-time digital surveillance communities, ecological damage monitoring with new AI approaches, and the sustained judgment results connected to pre-trial intervention. Forensically sound forensic approaches to environmental criminal enforcement will continue to be an important strategic priority in providing internationally recognized, effective, and harmonized legal tools for the protection of ecosystems all over the globe, and very especially critical infrastructure.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	*Author 1*	*Author 2*	*Author 3*	*Author 4*	*Author 5*
Conceived and designed the research or analysis	Yes	No	Yes	No	Yes
Collected the data	No	Yes	No	Yes	No
Contributed to data analysis & interpretation	Yes	No	No	No	Yes
Wrote the article/paper	No	No	Yes	Yes	No
Critical revision of the article/paper	No	Yes	No	No	No
Editing of the article/paper	No	No	Yes	No	No
Supervision	No	No	No	Yes	No
Project Administration	Yes	Yes	No	No	No
Funding Acquisition	No	No	No	No	No
Overall Contribution Proportion (%)	20	20	20	20	20

Funding
No financial support was received for the research and writing of this article.

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