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The role of bioindicator plants in environmental forensics: Potential applications for detecting heavy metal pollution in agricultural landscapes

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ABSTRACT

Background: Heavy metal contamination in Indonesian agricultural lands poses serious risks to ecosystem stability, food security, and public health. Major sources include excessive application of chemical fertilizers and pesticides, as well as industrial and domestic waste. Bioindicator plants can detect heavy metal pollutants through absorption and accumulation in plant tissues. Integrating bioindicator approaches into environmental forensic studies may strengthen pollution detection and support sustainable land management. **Methods:** This study employed a literature review and secondary data analysis to examine the potential of bioindicator plants in supporting environmental forensic investigations of heavy metal contamination in agricultural soils. **Findings:** Common heavy metals identified in Indonesian agricultural lands include Pb, Cd, Zn, Cu, Fe, and Mn. Frequently studied bioindicator plants are Oryza sativa, Eichhornia crassipes, Ipomoea aquatica, Ficus benghalensis, and Pteris vittata. Existing national research primarily focuses on ecological monitoring and phytoremediation, while limited attention has been given to contamination tracing, source identification, standardized analytical methods, and integration with environmental forensic frameworks. This indicates significant methodological and conceptual gaps in applying bioindicator science for evidentiary and investigative purposes. **Conclusion:** Bioindicator plants have strong potential as scientific tools for detecting and tracing heavy metal contamination. Strengthening their integration into environmental forensic frameworks can enhance evidence-based pollution control and promote sustainable agricultural land management in Indonesia. **Novelty/Originality of this article:** This study systematically positions bioindicator plants within an environmental forensic framework, moving beyond conventional ecological monitoring toward contamination tracing and evidentiary assessment, thereby providing a conceptual foundation for more reliable pollution detection strategies.

KEYWORD: agricultural soils; bioindicator plants; environmental forensics; heavy metals; sustainable land management.

1. Introduction

Environmental pollution in agricultural land is a major issue closely related to ecosystem stability, food security, and public health. In 2023, the total area of agricultural land in Indonesia reached 7,384,341 hectares (Ministry of Agriculture of the Republic of Indonesia, 2024). Excessive use of chemical fertilizers and pesticides leads to the accumulation of heavy metals such as lead (Pb), cadmium (Cd), and mercury (Hg) in soil, water, and crops (Sukarjo et al., 2021). Elevated concentrations of these metals not only reduce soil fertility and degrade environmental quality but also pose potential long-term health risks to farmers, consumers, and surrounding animals (Da Silva et al., 2024). In

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addition, high concentrations of metals in soil can decrease crop productivity, inhibit plant growth, and reduce both yield and nutritional quality (Vasilachi et al., 2023).

The accumulation of metals in soil, water, and air may cause bioaccumulation and biomagnification, posing serious risks to both wildlife and humans. Such exposure can lead to neurological disorders, developmental problems, increased cancer risk, and various other health issues (Ogwu et al., 2025) as well as potential human health risks through the consumption of agricultural products (Khurana et al., 2024). Sources contributing to soil contamination and heavy metal accumulation include organic and inorganic fertilizers, pesticides, industrial discharges, urban waste, mining activities, and factory effluents (Dewi et al., 2023). Although nationwide data on heavy metal concentrations are not yet available for all regions of Indonesia, several local studies have reported contamination in agricultural areas such as Wonosobo, the Lower Serayu Watershed, and the Citarum River in West Java. Despite the growing awareness of heavy metal pollution, limited studies have explored the forensic relevance of bioindicator plants in Indonesia. Bridging this knowledge gap is essential to transform ecological data into credible environmental evidence.

Bioindicator plants serve as one of the primary methods for assessing heavy metal concentrations in the environment, including agricultural lands. An effective bioindicator possesses several essential characteristics, such as high sensitivity to environmental stressors, measurable responses to contamination levels, and ease of observation. The ecological traits of plants being stationary and capable of photosynthesis enable them to consistently reflect environmental conditions over time. Several species commonly used as bioindicators include *Ficus benghalensis* L., the moss *Hypnum cupressiforme*, and *Festuca arundinacea* (Fahmi et al., 2025). However, in Indonesia, bioindicator species are typically represented by rice (*Oryza sativa*), water hyacinth (*Eichhornia crassipes*), and water spinach (*Ipomoea aquatica*) to detect heavy metal contamination.

This approach aligns with the concept of environmental forensics, which applies scientific principles and investigative methods to evaluate, document, and legally attribute environmental damage (Roy, 2025). It utilizes scientific evidence to identify the sources, pathways, and impacts of contaminants within an ecosystem. The application of forensic botany in analyzing pollutants in agricultural lands can provide significant supporting evidence during contamination investigations; however, it remains underutilized (Oliveira et al., 2023).

The implementation of bioindicator-based methods in Indonesia within the context of environmental forensic studies can strengthen pollution detection strategies and promote sustainable land management. However, the availability of data related to heavy metal contamination in agricultural soils remains limited, and the potential of local plant species as bioindicators has not been extensively explored. Furthermore, environmental forensic studies that integrate plant-based biological approaches are still rarely conducted, resulting in the suboptimal use of ecological evidence. Therefore, this article aims to explore the role of bioindicator plants in supporting environmental forensic analyses of heavy metal contamination in agricultural lands across Indonesia.

2. Methods

2.1 Literature review approach

This study employed a narrative literature review with systematic elements to examine the role of bioindicator plants in detecting heavy metal contamination within the framework of environmental forensics, particularly in agricultural landscapes of Indonesia. This approach was selected to allow a structured synthesis of existing studies while accommodating the interdisciplinary nature of environmental, agricultural, and forensic research. It also enables the identification of research gaps and emerging trends in the application of bioindicator plants for environmental contamination assessment.

2.2 Data sources

Secondary data were obtained from peer-reviewed national and international scientific publications, as well as official reports and environmental statistics issued by governmental and institutional sources. The reviewed literature included original research articles, review papers, and authoritative reports addressing heavy metal contamination, bioindicator plants, phytoremediation, and environmental forensic applications in agricultural and terrestrial ecosystems. These sources were selected to ensure the reliability and scientific relevance of the information used in this study.

2.3 Search strategy

Literature searches were conducted using commonly used academic search engines and scientific database in environmental and agricultural science. The search strategy applied combinations of keywords such as “bioindicator plants”, “heavy metals”, “agricultural soil”, “environmental pollution” and “environmental forensics”. The reviewed literature primarily covers publications from 2020 to 2025, ensuring that the analysis reflects recent scientific developments while incorporating several earlier foundational studies where relevant. Literature searches were performed using major academic platforms and databases, including Google Scholar, ScienceDirect (Elsevier), and other peer-reviewed environmental and agricultural science journals. Due to the interdisciplinary nature of the topic, relevant sources were also identified across multiple scientific publishers and journal platforms, as indicated by the DOI links and references provided in this study. This approach was adopted to maximize the breadth of literature coverage and minimize source selection bias. Additional relevant study were identified through backward citation tracking to ensure comprehensive coverage of the research topic.

2.4 Inclusion and exclusion criteria

The inclusion criteria consisted of studies focusing on heavy metal contamination in soil, water, or plant systems; research involving bioindicator or hyperaccumulator plant species; studies conducted in agricultural or environmentally relevant landscapes; and publications providing qualitative or quantitative data relevant to contamination detection, accumulation mechanisms, or forensic interpretation. Studies that were not relevant to the environmental or agricultural context, lacked scientific credibility, or did not contribute to the objectives of this review were excluded. This selection process was intended to ensure the relevance, quality, and reliability of the reviewed literature.

2.5 Literature scope

Most of the reviewed publications were drawn from the last five years, while several earlier key references were retained to support fundamental concepts related to heavy metal accumulation mechanisms, bioindicator characteristics, and environmental forensic studies, particularly with respect to contamination patterns, plant response mechanisms, and commonly applied analytical approaches such as Concentration Factor (CF), Translocation Factor (TF), ecological risk indices, and stable isotope analysis. This combination of recent and foundational literature ensures both the relevance and theoretical depth of the study. It also allows for a more comprehensive understanding of the development and application of bioindicator-based approaches in environmental contamination research.

2.6 Data analysis

The collected information was analyzed using a descriptive and thematic synthesis approach. Descriptive analysis was used to summarize dominant heavy metals, commonly reported bioindicator species, and contamination trends, while thematic analysis was applied to identify methodological strengths, limitations, and the relevance of bioindicator plants for environmental forensic investigations. This methodological framework was designed to enhance transparency and support the analytical interpretation of bioindicator-based evidence in environmental contamination studies. Furthermore, it facilitates a systematic comparison across studies to identify consistent patterns and key insights.

3. Results and Discuccion

3.1 Heavy metal pollution in Indonesian agricultural lands

Environmental pollution caused by heavy metals in agricultural areas has become an increasingly important environmental issue in Indonesia. Intensive agricultural activities have led to greater use of chemical fertilizers and pesticides during crop cultivation, thereby affecting soil fertility, public health, and the quality of food consumed by the population. In 2024, the allocation of government-subsidized fertilizers increased to 9.55 million tons, following a significant decline in subsidy allocations between 2014 and 2018 (Ministry of Agriculture of the Republic of Indonesia, 2024). Moreover, one of the major challenges in improving horticultural crop production in Indonesia is the excessive use of pesticides, which can degrade the physical and chemical properties of the soil, increase environmental pollution levels, and contribute to pesticide residue accumulation (Directorate General of Horticulture, 2024).

Several local studies have indicated that portions of agricultural land in Indonesia are contaminated with heavy metals such as Pb, Cd, Co, Ni, Cu, Mn, Zn, As, and Fe. Research conducted (Sukarjo et al., 2021) reported that the concentration of heavy metals in the Lower Serayu Watershed (DAS Serayu Hilir) was generally classified as low contamination, with a Concentration Factor (CF) value of less than 1. However, cadmium (Cd) showed a high contamination level ($3 \le CF < 6$), primarily due to the presence of Cd in both organic and inorganic fertilizers. The analysis results indicated that although the overall concentration of heavy metals in the Lower Serayu Watershed remained below the critical threshold, the Ecological Risk Index for several samples in the area ranged from 0.01 to 121.29, with an average of 140.4 ± 42.1, suggesting a moderate to high ecological risk associated with metal contamination.

A study conducted in the industrial region of Sidoarjo Regency (Khasanah et al., 2021) also revealed contamination by heavy metals such as Zn, Pb, Hg, Cu, and Mn, with analysis results showing a moderate level of contamination based on the Concentration Factor (CF). In addition, contamination by Fe and Cd was categorized as high, although the overall potential risk value remained below 40, indicating a low-risk level. Research by Handayani et al., (2022) further concluded that the concentrations of heavy metals found in agricultural soils in the upper Citarum River ranged from 0.25 to 28.22, corresponding to low to very high contamination levels. The concentration of Cd reached 28.22, classified as very high, whereas Pb, Cr, and Ni remained below the critical threshold. However, Cd and Co concentrations exceeded the critical limits at several sampling sites. These findings indicate that a substantial portion of agricultural lands in Indonesia are contaminated with accumulated heavy metals.

Various studies in Indonesia, particularly in Java and Sumatra, have shown that Cd and Pb are the dominant contaminants. (McDowell & Gray, 2022) reported that the primary sources of Cd detected in their research originated mainly from the use of phosphate fertilizers and the parent materials of the soils themselves. Soil acidity is one of the key factors influencing the chemical behavior of metals lower soil pH values correspond to higher concentrations of heavy metals within the soil (Oktavian et al., 2024). The reccurent dominance of Cd and Pb across multiple agricultural studies suggest a contamination pattern strongly associated with long-term anthropoghenic inputs rather than isolated point sources. Compared to other trace metals, Cd and Pb exhibit higher mobility in fertilized and acidic soils, increasing their bioavailability and persistence in agricultural systems. From an environmental forensic perspective, the consistent presence of these metals may serve as an indicator for tracing fertilizer-derived contamination and historical land management practices.

Heavy metal contamination in soils poses potential ecological and health risks. Health problems that may occur include kidney damage, increased cancer risk, neurological and immune system disorders, as well as reproductive, cardiovascular, skeletal, dermatological, gastrointestinal, renal, and cerebral impairments (Silva et al., 2022). Physical, chemical, and biological components, including water, soil, plant species, and the amount of metal absorbed by plants, can collectively contribute to adverse health effects (Ugulu et al., 2023). Such contamination often results from poor land management practices and the excessive application of inorganic fertilizers (Danapriatna et al., 2024).

Although contamination levels in several regions are still relatively low, long-term accumulation and recurring patterns can significantly increase ecological and health risks. For instance, the Pb concentration in rice, reaching 0.54 mg/kg, has already exceeded the recommended threshold (Mustofa & Roosmini, 2024) and aligns with several previously reported findings. Furthermore, a study by Yap & Al-Mutairi (2022) conducted across five ASEAN countries, including Indonesia, indicated that heavy metal accumulation has persisted for many years. The distribution patterns of heavy metals in agricultural soils are often associated with agricultural activities and local geological conditions. These recurring patterns reflect the presence of ecological forensic traces that can be used to identify pollution sources (McDowell & Gray, 2022) and highlight the potential application of stable isotope analysis and ecological fingerprinting to trace contaminant origins (Li et al., 2025). This condition emphasizes the need for a sustainable ecological monitoring system, including the use of bioindicator plants as an early detection tool and as supporting evidence in environmental forensic investigations.

3.2 Bioindicator plant

Heavy metal contamination in agricultural land requires efficient monitoring methods to establish appropriate control strategies. One of the most widely applied approaches is the use of bioindicators organisms capable of reflecting the presence of pollutants through concentration levels, specific physiological symptoms, or morphological changes. An effective bioindicator possesses several key characteristics, such as high sensitivity to environmental stressors, measurable responses to contamination levels, and ease of observation. Both mosses and vascular plants are among the organisms commonly used as indicators of heavy metal pollution (Cakaj et al., 2023) including species such as water hyacinth (*Eichhornia crassipes*) and water spinach (*Ipomoea aquatica*). Given these conditions, bioindicator plants hold great potential for sustainable ecological monitoring systems, as they exhibit sensitive biological responses and an early detection capability for changes in environmental quality.

Several plant species in Indonesia also demonstrate a high capacity to accumulate heavy metals, making them strong candidates as bioindicators of heavy metal contamination in soil, water, and air. A literature study by (Mahardika & Amizera, 2025) concluded that plants capable of functioning as bioindicators possess distinct adaptive abilities that allow them to survive and respond effectively in polluted environments. Several studies conducted in Indonesia have shown that heavy metal cadmium (Cd) can be detected in rice (*Oryza sativa* L.) (Mustofa & Roosmini, 2024) and mustard greens (*Brassica juncea*) (Dewi et al., 2023) Lead (Pb) has been found in aquatic plants such as *Typha angustifolia*, water spinach (*Ipomoea aquatica*), water hyacinth (*Eichhornia crassipes*) (Syafriliansah & Purnomo, 2022), as well as in ferns (*Pteris vittata*) (Gafur et al., 2022) and herbal species such as *Dryopteris* sp., *Calopogonium mucunoides*, and *Peperomia pellucida* (Muryani et al., 2025). A study by (Wang et al., 2022) in Singapore reported twelve tropical plant species with strong potential as bioindicator plants, which also play significant roles in phytoremediation processes (Durante-Yánez et al., 2022), as presented in table 1 below.

Study by (Zunaidi et al., 2023) on six vegetable species in agricultural lands of Brunei Darussalam (Amaranthus viridis L., Basella alba L., Brassica chinensis, Brassica rapa L., Capsicum frutescens L., and Ocimum tenuiflorum L.) reported that all of these species function as hyperaccumulators of Co, Cd, Zn, and Ni based on Metal Transfer Factor (MTF) analysis. The heavy metal contents detected in these plants indicate their ability to absorb, accumulate, and store metals within their tissues. This finding highlights the potential use of these plant species as bioindicators for monitoring heavy metal contamination in agricultural environments.

Table 1. Potential tropical bioindicator plants

Heavy metal	Plant species
As	*Ptetis vittata*
	Nephrolepis bisserata
Cd	*Tridax procumbens*
	Centella asiatica
	Axonopus compresseus
	Asystasia gangetica
Cu	*Fatou Pilosa*
	Syzygium grande
Mo	*Axonopus compressus*
	Hemigraphis reptans
	Desmodium sp.
	Mukia maderaspatana
Pb	*Dicranopteris linearis*
	Fatoua Pilosa
	Asystasia gangetica
Sb	*Fatoua Pilosa*
	Axonopus compressus
Zn	*Fatoua Pilosa*
	Asystasia gangetica

(Wang et al., 2022)

Bioindicator plants can be classified as either hyperaccumulators or non-accumulators. Hyperaccumulator plants are capable of storing heavy metals in their tissues at high concentrations without exhibiting toxicity symptoms (Nedjimi, 2021), whereas non-accumulator plants reflect environmental contamination through morphological or physiological changes (Mohamed et al., 2025). Some naturally occurring plant species possess distinct hyperaccumulative characteristics, enabling them to translocate large quantities of heavy metals and store them in stem or leaf tissues, with concentrations that may exceed 1,000 ppm. In contrast, non-accumulator plants can tolerate heavy metal levels of no more than 10 ppm (Nedjimi, 2021). Understanding this distinction is crucial, as both plant types play significant roles in the ecological detection of heavy metal contamination. From a forensic perspective, the pattern of heavy metal accumulation within plant tissues can serve as biological evidence for tracing contamination pathways. By analyzing the differences in metal concentrations between roots, stems, and leaves, such data can provide valuable support for environmental forensic investigations in identifying pollution sources.

3.3 Mechanisms of plants as bioindicators for detecting heavy metal pollution

The ability of plants to accumulate heavy metals depends on the values of the *Concentration Factor* (CF) and *Translocation Factor* (TF). CF reflects a plant's capacity to accumulate heavy metals from the environment, whereas TF describes the plant's ability to transfer metals from roots to shoots. CF values are classified into four categories: (i) low contamination with $CF < 1$, (ii) moderate contamination with $1 \leq CF \leq 3$, (iii) high contamination with $3 \leq CF < 6$, and (iv) very high contamination with $CF > 6$ (Gupta et al., 2021). Additionally, Li et al. (2025) and Mulenga et al. (2023) noted that heavy metal accumulation in plants is influenced by soil conditions, protein transport activity, and adaptive mechanisms inherent to the plants.

Beyond quantifying accumulation capacity, the distribution of heavy metals between roots and aerial plant parts provides important insight for environmental forensic interpretation. Root-dominated accumulation is commonly associated with soil-derived contamination, particularly from long-term fertilizer application and parent material weathering. In contrast, elevated metal concentrations in leaves are often linked to athmospheric deposition from traffic emissions, industrial activities, or resuspended contaminated dust, thereby enhanching the value bioindicator plants for differentiating contamination pathways in agricultural environments.

The initial mechanism of heavy metal uptake begins at the roots through adsorption on the cell wall, followed by entry into plant tissues via the apoplastic and symplastic pathways (Nedjimi, 2021). Heavy metal absorption predominantly occurs through the symplastic route, which relies on energy-dependent processes facilitated by metal ion transporters or complexing mediators (Islam et al., 2024). This process is influenced by various factors, including root structure, organic matter content, and soil pH (Ghuge et al., 2023). Acidic soil conditions enhance the solubility of heavy metals, thereby accelerating their uptake by hyperaccumulator plants (Mohamed et al., 2025).

Table 2 presents a comparative synthesis of heavy metals and bioindicator plant species reported in Indonesian agricultural environments, emphasizing dominant accumulation patterns and their relevance to environmental forensic applications. In contrast to previously presented descriptive value to illustrate how specific plant-metal association can support contamination source screening and preliminary forensic assessments. The table highlights the potential of bioindicator plants not only as ecological monitoring tools, but also as complementary evidence in environmental forensic investigations.

Table 2. Comparative synthesis of heavy metals bioindicator plant species and uptake characteristics reported in Indonesian agricultural environments

Heavy metal	Bioindicator plant species	Dominant accumulation organ	Uptake characteristics	Forensic relevance	Reference
Cd	*Oryza sativa*	Root	High accumulation capacity with limited translocation to aerial parts	Reflenct soil-derived contamination associated with agricultural inputs	(McDowell & Gray, 2022; Ugulu et al., 2023).
Pb	*Oryza sativa*	Root > shoot	Strong root retention and low mobility within plant tissues	Useful for identifying localized and persistent soil contamination	(Oktavian et al., 2024; Silva et al., 2022).
Cd	*Eichhornia crassipes*	Root	High bioaccumulation potential under soil-water interface conditions	Effective for screening diffuse contamination sources	(Ugulu et al., 2023).
Pb	*Ipomoea aquatica*	Root and shoot	Moderate translocation influenced by water and soil conditions	Indicates combines soil and water contamination pathways	(Ugulu et al., 2023; Danapriatna et al., 2024).

Heavy metals in the soil can pass through the plant epidermis, traverse the endodermis, and eventually reach the xylem (Nedjimi, 2021), as illustrated in Fig. 1. This movement occurs through apoplastic and symplastic pathways, allowing metals to be translocated from roots to other plant organs. Once inside the cells, heavy metals are chemically bound by molecules such as phytochelatins, glutathione, and metallothioneins, forming stable metal–ligand complexes. These complexes reduce toxicity by enabling sequestration within vacuoles and limiting damage to essential cellular components, thereby supporting metal tolerance and accumulation in certain plant species. In different plant species, various ligands can be found in the cytosol in differing ratios, resulting in competition among ligands for binding metal ions. These complexes are subsequently sequestered in vacuoles to prevent toxicity and maintain normal enzymatic activity (Seregin & Kozhevnikova, 2023).

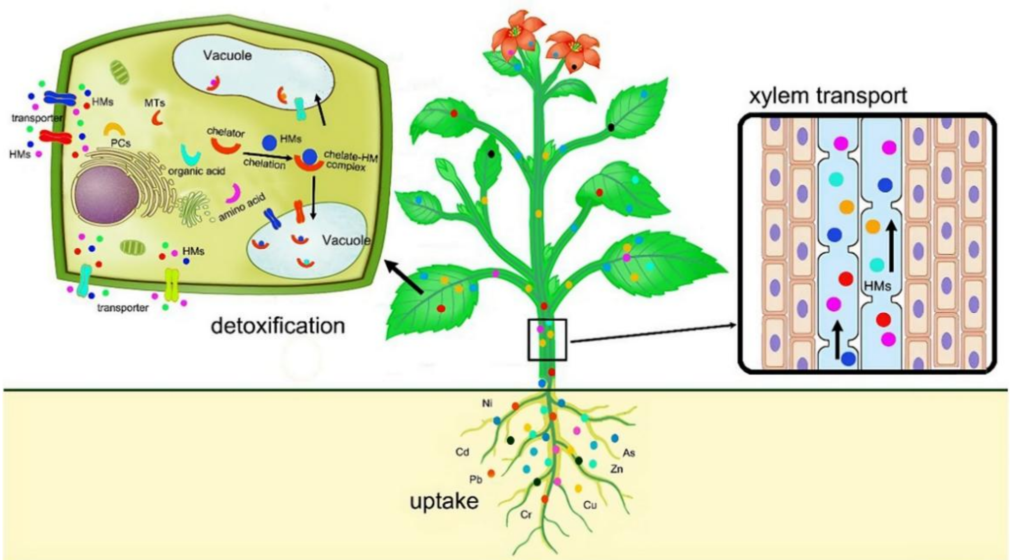

Fig. 1. Mechanisms of uptake, transport, and detoxification during heavy metal accumulation in plants (Yan et al., 2020)

In addition to physical and chemical mechanisms, plants also exhibit biological responses to heavy metal exposure by increasing the production of reactive oxygen species (ROS) such as H_2O_2 and O_2^- (Mansoor et al., 2023; Zandi & Schnug, 2022). These responses can have severe impacts on plant health by inhibiting growth, photosynthesis, and enzymatic activity, inducing oxidative stress, reducing biodiversity, and degrading ecosystems (Khan et al., 2025; Lovynska et al., 2024). As a defense mechanism, plants enhance the activity of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD) to mitigate oxidative effects. Stable isotope analysis can also be employed to trace the origin and movement of heavy metals in the environment (Moore et al., 2024; Sharma et al., 2025) by comparing metal ratios in plants with those from contaminant sources.

In addition, the stable isotope approach can be used to trace the translocation of heavy metals from roots to shoots (Zhou et al., 2023). According to Mu et al. (2025) isotope analysis enables comprehensive quantification and identification of the factors contributing to heavy metal contamination in agricultural soils. A study by Yao et al. (2024) reported that differences in stable isotope compositions among samples can be used to identify contamination sources, as samples exhibiting similar isotope values likely originate from the same pollutant source. Hence, this analytical approach plays a critical role in verifying cases of environmental contamination caused by heavy metals. However, isotope analysis often requires the integration of geostatistical analysis to enhance the accuracy and interpretability of the results.

Liao et al. (2024) stated that each plant species has specific characteristics in responding to heavy metal accumulation, resulting in distinct isotope fractionation patterns as a physiological response. This finding reinforces the role of bioindicator plants as valuable scientific evidence in cases of heavy metal contamination and highlights their potential contribution to environmental forensic assessments. In addition to isotope-based analysis, spectrophotometric methods are also widely employed to examine heavy metal concentrations in plants. This approach allows the detection of chemical forms, spatial distribution, absorption, and translocation of heavy metals within plant tissues (He et al., 2024).

Table 3. Summary of National and International studies on heavy metal contamination

Author & year	Study location	Species/ subject	Heavy metals analyzed	Methode/ approach	Key findings
(Sukarjo et al., 2021)	DAS Serayu Hilir (Indonesia)	Paddy (*Oryza sativa)*	Cd, Co, Pb, Ni, Fe, Mn, Zn, Cr, Cu, As	CF, Ecological Risk Index	Cd at high levels; ecological risk index categorized as moderate to high
(Khasanah et al., 2021)	Sidoarjo (Indonesia)	Rice field vegetation	Fe, Zn, Pb, Hg, Cu, Mn, Cd	CF, Ecological Risk Index	Hg and Pb at moderate to high levels; overall potential risk low
(Syafriliansah & Purnomo, 2022)	Mojokerto, Indonesia	*Water hyacinth (Eichhornia crassipes), Water spinach (Ipomoea aquatica), Cattail (Typha angustifolia)*	Pb	CF and metal content analysis	Aquatic plants are effective indicators of water quality
(Mustofa & Roosmini, 2024)	West Java, Indonesia	Rice (*Oryza sativa*)	Cd, Pb	Metal accumulation analysis in plant tissues	Carcinogenic risk due to heavy metal accumulation in rice plants
(Gafur et al., 2022)	Gorontalo, Indonesia	*Fern (Pteris vittata)*	As, Pb, Hg	Metal distribution analysis in ferns	High potential as hyperaccumulator of As, Pb, Hg; relevant for biomonitoring
(Gupta et al., 2021)	India	Local agricultural plants	Cu, Mn, Zn, Cd, Pb, Ni, Co	CF, Ecological Risk Index, Health Risk Analysis	Cd concentrations exceeded threshold limits
(Li et al., 2025)	China	*Anabasis aphylla* L., *Alhagi camelorum* Fisch, *Reaumuria songonica*	Cr, Hg, Cd, Cu, Zn, Pb, As	CF, Ecological Risk Index	High ecological risk from Cd and Hg
(McDowell & Gray, 2022)	New Zealand	Soil samples with P fertilizer content	Cd	Long-term trials, soil sample analysis	Discontinuing P fertilizer reduced crop yield but did not quickly lower Cd content
(Zhou et al., 2023)	Controlled experiment (Hydroponics)	*Sedum plumbizincicola*	Cd, Zn	Stable isotope analysis	Interaction between the two metals affected Cd and Zn uptake by plants
(Mu et al., 2025)	China	Agricultural lands	Hg, Cd, As, Pb, Cr, Zn, Ni, Cu	Isotope analysis, Ecological Risk Index	Able to quantify and identify factors contributing to heavy metal contamination

These mechanisms illustrate the integrative processes that enable bioindicator plants to absorb, neutralize, and safely store heavy metals. According to research by (Qader & Salih, 2023) and (Alghamdi & El-Zohri, 2024) bioindicator plants can prevent the redistribution of heavy metals into the environment and contribute to the restoration of ecosystem quality in contaminated areas. In addition to functioning as natural detectors, bioindicator plants also hold potential for use in phytoremediation—the application of plants to absorb and reduce heavy metal concentrations in soil by utilizing their inherent agronomic traits. Phytoremediation using bioindicator species is considered a cost-effective and efficient method due to their rapid growth and ability to restore the functionality of contaminated soils (Hanafiah et al., 2020; Widyasari, 2021).

Based on a review of relevant national and international literature discussed in Subsections 3.1 to 3.3, the key findings are summarized in Table 3. This table highlights the research focus, bioindicator plant species used, types of heavy metals identified or analyzed, and the principal methods supporting heavy metal contamination analysis in agricultural soils. It also provides a comparative overview that facilitates the identification of patterns and gaps across the reviewed studies.

3.4 Applications and forensic implications of bioindicator plants in heavy metal contamination

The application of bioindicator plants in environmental forensics represents a significant innovation for detecting and tracing the sources of heavy metal contamination in agricultural lands. In addition to the agricultural sector, industrial activities also play a considerable role in contributing to environmental pollution. The Government of Indonesia has established policies under Law No. 32 of 2009 on Environmental Protection and Management (UUPPLH), which aims to prevent, mitigate, and restore environmental pollution and degradation through the enforcement of legal sanctions (Lala & Kosim, 2025).

In Ukraine, the government has adopted specialized forensic knowledge in investigating environmental crimes, with forensic examinations recognized as one of the most effective and accurate investigative approaches (Bogatyrchuk, 2024). According to the National Institute of Standards and Technology (NIST) (Swofford, 2023) research and standardization programs in forensic science must provide explicit criteria for assessing the scientific validity and reliability of analytical methods. Therefore, analyses involving bioindicator plants can serve as valuable scientific evidence to support environmental forensic investigations of heavy metal contamination in agricultural areas.

Environmental forensics is a scientific approach used to identify the sources, pathways, and impacts of contamination within an ecosystem. The detection of plant toxins through phytochemical fingerprinting (Zakaria et al., 2025) and stable isotope analysis can provide *ecological fingerprinting* data from contaminated sites and bioindicator plants, serving as valuable forms of *biological evidence*. Contaminant history is also retained within plant tissues, allowing for the extraction of temporal and spatial information that is critical in pollution investigations (Oliveira et al., 2023). Moreover, analyzing heavy metal concentrations in leaves and stems at various plant growth stages can help estimate exposure duration and reconstruct the timeline of contamination events.

Environmental forensic analysis also employs botanical forensic approaches to investigate and address various environmental and legal issues, including ecological crimes such as illegal logging, habitat destruction, and pollution (Uddin et al., 2024). Forensic botany utilizes the unique characteristics of plant materials to provide essential information during investigations, including the use of bioindicator plants in heavy metal contamination cases on agricultural lands. Thus, forensic botany can generate scientific evidence that supports and complements other investigative methods (Khan et al., 2024). Although botanical evidence is not frequently used in criminal proceedings, it can function as indirect scientific evidence in environmental case investigations (Kasprzyk, 2023). The environmental forensic approach is not limited to identifying pollutant sources but can also be applied to understand the temporal dynamics of contamination over time.

Budianta et al. (2023) reported that the concentrations of heavy metals such as Cd and Pb tend to increase with the length of land utilization. The concentration of heavy metals in rice grown on newly cultivated land (0 years) was 0.05 mg/kg, whereas soil samples from areas that had been cultivated for 80 years contained 0.72 mg/kg of heavy metalscan increase of approximately 1,340%. This increase was attributed to the accumulation of residues from the intensive and excessive use of phosphate (P) fertilizers beyond the recommended dosage. These findings indicate that the duration of exposure and land-use history significantly influence the level of heavy metal contamination.

Plant samples selected for analysis should cover all potentially contaminated areas to ensure accurate analytical results. Such samples can be used to compare spatial and seasonal variations, validate analytical methods, and enhance the credibility of examination results in legal proceedings (Oliveira et al., 2023). In addition to heavy metal analysis, complementary methods such as stable isotope analysis can also be used to verify the origin of agricultural products based on climatic and topographic conditions (Cueni et al., 2021) Although not directly related to heavy metal assessment, isotope analysis plays a crucial role in *ecological fingerprinting* by linking geographical, environmental, and plant-related data.

Table 4. Comparison of national and international studies on bioindicator plants in heavy metal contamination

Research aspect	National studies (Indonesia)	International studies	Implication
Bioindicator species	Mostly focus on local species such as *Oryza sativa*, *Eichhornia crassipes*, *Ipomoea aquatica*, *Ficus benghalensis*, and *Pteris vittata*	Utilize hyperaccumulator plants and a variety of species such as *Sedum plumbizincicola*, *Centella asiatica*, and *Pteris vittata*	National studies are still dominated by food crops and aquatic plants; broader exploration of local species as hyperaccumulators is needed to support forensic applications
Type of heavy metals	Focus on Pb, Cd, Zn, Cu, Fe, Mn	Analyze multi-element metals: Pb, Cd, Zn, Cu, As, Hg, Ni, Cr	National studies should expand the range of heavy metal analysis to obtain more comprehensive and representative data
Methodological approaches	Dominated by CF (Concentration Factor), TF (Translocation Factor), and Ecological Risk Index	Integrate stable isotope analysis, ecological fingerprinting, spectrophotometry, as well as spatial modeling and isotope-source tracking	National studies are mostly descriptive; development of isotopic and spatial approaches would strengthen the forensic relevance of research outcomes
Research focus	Monitoring contamination levels and evaluating ecological risk in agricultural lands	Source contamination analysis and its relation to metal bioaccumulation across various ecosystems	Indonesian research can be directed to link bioindication results with contaminant source tracing
Implementation direction	Bioindicators are used to monitor soil and plant quality in agricultural lands	Bioindicators are applied in environmental forensic investigations and ecosystem restoration programs	Integration of bioindicator concepts with environmental forensic frameworks is required to make research findings more applicable and supportive of national policies

Source: (Sukarjo et al., 2021; Khasanah et al., 2021; Syafriliansah & Purnomo, 2022; Oliveira et al., 2023; Li et al., 2025; Mu et al., 2025).

All analyses in forensic science must adhere to rigorous scientific standards and ethical principles, and the results must be interpreted objectively without personal bias (Oliveira et al., 2023) This underscores that bioindicator plants hold strategic value not only in ecological monitoring but also in environmental forensic investigations of contamination. However, the implementation of this approach in Indonesia still faces technical and methodological limitations that require further research to address. A comparison of national and international studies is presented in Table 4 to illustrate research trends and potential gaps that remain open for development in Indonesia.

National studies in Indonesia generally focus on describing the concentrations of heavy metals in soils and plants, whereas international research has advanced toward the application of stable isotope analysis to trace contamination sources (He et al., 2024). Stable isotope analysis has proven effective in distinguishing the origins of heavy metal contamination, whether derived from agricultural activities, industrial emissions, or natural geological processes (Ning et al., 2023). This advancement provides a more precise and reliable approach for environmental forensic investigations of contamination pathways.

For instance, in the upper Nakdong River—an area contaminated with heavy metals such as Cd, Cu, Zn, As, and Pb—analyses were conducted to identify contamination sources, and contaminant concentrations were validated using isotope and GIS-based analyses (Jung et al., 2023). Furthermore, isotope analysis has demonstrated differences in Pb concentrations in soils near factories, ranging between 100–350 mg/kg, compared to only 20–50 mg/kg at more distant sites (Syu et al., 2023). From a forensic perspective, the distribution patterns and ratios among these metals can serve as potential indicators for tracing pollution sources. The integration of bioindicator data with the *ecological fingerprinting* approach allows for stronger scientific interpretation in determining the origin and dispersion pathways of contamination in agricultural lands.

The application of forensic science in establishing evidence of heavy metal contamination through bioindicator plants plays a vital role in confirming the scientific relationship between pollution sources and their effects on biological environments. It ensures legal validity through the implementation of forensic protocols that integrate analytical techniques with *ecological fingerprinting* data. Furthermore, the use of forensic science enables bioindicator plants to provide measurable scientific evidence that can be applied in environmental dispute resolution and law enforcement. Hence, the integration of environmental forensic research is expected to strengthen the scientific foundation for environmental law enforcement in Indonesia. This cross-disciplinary approach is consistent with global trends that recognize ecosystems as credible sources of *ecological evidence*.

3.5 Limitations and future research directions

The utilization of bioindicator plants within the context of environmental forensics still faces several limitations, including methodological and technical constraints, as well as the lack of comprehensive local data. To date, most studies conducted in Indonesia have primarily focused on ecological aspects. Heavy metal concentration analyses, and general environmental quality monitoring, while applications explicitly framed within an environmental forensic perspective remain relatively limited (Handayani et al., 2022; Oliveira et al., 2023).

In addition, the application of isotope-based methods using bioindicator plants in Indonesia is still minimal, despite their considerable potential for supporting contamination source attribution and ecological fingerprinting. Research on commonly used local bioindicator species, such as water hyacinth (*Eichhornia crassipes*), water spinach (*Ipomoea aquatica*), and rice (*Oryza sativa*), may serve as an initial foundation for integrating stable isotope analyses into environmental forensic monitoring frameworks (Ugulu et al., 2023). This approach could enhance the accuracy of identifying pollution sources and improve environmental management strategies in agricultural systems.

These conditions highlight the need for a more integrative and interdisciplinary research approach that bridges plant biology, geochemical analysis and stable isotope techniques to generate more accurate and representative forensic evidence. Extensive field-based studies are also required to map the spatial and temporal variations of heavy metal accumulation in bioindicator plants across different agricultural regions of Indonesia. Such efforts would not only strengthen the national research database but also support the implementation of bioindicator plants as scientific tools in environmental forensic investigations and environmental protection policy development.

Overall, addressing these methodological and data-related limitations is essential for advancing the application of bioindicator plants beyond ecological studies toward a more robust environmental forensic framework. By strengthening analytical integration and interdisciplinary collaboration, bioindicator-based approaches can play a more decisive role in contamination source identification and evidence-based environmental management. This will ultimately contribute to more effective environmental monitoring and policy development.

4. Conclusion

Based on the results of the review and literature analysis, bioindicator plants demonstrate strong potential as scientific tools for detecting and tracing heavy metal contamination in agricultural lands, while also contributing to the advancement of environmental forensic application in Indonesia. Plants function not merely as passive monitoring system, but as ecological recorders capable of reflecting contamination levels, transport pathways and potential sources through characteristic patterns of metal accumulation within their biological tissues. A thorough understanding of heavy metal accumulation mechanisms, including physiological and biochemical processes such as absorption, translocation and metal-ligand complex formation, is essential for evaluating the reliability and interpretative value of bioindicator plants. Furthermore, the integration of forensic-oriented approaches, particularly stable isotope analysis and ecological fingerprinting, can substantially enhance the scientific robustness of contamination source identification, whether derived from industrial activities, agricultural inputs or natural geological processes.

This review highlights the importance of adopting interdisciplinary frameworks that integrate bioindicator data with spatial analysis and chain of custody documentation to support the development of credible environmental forensic system. Accordingly, the utilization of bioindicator plants extends beyond conventional ecological monitoring and may be further developed as a forensic instrument to inform sustainable environmental protection and land management policies in Indonesia. Future research should prioritize the standardization of sampling and analytical protocols for bioindicator-based forensic investigations, supported by collaboration among environmental agencies, agricultural researchers and forensic laboratories. Such efforts are essential to establish reliable ecological database and ensure that bioindicator-derived evidence is scientifically validated and defensible in environmental dispute resolution.

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Author Contribution

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Data Availability Statement

All data used in this study were obtained from previously published and publicly accessible secondary sources available through scientific publication and official databases.

Conflict of Interest

The author declares that there are not potential conflicts of interest, whether academic, professional, or financial, in the preparation of this article. This manuscript was independently written for the Research Assistant Selection of the Environmental Cluster, Universitas Indonesia, without any affiliation or external influence that could affect the objectivity of the content.

Declaration of Generative AI Use

During the preparation of this manuscript, the author used ChatGPT (OpenAI), solely to assist with grammar checking, academic style editing, and bilingual translation in accordance with IASSSF journal standards. No core scientific content was generated by the AI tool. The author independently reviewed, edited, and verified all parts of the manuscript and takes full responsibility for the final published version.

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