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REVIEW ARTICLE

Heavy metal contamination in Hawaiian island soils: Sources, risks, and environmental assessment strategies

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Abstract: The Hawaiian Islands, shaped by a legacy of intensive plantation agriculture, continue to face persistent soil contamination with heavy metals, particularly arsenic and lead, which are remnants of historic pesticide and industrial chemical application. Today, these contaminants pose elevated environmental and human health risks, especially in areas repurposed as residential neighborhoods and public parks. This review consolidates current evidence on the primary contamination sources, spatial distribution, and potential health impacts of arsenic and lead in Hawaiian soils. It also evaluates and confirms advanced field and laboratory assessment techniques, namely, decision unit–multi-increment sampling and energy dispersive X-ray fluorescence, which are increasingly employed in Hawai'i for efficient and representative analysis. By synthesizing regulatory guidelines, historical land-use records, and recent case studies, this article emphasizes the necessity of thorough legacy contamination assessments to inform safe land conversion practices. These findings offer valuable insights for future research, remediation strategies, and policy development, both in Hawai'i and in similar post-agricultural contexts globally.

Keywords: Heavy metals; Arsenic; Lead; Hawai'i; Soil contamination; Decision unit–multi-increment sampling; Energy dispersive X-ray fluorescence; Environmental assessment; Land reuse

1. Introduction

This review provides a comprehensive overview of heavy metal contamination in Hawai'i's soils, focusing on the origins, risks, and regulatory responses associated with arsenic and lead. It also explores best practices in sampling and analysis and draws from recent case studies to illustrate the continuing impact of legacy pollution. By contextualizing Hawai'i's experience within broader environmental and public health frameworks, this review aims to inform future research and remediation strategies, both locally and in other post-agricultural regions facing similar challenges.

2. The plantation era in Hawai'i

The very first commercial sugar cane plantations in Hawai'i were experimented with in the 1840s and 1850s.[1] During the late 19th century, however, Hawai'i began supplying large amounts of sugar to the western U.S. market, which would last well into the 20th century.[2] Due to a high demand for sugar, Hawai'i became one of the primary agricultural producers of sugarcane, which led to economic growth and Hawai‘i's historical "plantation era." By 1937, approximately 310,195 acres of land across the state of Hawai‘i were dedicated solely to sugarcane farming.[3]

Sugarcane plantations were the backbone of the state's economy during 1860–1880.[4] Between 1875 and 1880, Hawai‘i went from having 20 total sugarcane plantations to 63.[5] The expansion of plantations was also propelled by a shift from animal and water power to steam power.[2] This growth of plantations led to a significant increase in economic revenue and workforce, a population composed mostly of immigrants.[6] Migrant workers originated from several countries such as Japan, China, Korea, the Philippines, and Portugal.[7] As income and jobs increased, there became a need for plantation infrastructure, such as housing, roads, and ports, to support the rising economic growth of Hawai‘i's future.

However, early cultivation practices of plantation farmland involved the use of heavy metal-based pesticides.[8] Pesticides made from substances like arsenic, and sometimes lead, became common, with the first recorded usage of arsenic for weed control conducted in 1913 at the Ola‘a plantation.[9] Arsenic, often used in the form of sodium arsenite, was a common herbicide used to control pests in Hawaiian plantations until the mid-20th century. Then, by the 1940s, the industry shifted to using other chemical pesticides, such as dichlorodiphenyltrichloroethane (DDT).[10] Thirty years of sodium arsenate use had long-lasting effects on Hawai‘i's soil, as levels of 50–100 ppm of arsenic are often measured in both residential and commercial areas today, with up to 900 ppm on former plantation lands.[11]

Former plantation camps and residential areas may also contain high levels of lead in the soil due to the use of lead paint in homes. Before it was banned in 1978, interiors and exteriors of homes used lead-based paint for durability and fast drying.[12] As exterior paint chipped over time, it seeped into the soil and accumulated, resulting in lead contamination. Many homes on former plantation settlements were built before 1978, so lead-based paints were frequently used. In Hawai‘i, levels of lead in soil have been shown to be elevated at 100–200 ppm due to past human activities such as lead discharge from paint and exceed 200 ppm in more concentrated polluted zones, exceeding the safety threshold of 200 ppm set by the U.S. Environmental Protection Agency (EPA).[12]

In the 1950s, when Hawai‘i's plantations began to decline in revenue, many shut down and sold off their land for repurposing. The decline was due mostly to the rising costs of labor that came after workers' protests in the 1940s and 1950s.[13] In addition, the commercialization of the jet aircraft shifted Hawai‘i's economy from sugar plantations to tourism.[14] Hawai‘i's last plantation, operated by Alexander and Baldwin Inc., ceased operations in 2017, ending this era of Hawaiian history.

Several plantation areas are now locations for parks and recreational zones. Heavy metals such as arsenic and lead are of particular concern due to their toxicity, environmental persistence, and potential for human exposure through direct contact with soil or airborne dust. Numerous studies have documented elevated levels of these contaminants in Hawai‘i's soils, often exceeding the EPA's regional screening levels (RSLs) and regional management levels (RMLs), particularly in former plantation regions on the islands of Hawai‘i, Maui, and O‘ahu.[11]

Hakalau Beach Park, which is situated on 3.2 acres of land, is a county park located in a gulch near the former Hakalau Sugar Mill. In 2017, Hakalau Beach Park was closed to the public by the Hawai‘i County Department of Parks and Recreation when lead levels above the 200 ppm screening level were detected in the soil.[15] The elevated lead levels were determined to come from the nearby old Hakalau Stream Bridge, which was built as part of the old Hakalau plantation community in 1930.[16] The bridge was coated in lead paint that seeped into the soil, resulting in lead contamination. Hakalau Beach Park has remained closed since, with no plans of reopening.

Kaiwiki Park, another county park on Hawai‘i Island, was often visited by residents, once served as a sugarcane plantation. Based on past land records, this park was formerly owned by the Kaiwiki Milling Company and developed as part of their 500 acres of sugarcane farmlands.[17] In 1930, Kaiwiki Milling, now under the name Hilo Sugar Company, gave a parcel of land to the territory of Hawai‘i in a land exchange. Since 1965, this land has been put to use as a park and maintained by the County of Hawai‘i.[18] When Hilo Sugar Company was acquired by Mauna Kea Sugar Company, their recorded use of pesticides was exposed, specifically trichloroacetic acid, atrazine, 3-(3,4-dichlorophenyl)-1,1-dimethylurea, and dalipon, likely referring to the pesticide dalapon (Figure 1), that were industry standard chemical pesticides after the 1940s.[19]

Current assessment efforts focus mainly on persistent metal contaminants detectable through energy dispersive X-ray fluorescence (EDXRF). Hawai‘i's mid-20th century implementation of synthetic organic pesticides, including organochlorines such as DDT, chlordane, and heptachlor created a co-contamination

Hawaii Sugar Waste Study

Mauna Kea Sugar Company, South Plant (Hawaii)

Date of Visit:

December 13, 1966

Parent Company:

C. Brewer and Company, Ltd.

Fertilizer:

Nitrogen – 400 lbs. (as N) /acre/ crop as urea.

Potash – 600 lbs. (as K_2O) /acre/ crop.

Phosphorus – 400 lbs. (as P_2O_5) /acre/ crop.

$CaCO_3$ – up to 1,500 lbs. /acre for acid soil.

Pesticide Usage:

TCA – 8 lbs. /acre/ crop

Dalipon – 3 lbs. /acre/ crop

Artrazine – 4 lbs. /acre/ crop - pre-emergence application

DCMU – 2 lbs. /acre/ crop

Figure 1. Selected results portion of the Hawai‘i Sugar Waste Study report depicting the utilization of recorded fertilizers and pesticides used in 1966 at the Mauna Kea Sugar Company. Transcription taken from original typewritten text

potential that remains largely uncharacterized. The chlordecone contamination crisis in Guadeloupe, stemming from its widespread use on former banana plantations, demonstrates that organochlorine pesticides can persist in tropical soils for decades after application ceased. This leads to the ongoing contamination of food crops and creates potential public health exposure. The focus solely on heavy metal screening may therefore provide an incomplete risk assessment that misses significant organochlorine residues at sites that appear clean for metals. Hawai‘i has expanded its urban agriculture and residential development on former plantation lands, and therefore, the site characterizations should include both metal and persistent organic pollutant analysis. Establishing baseline data on organochlorine persistence in Hawaiian post-plantation soils is an urgent research priority specific to the islands' unique agricultural history.

The detrimental health effects of heavy metal exposure are widely known and demonstrated in different cases around the world. For instance, in Zamfara, Nigeria, workers and villagers suffered vomiting, abdominal pain, headaches, and seizures due to mass lead poisoning from the local mining industry.[20] In two of these villages, 25% of children died.[21] Elevated levels of arsenic and lead in soil pose many health risks to people if long-term exposure occurs.[22] Inorganic forms of arsenic, such as sodium arsenite, are more toxic than organic versions and can cause skin lesions, pigment change, and cancers of the skin, bladder, and lungs after about 5 years of exposure.[23] In addition, arsenic exposure can affect reproductive health and pregnancy, leading to conditions such as low birth weight, congenital deformities, and in the worst cases, the loss of a pregnancy.[24] Lead exposure can impact children in a multitude of ways, as children who are poisoned can experience delayed growth, intellectual disability, behavioral disorders, and decreased attention spans.[25] In adults, reproductive damage, hypertension, high blood pressure, and memory issues are common symptoms of lead poisoning.[26] Negative effects of lead exposure can occur at blood lead levels as low as 10 μg/dL.[27]

There are no records of how much of the 310,195 acres of former sugarcane fields remain untested for heavy metal contamination. This obscurity demonstrates a need to perform continuous environmental assessments of parks to determine if elevated levels of arsenic and lead stemmed from pesticides or paint, and if the levels could pose a risk to human health. The purpose will be to determine the presence of deleterious metals, inform the local community, and provide a vehicle for remediation efforts.

Assessing and managing soil contamination in Hawai‘i poses unique challenges due to the state's complex land ownership history, varied geology, and tropical climate. However, standardized approaches such as decision unit–multi increment sampling (DU-MIS) and analytical techniques like EDXRF have gained traction as effective tools for site assessment in Hawai‘i. These methods are now incorporated into the Hawai‘i Department of Health's Technical Guidance Manual (TGM) for environmental site investigations.

3. Common practices for heavy metal assessment in soil

This review synthesizes field and laboratory methodologies commonly employed to assess heavy metal contamination in soils, with particular emphasis on tropical and volcanic island environments such as the Hawaiian Islands. The methods were evaluated based on their sampling strategies, sample preparation protocols, analytical techniques, and adherence to regulatory frameworks, including the EPA's RSLs and RMLs.[28,29]

RSLs were selected as criteria, as it is an efficient way to identify sites needing further assessments for possible bioavailability studies in the future, while still fitting the scope and budget limitations of this review.

The recommendation for decision unit (DU)-MIS in this review over traditional discrete sampling methods in Hawaiian soil assessments is driven by statistical and practical considerations in heterogeneous volcanic soil studies. Discrete sampling is known to have limitations in post-agricultural Hawaiian landscapes where past pesticide applications were often non-uniform. This created high level contamination patterns interspersed with relatively normal soil. Studies comparing sampling methodologies in heterogeneous contaminated soils have consistent results that show discrete sampling produces coefficient of variation (CV) values of 50–150%, whereas the CV or DU-MIS is reduced to 15–35%.[30,31] In addition, discrete samples can miss zones that are contaminated or can over-analyze local high levels, which can cause a misrepresentation on the scope of work. In addition, discrete sampling requires 5–10 times more laboratory analyses than DU-MIS, thereby causing higher costs without increasing data significance levels.[31,32] In comparison, DU-MIS sampling collects specimens in increments around the entire targeted area, which provides a more statistically robust mean concentration. The DU-MIS method is better suited to Hawaiian volcanic soils because variable ash deposition, organic matter distribution, and historical land management practices cause heterogeneous contamination. In its TGM, the Hawaii Department of Health directly recommends DU-MIS because the outcomes therein can be specifically connected to risk-based screening levels.[32]

The recommendation in this review of EDXRF for assessments over traditional analytical methods, such as inductively coupled plasma–mass spectrometry (ICP-MS) or ICP–atomic/optical emission spectroscopy (ICP-AES), provides distinct advantages. EDXRF testing and analysis takes only minutes per sample compared to days or weeks for traditional ways, which enable field-time decision making.[32] Comparative studies have displayed strong relationships between EDXRF and ICP-MS outcomes for lead ($R^2 = 0.89$) and arsenic ($R^2 = 0.84$) in environmental soil samples.[36-39] EDXRF provides sufficient sensitivity for approved screening at a significantly lower cost and does not harm the structure of the samples in any way.[33-38] In most cases, EDXRF is utilized for screening and assessment purposes and then if the samples exceed certain levels, the confirmation will be accomplished by ICP-MS or ICP-AES 12. For Hawai‘i soil studies, this tiered analytical approach provides the quality and cost benefits for significant data collection.

Environmental soil assessments typically begin with a structured planning phase to define the investigation's scope, select contaminants of concern, and determine the spatial resolution of data collection. In Hawai‘i, the Department of Health's TGM outlines a nine-step environmental investigation process, which includes defining DUs and preparing detailed sampling plans.[40] This framework is widely recognized for its alignment with risk-based environmental management goals, particularly in volcanic island settings.

A central component of these assessments is the DU-MIS methodology. DU-MIS designates a specific area or soil volume as a DU and then collects numerous small increments to form a composite sample. This strategy has been shown to improve representativeness in heterogeneous soils and to reduce sampling error compared to traditional grab or discrete sampling methods.[41,42] Figure 2 depicts an example of DU-MIS

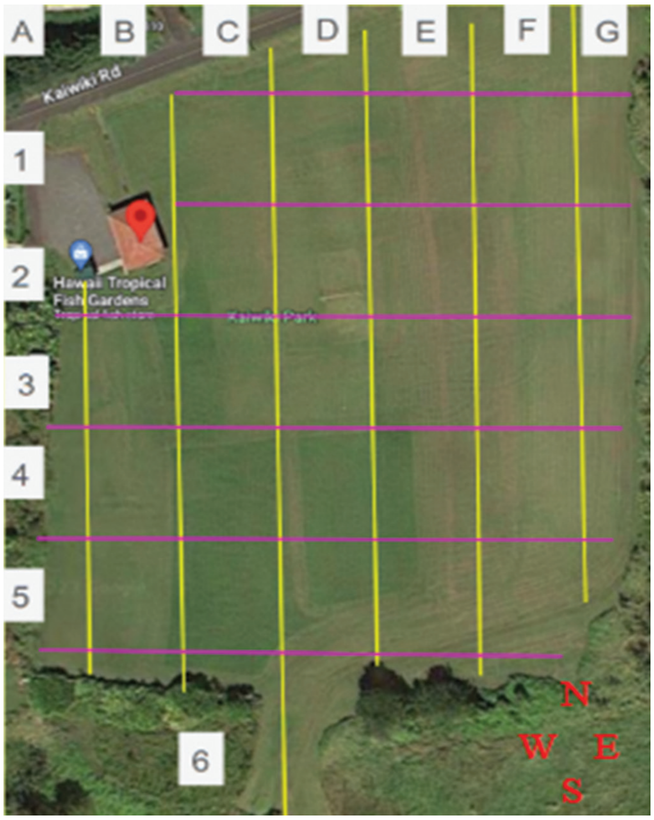

Figure 2. Designation of decision units on an image of Kaiwiki Park captured by Google Earth using a 7 × 6 grid following the DU-MIS methodology

Abbreviation: DU-MIS: Decision unit–multi increment sampling designation employed on a plot of land using a 7 × 6 grid. In volcanic soils, where contaminants are often distributed unevenly due to ash layers and organic accumulation, DU-MIS is especially advantageous for producing reliable spatial data.

After field collection, soil samples undergo standardized preparation to ensure analytical consistency. This typically involves air-drying or oven-drying samples at approximately 200°F (95°C) for up to 2 h, followed by homogenization and sieving to remove organic debris and coarse particles.[34] Proper drying minimizes moisture interference in spectrometric analyses, while homogenization helps ensure reproducibility across subsamples. Prepared samples are transferred to labeled containers or analytical sample cups for instrumental analysis. Adherence to uniform preparation and storage protocols are essential for maintaining data integrity, especially when comparing against regulatory thresholds.

Among available analytical techniques, EDXRF has gained popularity due to its non-destructive nature, rapid analysis time, and ability to detect multiple elements simultaneously. The method is especially well-suited for preliminary and confirmatory assessments of heavy metal contamination in field and laboratory settings.[42,34] In typical protocols, sample cups are sealed with ultrathin films (e.g., 3.6 μm SpectroFilm) and analyzed alongside certified reference materials (CRMs) to ensure calibration accuracy and instrument reliability. Common CRMs include: BHVO-2 (Hawaiian Basalt), which represents unaltered volcanic rock matrix and Standard Reference Material (SRM) 2710 and SRM 2711 (Montana Soils), which are commonly used to represent highly and moderately contaminated soil samples, respectively.[43,44,47]

Isotopic fingerprinting represents one of the gold standards for source apportionment.[47] However, the studies reviewed in the background research distinguish anthropogenic from geogenic metal concentrations by comparing EDXRF measurements against established Hawaiian volcanic soil reference materials, in particular BHVO-2 (Hawaiian basalt standard). This represents the baseline for uncontaminated volcanic soils in the region.[43] Metal concentrations that substantially exceed these reference values, particularly for elements associated with historical pesticide use such as Pb, As, and Cu, are interpreted as indicating anthropogenic contamination.[48] This approach is strengthened when higher concentrations match documented areas of intensive historical agricultural pesticide application. While other advanced methods, such as isotopic fingerprinting, would provide more definitive source attribution, comparison to well-characterized volcanic soil reference data provides a solid initial assessment for identifying sites where anthropogenic inputs have exceeded natural background levels.[48]

Target analytes typically include arsenic (As), lead (Pb), nickel (Ni), zinc (Zn), rubidium (Rb), strontium (Sr), and zirconium (Zr), though regulatory focus often centers on Pb and As due to their acute toxicity and historical use in pesticides and military applications.[28,29,45] Analytical results are interpreted against national soil screening thresholds. A graphical representation of this methodology is summarized in Figure 3. The EPA's RSLs and RMLs provide guidance for identifying contamination that may warrant further investigation or remediation. For example, the current EPA guidelines establish: Pb with: RSL and RML at 200 ppm and As at RSL and RML at 0.68 ppm.[28,29] Exceeding these benchmarks often prompts follow-up actions such as triplicate resampling, perimeter testing, or remedial planning. These data-driven thresholds serve as key decision points for environmental managers in prioritizing risk and response strategies.[40]

4. Evaluation of heavy metals in other volcanic regions

The Hawaiian Islands present a unique case for studying heavy metal contamination due to their volcanic origin, varied land uses, and rapid development. To contextualize patterns observed across the Hawaiian archipelago, this section compares regional findings with similar volcanic islands and tropical environments globally. These comparisons highlight both geogenic and anthropogenic influences on soil heavy metal content.

Studies from O'ahu, Hawai'i Island, and other Hawaiian locations have documented moderate to elevated concentrations of heavy metals such as Pb, As, Cd, and Zn, particularly in areas influenced by urbanization, agriculture, or legacy military activity. Volcanic soils in Hawai'i (especially Andisols) naturally contain higher levels of iron, manganese, and aluminum oxides, which influence metal mobility and adsorption capacity. Urban soils in Honolulu, for example, have shown elevated Pb and Zn from vehicular emissions and construction materials.[46] Meanwhile, agricultural soils in Hāmākua and Puna have revealed residual As and Cd from pesticide and fertilizer application.

In other parts of the world, volcanic soils have been shown to exhibit long-term contamination by chlordecone and heavy metals such as Pb and Cd, especially in areas historically used for banana cultivation, such as

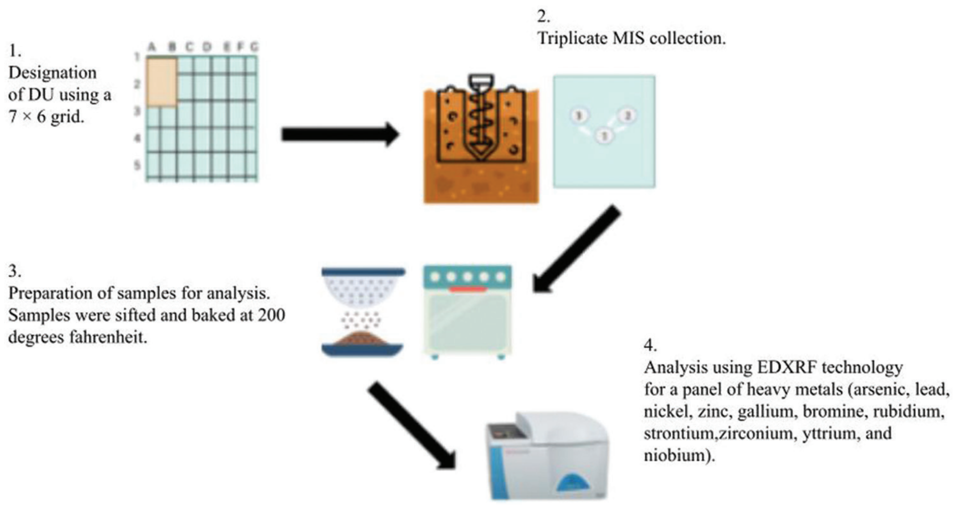

Figure 3. Schematic depicting evaluation of soil metals using EDXRF technology, spanning from sample collection to analysis. Designation of decision units are initially plotted on a 7 × 6 grid and samples are collected in triplicate following multi-incremental sampling techniques. Samples are then prepared by separating large debris and drying through baking. Subsequently, the samples are analyzed for the presence of metals using EDXRF technology. Clipart graphics were obtained from Freepik

Abbreviation: EDXRF: Energy dispersive X-ray fluorescence

Table 1. Soil contamination characteristics across selected volcanic and urban regions

Region	Key soil type	Dominant sources	Main metals
Hawai‘i	Volcanic Andisols	Agriculture, urbanization, legacy military	Pb, As, Cd, Zn
Guadeloupe	Volcanic soils	Pesticides, agriculture	Pb, Cd, chlordecone
Madeira	Basalt-derived soils	Traffic, tourism, waste	Pb, Zn, Cr
Sicily	Volcanic ash soils	Natural (geogenic)	Cu, Ni, Zn
Metro Manila	Alluvial/urban fill	Industry, vehicles	Pb, Cd, Cr

Guadeloupe. Like Hawai‘i, these islands experience tropical rainfall and volcanic weathering, contributing to enhanced leaching and mobility of metals. However, Guadeloupe’s contamination stems more from pesticide persistence than natural geogenic sources.[49]

The Atlantic volcanic islands demonstrate geogenic enrichment of trace metals in soils derived from basaltic parent material. Studies on Madeira have revealed elevated background levels of Cr, Ni, and Co. Urbanized areas also show anthropogenic enhancement of Pb and Zn concentrations. The influence of tourism, traffic, and domestic waste disposal parallels concerns observed in Hawai‘i’s urban environments.[50]

Mount Etna’s surroundings provide a prime example of volcanic soils with naturally elevated heavy metal concentrations. Ash deposits contribute to high levels of Cu, Zn, and Ni. Despite minimal industrial pollution, these metals occur in concentrations that sometimes exceed agricultural soil thresholds. This case illustrates the challenge of distinguishing between natural and anthropogenic sources in volcanic environments.[51]

In contrast to the Hawaiian case, Metro Manila soils exhibit heavy metal contamination primarily from industrialization, urban runoff, and unregulated waste disposal. High concentrations of Pb, Cd, and Cr have been reported in peri-urban and roadside soils, reflecting a more acute urbanization footprint. While climatic similarities exist in Metro Manila, the lack of volcanic influence differentiates its geochemical profile from Hawai‘i.[52]

Table 1 summarizes the presence of different heavy metals in various volcanic regions, highlighting the importance of context when assessing soil contamination. Volcanic regions, especially island environments, often exhibit naturally elevated baseline metal levels, complicating the establishment of regulatory thresholds. Nevertheless, human activities—especially agriculture, urbanization, and military use—can further exacerbate contamination and require region-specific risk assessment strategies.

5. Conclusion

5.1. Summary

Heavy metal contamination in Hawaiian soils, particularly from arsenic and lead, reflects a complex interplay between historical land use, volcanic geology, and environmental persistence. Case studies from across the Hawaiian Islands, including those formerly used for plantation agriculture, reveal that arsenic is often present in concentrations that exceed U.S. EPA RSLs and, in some cases, RMLs, indicating potential chronic exposure risks. In contrast, lead contamination tends to be more spatially variable, with exceedances typically confined to isolated DUs rather than widespread distribution.

Review of sampling and analytical methodologies, such as DU-MIS and EDXRF, demonstrates the importance of employing high-resolution, representative, and risk-aligned techniques—especially in heterogeneous volcanic soils. These methods not only enhance data quality but also guide meaningful decision-making for environmental and public health management.

5.2. Implications

The widespread presence of arsenic and localized hotspots of lead in Hawaiian soils—particularly in areas with agricultural or urban legacies—pose meaningful environmental and public health concerns. In recreational spaces, residential zones, and schoolyards built on former plantation land, chronic exposure to residual contaminants could increase long-term health risks, especially for children. The persistence of heavy metals decades after application demonstrates the slow natural attenuation in volcanic soils and the inadequacy of relying solely on passive degradation. Most existing studies in volcanic island regions, including the Hawaiian Islands, are geographically limited to urban centers or former agricultural zones. Large areas, particularly in remote, residential, or ecologically sensitive regions, remain unassessed. Moreover, longitudinal data tracking metal accumulation trends over time are scarce. Without consistent monitoring, it is difficult to evaluate the long-term effectiveness of mitigation strategies or to detect emerging contamination risks.

Volcanic soils naturally contain elevated concentrations of certain trace elements due to parent rock material.[53] However, the extent to which elevated heavy metal levels are geogenic or due to anthropogenic inputs (*e.g.*, fertilizers, military waste, and construction materials) is often unclear. There is a need for improved source attribution methods, including isotopic fingerprinting and geostatistical modeling, to distinguish between natural background levels and pollution-related enrichment. While many studies report total metal concentrations, few incorporate standardized risk evaluation protocols such as the U.S. EPA's RSLs, pollution load indices, or bioavailability assessments. This inconsistency hinders cross-study comparisons and limits the ability to translate findings into actionable regulatory guidance. Harmonization of risk assessment approaches across tropical island studies would enhance comparability and utility. Furthermore, consistent use of modern assessment methods such as DU-MIS and EDXRF enhances the detection, monitoring, and prioritization of sites in need of remediation or restriction.

Current research often focuses on total metal content without considering the bioavailable fraction that poses immediate risk to humans, plants, and soil microbes. Understanding the mobility and toxicity of metals in volcanic soils, especially under varying pH and organic matter conditions, is essential for accurate ecological risk assessment. Integrating ecotoxicological studies and plant uptake research would provide a more complete picture of contamination impacts.

Environmental assessments in Hawai‘i and other island settings often overlook the role of local and indigenous knowledge systems in identifying contamination hotspots or land-use histories. Incorporating community observations and traditional ecological knowledge into scientific frameworks could improve site prioritization and foster public trust in remediation efforts. Traditional ecological knowledge could improve contamination assessment by providing detailed oral histories from local kupuna (elders) regarding the precise locations of former pesticide mixing stations, storage facilities, and disposal sites that may be absent from official records. Furthermore, they may be able to identify culturally significant sites, such as traditional gathering areas or lo'i kalo (taro patches) that should be prioritized for assessment despite lower population density. These findings underscore the need for proactive, community-informed environmental management and call for attention to the disproportionate impact contamination may have on underserved or rural populations living near legacy sites.

It is also important to note that former Hawai‘i's plantation likely left behind more than just heavy metal residues. During the mid-1900s, sugarcane and pineapple growers also used a suite of long-lasting organochlorine pesticides, such as DDT, chlordane, and heptachlor, which can remain in tropical soils for decades. The situation referred to in this paper regarding Guadeloupe shows how these chemicals—in this case chlordecone—can continue to affect soils, crops, and communities in the long term. This example is a significant reminder that Hawai‘i may have similar lingering organic contaminants that simply have not been studied in depth. It will be prudent for future research to look beyond metals and include persistent organic pollutants as part of routine site assessments. Building this data base is essential for obtaining a more complete picture of the risks and providing logical recommendations about land reuse.

5.3. Remediation strategies and policy considerations

Effective management of heavy metal contamination in soils requires both consistent environmental monitoring and the implementation of appropriate remediation techniques. In island ecosystems like those of Hawai‘i, these efforts are particularly critical due to the unique interplay of volcanic geology, high rainfall, and concentrated land use near coastal zones. Environmental monitoring forms the basis for evaluating human health and ecological risk. In Hawai‘i and similar environments, the following practices are commonly used:

(i) Periodic soil sampling follows protocols established by the U.S. EPA and local agencies to capture vertical and spatial variations in metal distribution.[54]
(ii) Geochemical analysis using ICP-MS, atomic absorption spectroscopy, and portable X-ray fluorescence is common in environmental surveys and offers reliable quantification of metals such as Pb, Cd, Cr, Zn, and Cu.[55]
(iii) Bioindicators and phytomonitoring have been used in tropical systems, including the use of species such as *Cenchrus ciliaris* (buffelgrass) or *Helianthus annuus* (sunflower), which are effective accumulators of certain metals.[56]

Due to the complexities of tropical ecosystems, cost, and remote access to certain technologies, remediation strategies must be carefully planned. Furthermore, as heavy metals are bioaccumulative and often difficult to degrade, there is a distinct need to establish suitable methods to effectively remove them from the environment. Phytoremediation, which involves the use of hyperaccumulator plants to extract heavy metals, is a cost-effective and environmentally friendly approach of removing substances from soil.[57-69] For instance, vetiver grass (*Chrysopogon zizanioides*) has shown efficacy in heavy metal uptake.[60,61] However, plant-metal uptake efficiency depends on pH and metal speciation; therefore, recent studies suggest a combination of phytoremediator plants with microbial or engineering assistance to mitigate soil pollution.[62-64] Soil supplements, such as biochar, compost, lime, and volcanic ash derivatives, have been shown to reduce heavy metal bioavailability and leaching risk.[65,66] *In situ* stabilization using phosphate minerals or clay amendments has been used successfully in tropical soils to reduce lead and arsenic mobility.[68,69] Electrokinetic remediation technology has also shown success in removing heavy metals, particularly from low permeability soil, but its adoption may not be favorable and feasible in areas like Hawai‘i due to its generally high-energy consumption.[70] Alternatively, excavation and replacement has been utilized in urban redevelopment zones but shown to be cost-prohibitive and environmentally disruptive for large areas, especially in sensitive island ecosystems.[71]

Integrating technical remediation with policy, education, and traditional knowledge is critical to preserving the ecosystem of Hawai‘i. Agencies such as the Hawai‘i Department of Health Office of Hazard Evaluation and Emergency Response have developed guidance and response since hazardous substances are an endangerment to the public health and the environment; however, prevention strategies and consistent monitoring is lacking.[72] It is important that policymakers consider the impact of sustained heavy metal accumulation in areas of frequently visited locations and take appropriate action to reduce additional risk. While the State of Hawai‘i has established a comprehensive framework of evaluating environmental, social, cultural, and economic impacts of proposed projects before implementation through the Hawai‘i Environmental Policy Act, the following are recommendations to complement ongoing strategies to protect and conserve Hawai‘i’s rural or agricultural environments.[73]

5.3.1. Mandating baseline soil assessments for land repurposing

Require environmental due diligence using standardized protocols (e.g., DU-MIS and TGM guidance) before redevelopment of former agricultural or industrial lands.

5.3.2. Establishing bioavailability-focused risk guidelines

Supplement existing EPA’s RSLs with region-specific bioaccessibility studies to better reflect actual exposure risks in volcanic soils.

5.3.3. Creating a statewide legacy contamination registry

Develop a publicly accessible database of contaminated and remediated lands, helping communities make informed decisions about land use, housing, and recreation.

5.3.4. Prioritizing remediation funding for public parks and schools

Allocate state or federal funds toward testing and remediation in high-use areas such as parks, schoolyards, and public housing sites built on historic plantation lands.

5.3.5. Encouraging community participation in soil monitoring

Promote citizen science and local stewardship by offering training, low-cost test kits, and educational outreach on soil health and contamination risks.

5.3.6. Strengthening interagency collaboration

Enhance coordination between the City and County of Honolulu, Hawai'i Department of Health, EPA, local governments, non-profit organizations, and researchers to streamline site investigations, data sharing, and remediation planning.

With projected increases in extreme weather events and sea level rise, climate-resilient remediation planning is increasingly important.[62,63] Mobilization of legacy contaminants due to flooding or saltwater intrusion has already been observed in other coastal and island communities.[64] Incorporation of Native Hawaiian ecological stewardship and community engagement may also offer more sustainable and culturally grounded solutions.[65] Future research across the Hawaiian Islands should focus on refining spatial resolution in soil sampling, assessing co-contaminants such as pesticides or organic pollutants, and implementing remediation efforts and customizing treatment strategies to suit Hawai'i's ecosystem.

The persistence of arsenic in surface soils decades after its agricultural application underscores the need for long-term monitoring and site-specific remediation strategies. Risk assessment should extend beyond detection to include bioavailability studies, especially in recreational or residential areas. While regulatory thresholds provide clear benchmarks, interpretation must also consider local geology, climate-driven mobility, and land use context. Despite growing research on heavy metal contamination in tropical and volcanic island environments, several key knowledge gaps remain, limiting effective environmental management, risk mitigation, and policy development. This review paper also identifies the integration of traditional ecological knowledge as a necessary addition in the current contamination assessment approaches for post-plantation fields in Hawai'i. It would be prudent for future research to incorporate traditional ecological knowledge systematically from the planning phase through site prioritization and interpretation. Ultimately, integration of historical and cultural context with rigorous environmental assessment and political partnerships will be key to safeguarding communities and ecosystems in post-agricultural and rapidly urbanizing island environments.

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

Conceptualization: All authors
Writing–original draft: All authors
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Availability of data

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