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ENVIRONMENTAL FORENSICS AND RESOURCE MANAGEMENT: THE MODERNIZATION OF THE WATER AND EFFLUENT ANALYSIS LABORATORY AT THE INSTITUTE OF CRIMINALISTICS IN GOIÁS

PERÍCIA AMBIENTAL E GESTÃO DE RECURSOS: A MODERNIZAÇÃO DO LABORATÓRIO DE ANÁLISE DE ÁGUA E EFLUENTE NO INSTITUTO DE CRIMINALÍSTICA EM GOIÁS

PERICIA AMBIENTAL Y GESTIÓN DE RECURSOS: LA MODERNIZACIÓN DEL LABORATORIO DE ANÁLISIS DE AGUA Y EFLUENTES EN EL INSTITUTO DE CRIMINALÍSTICA DE GOIÁS

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ABSTRACT

This study addresses the technical, economic, and operational feasibility of implementing the Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) at the Laboratory for Water and Effluent Analysis (LAAE), under the Goiás Police Technical- Scientific Superintendency (SPTC/GO). The research emphasizes the importance of environmental forensics for producing technical evidence related to water pollution crimes and other environmental infractions. The study also explores the strategic feasibility of securing institutional and private funding for implementing the equipment. A qualitative approach was employed, including a bibliographic review, documentary analysis, and

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consultations with case studies and technical literature. The results indicate that the ICP-OES is an indispensable tool for identifying and quantifying heavy metals and other pollutants at trace levels, capable of meeting the requirements of Resolutions CONAMA No. 357, 396, and 430. Despite the high acquisition and maintenance costs, the equipment demonstrates strong technical and economic feasibility, particularly when supported by institutional partnerships and external funding sources. The implementation of the ICP-OES at LAAE will enhance custody chain procedures, expand the laboratory's technical capacity, and establish Goiás as a reference in environmental forensics in Brazil. It is concluded that investing in the ICP-OES will not only meet the growing demand for precise analyses but also contribute to holding offenders accountable and mitigating environmental impacts.

Keywords: ICP-OES. Environmental forensics. Water pollution. Environmental crimes. CONAMA Resolutions.

RESUMO

Este trabalho aborda a viabilidade técnica, econômica e operacional da implementação do Espectrômetro de Emissão Óptica com Plasma Indutivamente Acoplado (ICP-OES) no Laboratório de Análises de Águas e Efluentes (LAAE), vinculado à Superintendência de Polícia Técnico-Científica de Goiás (SPTC/GO). A pesquisa enfatiza a importância da perícia ambiental para a produção de provas técnicas relacionadas a crimes de poluição hídrica e outras infrações ambientais. O trabalho também explora a viabilidade estratégica de captação de recursos institucionais e privados para a implementação do equipamento. O estudo foi conduzido por meio de uma abordagem qualitativa, com revisão bibliográfica e análise documental, além de consultas a estudos de caso e literatura técnica. Os resultados indicam que o ICP-OES é uma ferramenta indispensável para identificar e quantificar metais pesados e outros poluentes em níveis traços, sendo capaz de atender aos requisitos das Resoluções CONAMA nº 357, 396 e 430. Apesar do custo elevado de aquisição e manutenção, o equipamento apresenta alta viabilidade técnica e econômica, especialmente quando associado a parcerias institucionais e fontes externas de financiamento. A implementação do ICP-OES no LAAE aperfeiçoará os procedimentos da cadeia de custódia, ampliará a capacidade técnica do laboratório e consolidará Goiás como referência na perícia ambiental no Brasil. Conclui-se que, o investimento no ICP-OES não apenas atenderá à crescente demanda por análises precisas, mas também contribuirá para a responsabilização de infratores e a mitigação dos impactos ambientais.

Palavras-chave: ICP-OES. Perícia ambiental. Poluição hídrica. Crimes ambientais. Resoluções CONAMA.

RESUMEN

Este trabajo aborda la viabilidad técnica, económica y operativa de la implementación del Espectrómetro de Emisión Óptica con Plasma Inductivamente Acoplado (ICP-OES) en el Laboratorio de Análisis de Aguas y Efluentes (LAAE), vinculado a la Superintendencia de Policía Técnico-Científica de Goiás (SPTC/GO). La investigación resalta la importancia de la pericia ambiental para la obtención de pruebas técnicas relacionadas con delitos de contaminación hídrica y otras infracciones ambientales. El trabajo también explora la viabilidad estratégica de obtener recursos institucionales y privados para la implementación del equipo. El estudio se llevó a cabo mediante un enfoque cualitativo, con revisión bibliográfica y análisis documental, además de consultas a estudios

de caso y literatura técnica. Los resultados indican que el ICP-OES es una herramienta indispensable para identificar y cuantificar metales pesados y otros contaminantes en niveles traza, siendo capaz de cumplir con los requisitos de las Resoluciones CONAMA nº 357, 396 y 430. A pesar del elevado costo de adquisición y mantenimiento, el equipo presenta una alta viabilidad técnica y económica, especialmente cuando se asocia con alianzas institucionales y fuentes externas de financiamiento. La implementación del ICP-OES en el LAAE perfeccionará los procedimientos de la cadena de custodia, ampliará la capacidad técnica del laboratorio y consolidará a Goiás como referente en pericia ambiental en Brasil. Se concluye que la inversión en el ICP-OES no solo atenderá la creciente demanda de análisis precisos, sino que también contribuirá a la responsabilización de los infractores y a la mitigación de los impactos ambientales.

Palabras clave: ICP-OES. Pericia ambiental. Contaminación hídrica. Delitos ambientales. Resoluciones CONAMA.

INTRODUCTION

Environmental crimes, like all other crimes, leave traces and evidence. In cases of water pollution, it is no different. Heavily polluted water sources are a common problem across all federal units of Brazil, affecting both major capitals and the watercourses that run through small towns (Morrison; Murphy, 2006). However, the mere discharge of effluents into a water body does not, in itself, constitute a criminal act. For an environmental crime to exist, the discharge must occur outside the limits set by laws and regulations, such as those outlined in CONAMA Resolution No. 357/2005, which establishes the conditions and standards for effluent discharge (National Environmental Council, 2005), and in the Environmental Crimes Law (Brazil, 1998).

Therefore, during criminal investigations of water pollution cases, the occurrence of the crime cannot be determined solely through visual observation by the forensic expert. In order to investigate and substantiate the potential crime, it is necessary to collect samples for laboratory analysis. This enables verification and measurement of parameters indicating the quality of the water and effluents, thus allowing one to determine whether a specific discharge is occurring outside the legal parameters and constituting an environmental offense.

In 2019, the Water and Effluent Analysis Laboratory was inaugurated at the Leonardo Rodrigues Institute of Forensics in Goiânia, Goiás, becoming a pioneer among Forensic Institutes in Brazil. This laboratory represents a milestone in environmental forensics, providing the necessary infrastructure to substantiate evidence in water pollution crimes and establishing Goiás as a national reference in the field (Goiás, 2019; A Redação, 2019).

The expansion of environmental crime and its devastating impacts on water resources demand increasingly swift, effective, and scientifically grounded responses from public institutions

such as the Technical-Scientific Police Superintendency of Goiás (SPTC-GO). In light of this, the present work proposes an in-depth analysis of the feasibility of implementing the Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) in the Water and Effluent Analysis Laboratory (LAAE) of the SPTC. The ICP-OES is a cutting-edge technology that would significantly enhance the laboratory's capacity for chemical analysis, enabling precise identification of contaminants in water and effluent samples and, thereby, providing robust technical evidence in water pollution cases. Its practical application would represent a major advancement in the strategic management of environmental forensics, directly benefiting the production of material evidence that supports the accountability of offenders and strengthens efforts to combat environmental crimes (Kemp et al., 2004).

This equipment is widely used in identifying pollutants linked to mining and industrial activities, contributing to the production of strong material evidence. According to Zhang, in China, for example, the equipment was used to map the distribution of heavy metals such as lead and mercury in areas near smelters. The results revealed high concentrations of these elements in both soil and water, exceeding environmental limits and highlighting the impact of human activities on environmental quality (Zhang et al., 2018). Furthermore, the ICP-OES has proven effective in identifying contamination sources, supporting mitigation measures and legal accountability.

In the United States, the Environmental Protection Agency (EPA) adopted the ICP-OES to assess contamination of sediments and soils in industrial areas, revealing the presence of arsenic and cadmium in critical concentrations. These analyses were fundamental in establishing a causal link between industrial activities and environmental damage, reinforcing legal actions and public policies aimed at environmental protection (Arroyo et al., 2010).

Implementing the ICP-OES in the Water and Effluent Analysis Laboratory (LAAE), part of the Technical-Scientific Police Superintendency of Goiás (SPTC/GO), will bring significant advancements to environmental forensics in the state. The equipment will allow for the analysis of contaminated water samples, identifying pollutants such as heavy metals often associated with mining and the intensive use of agrochemicals in agriculture. Such contamination not only affects biodiversity but also poses serious risks to human health—for instance, the bioaccumulation of mercury in food chains, which can lead to severe neurological damage (Egger et al., 2021; Nain et al., 2020).

The use of Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) in environmental investigations in Brazil has proven to be an essential tool for identifying and quantifying pollutants in the context of environmental crimes. In a study conducted in the state of São

Paulo, the equipment was employed to analyze contaminated soils and sediments in a region affected by industrial discharges. The results identified high levels of heavy metals such as lead (Pb), cadmium (Cd), and mercury (Hg), with concentrations exceeding the limits established by Brazilian environmental regulations, as outlined in CONAMA Resolution No. 357 (Brazil, 2005).

The analytical precision of the ICP-OES enabled the spatial mapping of contaminants, highlighting the most affected areas and the likely sources of pollution. This approach provided technical support for the preparation of robust forensic reports, which were used as scientific evidence in legal proceedings and in the formulation of environmental remediation measures (Arroyo et al., 2010). The investigation illustrated how the use of advanced technologies strengthens the capacity of environmental enforcement agencies and contributes to holding offenders accountable.

Another significant example was recorded in Minas Gerais, where the ICP-OES was used to analyze groundwater contaminated by waste from mining activities. The investigation revealed critical concentrations of arsenic (As), a highly toxic element, demonstrating the severity of environmental damage caused by the improper disposal of mining residues. The data obtained were fundamental in guiding environmental compensation efforts and reinforcing inspection measures in mining regions, consolidating the role of the ICP-OES as an indispensable instrument in environmental forensics (Arroyo et al., 2010).

These cases underscore the importance of the ICP-OES in detecting pollutants associated with highly complex environmental crimes. By allowing the identification of elements at minimal concentrations, the equipment significantly contributes to the production of technical evidence that supports legal proceedings and environmental mitigation efforts. Its application in the Brazilian context reinforces the urgent need to modernize forensic laboratories, especially in states like Goiás, where expanding technological infrastructure is essential to meet the growing demand for environmental investigations.

Within this context arises the central question guiding this study: Is there technical, operational, and economic feasibility for the implementation of ICP-OES in the LAAE-SPTC/GO? Introducing this equipment requires a careful analysis of its benefits and the challenges involved, both from the perspective of existing infrastructure and the investment required for its operation. Moreover, the study seeks to understand the potential impact that adopting this technology would have on the quality of environmental forensic work and the responsiveness of institutions. Accordingly, the general objective of this article is to understand the challenges and potentials associated with the implementation of ICP-OES in the LAAE. To that end, specific objectives were defined, including: assessing the strategic need to invest in advanced technologies for the production

of forensic evidence; describing the physical and organizational structure of the LAAE and the adjustments it requires; and examining the technical and financial feasibility of installing the ICP-OES in the institution (Tochetto, 2017).

Given the complexity and severity of environmental crimes, environmental forensics emerges as an indispensable instrument for producing technical evidence and ensuring the accountability of offenders. It stands out as a crucial field of study for promoting justice and environmental protection, while reducing the prevailing sense of impunity in society.

The relevance of this study is evident on academic, social, and economic levels. Academically, the scarcity of research focused on the application of technologies such as ICP-OES in environmental forensics highlights the need for a pioneering analysis of its impact on environmental crimes. Socially and economically, the implementation of more precise and advanced technologies in water pollution forensics offers benefits that go beyond the criminal sphere: by providing robust evidence, the institution not only strengthens environmental protection but also contributes to public health and the economy, mitigating the damage caused by water contamination (Pereira et al., 2022; United Nations Environment Programme, 2018). Additionally, the absence of consistent evidence in environmental crimes is often the reason cases are dismissed during the final stages of legal proceedings. This contributes to the perpetuation of a cycle of impunity, undermining environmental security and encouraging the recurrence of such crimes.

To carry out this research, a qualitative approach with a deductive method was adopted, based on bibliographic and documentary reviews, as well as the analysis of secondary data. This method allows for an in-depth exploration of the implications of implementing ICP-OES within the forensic context of the State of Goiás. Gil (2002) and Lakatos and Marconi (2003) emphasize that qualitative analysis is essential for exploratory studies such as this, where understanding the technical and financial factors requires a detailed examination of data and previous experiences in the field of environmental forensics.

The structure of this article is organized as follows: the first chapter discusses new technologies and resource management to support technical and forensic evidence, highlighting the importance of investing in environmental forensics and the financial challenges involved. The second chapter examines the organizational and technical structure of the LAAE, addressing its capacity and the adjustments required to operate the ICP-OES. The third chapter presents a detailed analysis of the functioning and applications of the ICP-OES in environmental crimes, considering its economic feasibility and potential impact on the effectiveness of forensic procedures. These elements are

interconnected to provide an integrated analysis of the implementation of the ICP-OES, offering a solid foundation for future decision-making in the field of environmental forensics in Goiás.

1 THE IMPORTANCE OF NEW TECHNOLOGIES AND RESOURCE MANAGEMENT IN THE PRODUCTION OF ENVIRONMENTAL FORENSIC EVIDENCE

Criminal forensics plays an essential role in the elucidation of crimes, as it is responsible for producing technical evidence that guides investigations and ensures the accountability of offenders. However, the high cost and complexity of forensic processes present a constant challenge for the institutions that make up the criminal justice system. According to data from the National Secretariat of Public Security (SENASP), investments in forensics in Brazil have been limited, which compromises both the modernization capacity and the performance of forensic institutes. The lack of resources directly affects the implementation of new technologies—tools that are essential to making forensic work more precise and efficient (SENASP, 2020).

Technologies applied in the forensic field have advanced significantly in recent decades, with the development of sophisticated equipment capable of performing detailed chemical and biological analyses, as well as detecting and quantifying substances with great accuracy. Instruments such as the Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) represent a technological leap, as they enable the analysis of traces with high sensitivity, facilitating the identification of contaminants in cases of environmental pollution and providing robust evidence to support criminal prosecution. According to SENASP, the use of advanced technology in forensic work is a determining factor for the effectiveness of criminal investigations—especially in environmental crimes, where evidence is often difficult to detect without the use of sophisticated laboratory methodologies (SENASP, 2019).

However, the implementation of new technologies requires substantial investment, not only in the acquisition of equipment but also in the training of professionals who operate them. Forensics is a highly specialized field, and the improper use of technologies can compromise the integrity of evidence and the accountability process. In addition to the initial installation and operation costs, there are ongoing expenses related to equipment maintenance and the replacement of specific supplies, such as reagents and laboratory consumables, which increase the operational costs of forensic units.

It is also important to consider the operational costs of the ICP-OES as part of the planning process for its implementation. Regular maintenance of the equipment—which includes calibrations

and the replacement of critical components—may range between R$30,000.00 and R$50,000.00 per year, depending on usage intensity (Thermo Scientific, 2024). Moreover, the use of high-purity argon, which is essential for plasma generation, has an average cost of R$800.00 per cylinder, with the frequency of replacement depending on analytical demand. Other consumables, such as chemical reagents for specific analyses, add approximately R$10,000.00 annually to the budget. These figures reinforce the need for detailed budget planning and institutional partnerships to ensure the long-term operation of the equipment.

The integration of advanced technologies and the continuous training of forensic experts is an essential element for maximizing the impact of new tools in the field of environmental forensics. Introducing equipment such as the ICP-OES requires not only technical knowledge for its operation but also analytical skills for interpreting the results. This training must be dynamic, keeping pace with technological updates and the evolving demands of investigated cases. In the context of Goiás, where the LAAE plays a strategic role, specific training could include methodologies for the analysis of heavy metals, as well as practical simulations of the equipment's use in real cases of water pollution and environmental crimes.

In Brazil, environmental forensics has become an increasingly relevant field, given the intensification of environmental crimes and the growing demand for proper accountability of offenders. However, the resources available for this area remain limited, and few forensic institutes have adequate infrastructure to conduct water and effluent analyses. The Water and Effluent Analysis Laboratory (LAAE) in Goiás, for example, is one of the few initiatives in the country dedicated to substantiating water pollution crimes. Nevertheless, even with its current structure, the LAAE still lacks investment in advanced technologies such as ICP-OES, which would allow for more detailed analyses and provide more precise technical evidence (Goiás, 2019).

Goiás faces significant challenges related to environmental crime, particularly water pollution stemming from industrial and agricultural activities, as well as improper disposal of solid waste. A study conducted in the judicial district of Rubiataba between 2012 and 2018 revealed that a large portion of environmental complaints were linked to the contamination of water bodies, highlighting the need for stronger enforcement and effective application of environmental laws (Sainça et al., 2021). The state of Goiás is home to a range of potentially polluting enterprises that, if mismanaged, could cause significant environmental contamination. Modernizing the LAAE by implementing the ICP-OES would enable not only the precise analysis of heavy metals and other pollutants but also increase the robustness of forensic reports, by allowing the assessment of a wider

range of environmental parameters. This would offer a deeper understanding of the extent of pollution and could even assist in determining the perpetrators of water pollution crimes.

Reports by SENASP emphasize the importance of equipping forensic laboratories with appropriate technologies, as environmental crimes—especially water pollution—leave complex traces that often require meticulous chemical analyses to be identified. Without modern equipment, the ability of forensic experts to produce conclusive reports is compromised, making it more difficult to hold polluters accountable and to protect the environment (SENASP, 2020; Goiás, 2019).

It is also worth emphasizing that having an adequately staffed team of forensic experts to meet the demands of environmental crimes in the state is of utmost importance. Financial resources alone are not enough if they are not accompanied by qualified human resources, which are fundamental to effective criminal forensics.

The use of new technologies in criminal forensics is increasingly necessary to keep pace with the sophistication of environmental crimes and to ensure that the evidence produced is scientifically sound and reliable. However, implementing advanced technologies such as the ICP-OES faces substantial financial challenges, given the high cost of such equipment and the complex procurement process, which requires careful budget planning and rigorous technical justification. According to SENASP (2020), the lack of allocated resources for the forensic field is one of the main barriers to the modernization of forensic institutes in Brazil. This situation creates disparities among states, where only a minority have the technical capacity to conduct sophisticated chemical analyses that are essential for proving crimes such as water pollution.

The high costs associated with forensics extend beyond the acquisition of equipment. Maintaining a state-of-the-art laboratory requires continuous investment in maintenance and updates, as well as the purchase of reagents and other specific supplies. The use of equipment like the ICP-OES demands complex laboratory infrastructure and highly trained professionals, since the analysis of environmental samples—especially water and effluents—involves rigorous procedures to ensure result accuracy. Investments in training are also necessary so that experts can operate the equipment efficiently and interpret results accurately, thus improving the quality of forensic reports and strengthening investigations.

In Brazil, the lack of infrastructure in forensic laboratories prevents many regions from having access to appropriate technologies for analyzing pollutants in water bodies. The implementation of equipment such as the ICP-OES in the Water and Effluent Analysis Laboratory (LAAE) in Goiás, for instance, could consolidate the state as a national reference in the production of forensic evidence in water pollution crimes. This laboratory, inaugurated in 2019, was a pioneer

in its category but still lacks cutting-edge equipment to expand its analytical capacity and meet the growing demand for material evidence in environmental crime cases (Goiás, 2019). SENASP emphasizes that access to advanced technologies is essential for forensic reports to have scientific validity and to be used in judicial proceedings, ensuring that environmental offenders are held accountable and that environmental damage is effectively mitigated (SENASP, 2020).

Environmental forensics is particularly challenging due to the nature of the crimes it investigates. Unlike other types of offenses, where evidence may be visible or tangible, environmental crimes often leave traces that can only be detected through complex laboratory analyses. In the case of water pollution, for example, chemical substances discharged into water sources may not be visible to the naked eye but still pose a significant threat to the environment and public health. The introduction of technologies such as ICP-OES would enable the accurate identification and quantification of heavy metals, organic compounds, and other contaminants, providing compelling evidence to support the fight against such crimes. According to the United Nations, the contamination of water bodies is one of the main causes of environmental degradation and requires a rapid, science-based response to be effectively addressed (United Nations Environment Programme, 2018).

Despite its importance, the implementation of new technologies in environmental forensics still faces resistance due to high costs and the lack of public policies prioritizing the strengthening of forensic infrastructure. According to SENASP, one of the greatest challenges is aligning the public budget with the specific needs of the forensic field, which is often considered secondary compared to other areas of public security. However, the production of reliable material evidence is one of the pillars of environmental justice, and neglecting this area undermines the State's ability to respond adequately to environmental crimes. Investing in environmental forensics is, therefore, not merely a matter of improving investigative efficiency, but also of ensuring that Goiás is prepared to face the challenges of a world where environmental protection is key to sustainability and the well-being of society.

Recent SENASP (2020) reports highlight that expert training is just as essential as equipment acquisition, as without adequate technical knowledge, technology becomes underutilized and the results of forensic work may be compromised. In states like Goiás, where the establishment of specialized laboratories already represents progress, the next step must be to ensure that these labs receive the financial and technical support necessary to operate at full capacity.

Environmental forensics, specifically concerning the analysis of water and effluents, demands robust infrastructure and equipment capable of identifying a wide range of contaminants. The lack of investment in this area not only limits the scope of investigations but also allows crimes

with significant environmental impacts to go unpunished, harming sustainable development and the population's quality of life.

The use of new technologies in criminal forensics is increasingly necessary to enable the identification of perpetrators responsible for illegal discharges or environmental contamination. Technologies such as ICP-OES make it possible to identify and quantify compounds, allowing the characterization of the source of contamination and the determination of whether it is consistent with mining activities or certain chemical industries. This greatly facilitates the investigative process and the substantiation of criminal evidence, which often relates to public health risks.

Environmental crimes can sometimes affect large numbers of people simultaneously. Unlike a homicide, an environmental crime can impact the entire population of a city—such as in the case of contamination of the only water source available for public supply.

In this sense, it is imperative that the State has the capacity to detect water pollution crimes, which are not visible to the naked eye. A laboratory structure equipped with cutting-edge technology is essential to ensure that no crime goes unnoticed and to guarantee that crimes are substantiated, properly judged, and environmental damage restored.

Some of the country's most important mineral reserves are located in the State of Goiás. As a result, there are a considerable number of activities forming part of the productive chain in this sector. According to the Mineral Sector Diagnostic Report of the State of Goiás, the state contains 9.25% of Brazil's gold reserves (in the Crixás region), 12.8% of titanium reserves (Catalão region), 72.98% of nickel, 98.14% of cobalt, among others (Goiás, 2002).

In addition to these reserves, Goiás has a highly diversified mineral production, with six enterprises occupying key positions in the national production chain. Goiás's national share by mineral type includes: asbestos – 99%, nickel – 65%, niobium – 40%, phosphate – 30%, vermiculite – 20% (Goiás, 2002). These figures demonstrate the State's important and significant role in Brazil's mineral landscape.

Given the extent of mining activities, environmental crimes are to be expected due to poor management of certain operations, tailings dam failures, among countless other possibilities. In this context, it is essential that the State possesses the necessary infrastructure to properly substantiate environmental crimes occurring in these areas, with the aim of upholding the right to a balanced environment and ensuring justice and public security in Goiás.

The absence of forensic reports is often the reason why criminal cases are dismissed, reinforcing a sense of impunity and potentially increasing the incidence of environmental crimes—generating consequences not only for the environment but also for public health.

To illustrate, consider the case that occurred in 2022 in Campos Verde, Goiás. The severe contamination of the Rio dos Bois in that municipality revealed an alarming scenario of environmental and human impact attributed to mining operations in the region. Technical reports identified high levels of heavy metals in water intended for public consumption, leading to serious illnesses among the population, including cancer diagnoses. In addition to the death of fish stocks that compromised food security, more than 100 families faced difficulties accessing potable water. Despite court orders mandating mitigation measures—such as toxicological analyses of the population and emergency actions—the mining company responsible denied liability, highlighting the complexity of determining the source of contamination in a region naturally rich in minerals (Metrópoles, 2022).

For Brazilian forensic institutes to fulfill their role in environmental protection, it is essential that there be a continuous commitment to modernizing infrastructure and training personnel. Environmental forensics requires not only equipment such as the ICP-OES, but also trained professionals capable of conducting precise analyses and interpreting scientific results rigorously.

2 THE LABORATORY FOR WATER AND EFFLUENT ANALYSIS (LAAE) AND THE EXPANSION OF ENVIRONMENTAL FORENSICS IN GOIÁS

The Laboratory for Water and Effluent Analysis (LAAE), implemented in 2019 at the Leonardo Rodrigues Institute of Forensics (ICLR) in Goiânia, Goiás, marked a turning point in environmental criminal forensics in Brazil. Initially developed as a final project of the CEGESP (Public Security Management Program – UEG/SSP), the laboratory became a reality thanks to resources provided by the Public Prosecutor's Office and the Environmental Operational Support Coordination Office (CAO) (Goiás, 2019; Linhares et al., 2024). Its implementation aimed to meet the growing demand for laboratory analyses that would ensure the materialization of environmental crimes, strengthening the chain of custody[3] and the credibility of the evidence presented (Linhares et al., 2024).

Before the creation of the LAAE, chemical analyses relied on external institutions—a process that often compromised the chain of custody and the quality of the evidence obtained. According to Linhares et al. (2024), the inauguration of the LAAE solved part of these problems by

[3] The chain of custody refers to the set of documented procedures that ensure the control, traceability, and integrity of material evidence from its collection to its presentation in court, being essential for the legal validity of forensic evidence (BARBOSA, 2023).

enabling detailed and reliable analyses to be carried out within the state itself, ensuring the integrity of the chain of custody.

Furthermore, environmental forensics has been gaining importance in Goiás, following the growing public awareness of the need for environmental protection. However, it still faces challenges, mainly related to the lack of investment in infrastructure and human resources (SENASP, 2020). This gap directly impacts the state's ability to respond to the increasing demand for environmental investigations, which has grown significantly in recent years (Goiás, 2019).

Currently, the LAAE staff consists of two forensic experts, one administrative assistant, and one glassware cleaning assistant—a workforce clearly insufficient to meet the growing demand (Linhares et al., 2024). The laboratory's physical structure includes two main rooms where physicochemical and microbiological analyses are conducted, as well as a room for preparing forensic reports. The tests include parameters such as Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), total coliforms, *Escherichia coli*, and settleable solids (Linhares et al., 2024). Recently, analyses for nitrite, nitrate, and ammoniacal nitrogen have also been incorporated.

Despite this progress, the LAAE's current technical capacity is still insufficient to handle all cases with the necessary agility. According to SENASP (2020), the introduction of more advanced equipment, such as the Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES), could significantly expand the range of analyses performed and enhance the quality of evidence presented in criminal investigations. However, acquiring such equipment requires not only substantial financial investment but also specific technical training for the professionals involved.

Among LAAE's strengths is the fact that it is the first laboratory in the country to conduct water and effluent analyses with an exclusive focus on criminal investigations. This feature gives the laboratory a prominent position nationally and reinforces the credibility of its forensic work (Linhares et al., 2024). Additionally, the use of internationally recognized methodologies, such as those described in *Standard Methods for the Examination of Water and Wastewater*, ensures the accuracy of results and increases confidence in the issued reports (Hammer; Viessman, 2005).

However, limitations persist, including the lack of advanced equipment and the small number of qualified personnel. These shortcomings restrict the LAAE's ability to expand operations and handle more complex cases (Linhares et al., 2024). According to SENASP (2020), the lack of continuous investment in infrastructure and personnel compromises not only the laboratory's efficiency but also its long-term sustainability.

To reach its full potential, the LAAE must receive significant investments in infrastructure modernization and professional training. The implementation of new equipment, such as the ICP-

OES, would not only expand the laboratory's analytical capacity but also solidify Goiás as a national reference in environmental forensics (Linhares et al., 2024; SENASP, 2020). Moreover, obtaining laboratory certification under international standards, such as ISO 17025, would be a crucial step toward increasing the reliability of its forensic reports (Hammer; Viessman, 2005).

The expansion of the LAAE also requires greater coordination with environmental agencies and strategic partnerships for resource mobilization. Such initiatives would not only improve the quality of services provided but also support the creation of a sustainable management model aligned with international best practices.

3 ICP-OES AND ITS APPLICATIONS IN ENVIRONMENTAL FORENSICS

The Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) is widely recognized for its ability to perform highly sensitive and precise elemental analyses. It enables the detection and quantification of environmental parameters. In the case of the Laboratory for Water and Effluent Analysis, the equipment would be acquired with the necessary configuration to comply with CONAMA Resolutions No. 357, No. 430, and No. 396, with the aim of determining whether a sample collected at a suspected environmental crime scene exceeds the limits established by these resolutions, thus constituting an environmental crime under Law No. 9.605/98.

The State of Goiás has intense mining, agro-industrial, and industrial activity. This type of equipment would allow for the detection of environmental crimes and, in many cases—depending on the type and method of field sampling—even make it possible to link pollution in a specific water body to the discharge of effluents from a particular type of activity. This is because the ICP-OES enables both precise identification and quantification of substances.

3.1 ICP-OES as an Instrument for Promoting Justice

Using a high-temperature argon plasma, this equipment excites atoms and ions present in the samples, resulting in the emission of light characteristic of each chemical element. This analytical approach allows for the simultaneous detection of multiple elements at concentrations as low as parts per billion (ppb), with superior efficiency in terms of speed and accuracy compared to traditional methods (Milestone, 2024; Thermo Scientific, 2024).

In the context of environmental forensics, ICP-OES plays a crucial role in identifying contaminants such as heavy metals, which are among the most hazardous pollutants to human health and the environment. Its importance in environmental analyses lies in its ability to detect elements at trace levels, a common requirement in environmental investigations and criminal forensics. Once

configured to meet the requirements of CONAMA Resolutions No. 357, 396, and 430, the LAAE will be equipped to accurately identify and quantify elements such as mercury, lead, cadmium, arsenic, among others, typically present in industrial and mining activities (Brasil, 2005).

ICP-OES is widely used to investigate environmental crimes involving water pollution, particularly in regions affected by mining and industrial activities. In a study conducted in abandoned gold mining areas, contamination of soil and water by mercury and lead—elements associated with mineral extraction processes—was detected. Samples analyzed with ICP-OES revealed concentrations above legal limits, highlighting both environmental impact and public health risks (Dhayalan; Saraswathi; TV, 2024). Documented cases in China demonstrated how ICP-OES was used to map the spatial distribution of heavy metals, including mercury, in lead smelting regions. This study showed how pollution from industrial activities accumulated in the soil and water, causing severe ecological damage and posing direct risks to local communities (Zhang et al., 2018).

In Brazil, similar cases have been identified in illegal mining operations, where the indiscriminate use of mercury for gold extraction has caused serious damage to the Amazon's river ecosystems.

In southeastern Goiás, studies have shown how mining activities have contributed to the contamination of water bodies with heavy metals such as lead and mercury. These substances were found in concentrations exceeding legal limits, harming aquatic fauna and local ecosystems (Vaz et al., 2016). ICP-OES would allow for a detailed analysis of these contaminants, enabling the production of robust scientific evidence to hold offenders accountable and support environmental remediation efforts (Thermo Scientific, 2024).

The environmental and health impacts associated with mining and pesticide use are significant. In the case of mercury—a common pollutant in gold mining—its bioaccumulation in food chains poses a serious threat to riverine communities that rely on fish as a primary source of protein. This heavy metal is associated with neurological damage and chronic illnesses in humans (Egger et al., 2021).

Also common in the state of Goiás is the development of activities such as tanneries, which, if poorly managed, can lead to environmental contamination by hexavalent chromium—a metal toxic to humans, animals, plants, and microorganisms (Kimbrough et al., 1999, apud Ferreira, 2011). The ICP-OES, when configured to comply with CONAMA Resolutions No. 357, 396, and 430, can be used to analyze elements such as chromium, phosphorus, sulfur, mercury, and arsenic, providing reliable data for environmental investigations and supporting legal actions (Brasil, 2005; Milestone, 2024).

These analyses are essential for the substantiation of environmental crimes, offering robust technical data that can serve as evidence in legal proceedings. For example, studies indicate that the analysis of elements such as arsenic and cadmium—frequently found in industrial waste—is crucial for holding polluters accountable and for proposing mitigation measures (Brasil, 2005; Milestone, 2024).

The presence of heavy metals in the environment poses a significant threat to human health. Mercury, for instance, is well known for its toxicity and its ability to bioaccumulate in food chains, especially affecting riverine populations that rely on contaminated fish as their main source of protein. Research shows that prolonged exposure to mercury can cause irreversible neurological damage and increase the risk of chronic diseases (Zhang et al., 2018; Milestone, 2024).

In the agricultural sphere, the use of pesticides containing heavy metals not only compromises soil and water quality but also directly affects biodiversity. Studies have demonstrated that pollution by these elements is linked to the reduced regenerative capacity of natural ecosystems, particularly in Cerrado regions with intensive agricultural activity (Lima-Junior et al., 2024).

From an environmental standpoint, heavy metal pollution undermines the quality of water resources, reduces aquatic biodiversity, and impacts ecosystem services. Implementing ICP-OES at the LAAE will allow for a more effective response to these challenges, expanding the range of parameters analyzed by the laboratory and thus improving the detection of various forms of contamination and environmental crimes.

3.2 On Technical and Economic Feasibility and Usage Perspectives

Although the initial cost of the equipment and the required laboratory adaptations is high (approximately R$ 1,850,000.00), the economic feasibility of the project can be ensured through institutional partnerships, such as those with the Public Prosecutor’s Office and environmental agencies. Moreover, the use of ICP-OES will reduce dependence on external laboratories, thereby saving resources and speeding up criminal investigations (Thermo Scientific, 2024).

In addition to the equipment itself, it will be necessary to acquire consumables, such as high-purity argon gas (≥4.5), and invest in periodic preventive maintenance. The project will also require upgrades to the electrical infrastructure, including the installation of a dedicated uninterruptible power supply (UPS) and exclusive outlets, as well as physical modifications to the laboratory, such as reinforcing the workbench to support the equipment's weight (Milestone, 2024).

Partnerships with government bodies and institutions such as the Public Prosecutor’s Office may assist in financing the project. These collaborations not only make the acquisition of the

equipment feasible but also strengthen institutional integration and promote transparency in the use of public funds (Thermo Scientific, 2024).

The use of ICP-OES will also enhance chain-of-custody procedures and increase the credibility of evidence presented in judicial proceedings. This will be especially relevant in high-profile cases, such as environmental disasters resulting from dam failures or the illegal discharge of industrial effluents.

Thus, the installation of the ICP-OES at the LAAE will represent a significant leap in the quality of environmental forensics conducted in Goiás. Currently, the laboratory's capabilities are limited to less complex analyses, hindering its ability to respond effectively to severe water pollution crimes. The introduction of this equipment will enable detailed analysis of heavy metals and other trace elements, increasing the laboratory's efficiency and strengthening the credibility of the expert reports issued (Milestone, 2024).

Furthermore, this technology will improve chain-of-custody protocols by reducing the need to send samples to external laboratories. This not only ensures faster results but also minimizes the risks of contamination and loss during transport (Thermo Scientific, 2024). The technical training of forensic experts to operate the ICP-OES will be essential to maximize the benefits of the new technology and to ensure the accuracy of the forensic reports.

4 CONCLUSION

The Implementation of the Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) at the Laboratory for Water and Effluent Analysis (LAAE) of the Scientific-Technical Police of Goiás will represent a significant technical and scientific advancement in addressing environmental crimes in the State. By enabling the identification and quantification of heavy metals at trace levels, this equipment will provide essential technical support for the production of robust and reliable forensic reports—indispensable elements to strengthen inspection efforts and ensure the accountability of offenders. Such modernization consolidates the relevance of environmental forensics as a central tool in the promotion of justice and the protection of natural resources.

As discussed throughout this paper, the modernization of the LAAE not only addresses the growing demand for more precise environmental analyses, but also aligns with the strategic objectives of public security. The introduction of technologies such as the ICP-OES reinforces the institutional capacity to meet the demands of criminal investigations, allowing for a faster and more effective response in the fight against environmental crime. In this regard, it is concluded that the

modernization of the LAAE is an essential strategy to ensure the effectiveness of public policies for environmental protection and to promote sustainable development in the state of Goiás.

Among the short- and medium-term goals highlighted in this study, the importance of forming institutional and cross-sectoral partnerships stands out as one of the pillars for enabling the implementation of the ICP-OES. These partnerships—potentially involving the Public Prosecutor's Office and universities—will contribute both to the initial funding and to the technical support required for operating the equipment. Furthermore, the ongoing training of forensic experts must be prioritized to ensure that the new technologies are used to their full potential, optimizing the production of technical and scientific evidence.

The objectives outlined throughout this work—including the assessment of the technical, operational, and economic feasibility of implementing the ICP-OES, as well as the description of the necessary structure for its installation—have been addressed through qualitative and documental analysis. The evidence presented demonstrates that, despite financial and logistical challenges, the acquisition of the equipment is both feasible and essential to overcome the current limitations of the LAAE. Moreover, it is concluded that the integration of advanced technologies, such as the ICP-OES, with efficient resource and infrastructure management is the most effective path to confront the complex environmental crimes affecting Goiás.

Finally, the technological modernization of the LAAE is not merely about improving forensic techniques—it is a commitment to environmental preservation, to holding offenders accountable, and to promoting sustainable development. By strengthening the Rule of Law and ensuring the protection of natural resources, the modernization of the laboratory also positions Goiás as a national reference in environmental forensics, reaffirming the importance of investing in science as a pillar in the fight against crime and in building a more just and environmentally conscious society.

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