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METHOD

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Current methods for the evaluation of chemical contamination risks from abandoned coal and lead-zinc mine lands: protocol for a systematic evidence map

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ABSTRACT
Abandoned mine lands (AMLs) pose significant environmental risks by releasing contaminants that can adversely affect plants, animals, and human health, especially in highly contaminated areas. Guidance exists on conducting contaminated land risk assessments. Understanding and documenting changes in the methods used for AMLs risk assessments can help identify gaps and advances in practice, influencing future research, policy, and remediation efforts. The study aims to synthesise current methods for characterising the risks of chemical contamination associated with AMLs, with a focus on coal and lead-zinc mines due to their enduring toxic legacies. Searches will be conducted across six electronic databases, including Web of Science, Scopus, ScienceDirect, PubMed, Academic Search Complete, and Business Source Premier (via EbscoHost), as well as grey literature sources. Eligible studies must include primary research assessing chemical risks from abandoned coal and lead-zinc mines. They must have assessed or measured risks associated with chemicals on ecological or human receptors at the community, population, or individual level. Studies retrieved from literature searches will undergo title and abstract screening, followed by a full-text assessment for eligibility. Following pilot screening, a single reviewer will screen all articles independently, with a second reviewer verifying accuracy for 20% of the sources. Data on methods for exposure assessment, including exposure modelling where relevant, selected safety thresholds, risk characterisation will be extracted from all eligible studies. Accuracy of the extraction process will also be verified by a second reviewer for 20% of the eligible articles. Collated methods will be categorised to establish current practices and compared with existing guidance to assess alignment and deviations. Results will be summarised narratively and presented in interactive, publicly accessible visualisations.

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Abandoned mine lands; contaminants; risk assessment; toxicity; environmental health

Background

Historically, the mining of natural resources did not always adequately consider impacts on health and the environment (Gallart 2017; Macklin et al. 2023). Mining activities vary greatly in method and scale, including artisanal and industrial mining at small, medium, or larger scales, and open-pit, surface, and underground methods. Many past mining operations lacked planning and were conducted haphazardly, leaving behind a legacy of contaminated mine lands (Hasheela et al. 2015). Mine closure, the planned or unplanned cessation of a mining operation, is a critical phase in the mining life cycle that ought to be designed and included in the mine operation plan (De Graff 2020). Properly designed closure aims to

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restore land for ecological or alternative uses, ensure ecological and human safety, and reduce environmental and social damage (Laurence 2006; ICMM 2019; De Graff 2020; ICMM 2021). The costs of mine closure are significant and, as a result, mine lands are often left unattended when mineral resources are exhausted (ICMM 2019, 2021). An abandoned mine refers to a former mine where extraction and processing occurred that is no longer in operation and for which there is no responsible entity to finance the cost of remediation or restoration. By contrast, abandoned mine lands (AMLs) include waste repository sites, water bodies, and surrounding watersheds where extraction, beneficiation, or processing of mineral resources has occurred. AMLs are also defined by the absence of responsible parties to oversee their management or restoration (EA 2008; Holmes and Stewart 2011; US EPA 2024). The difference is in their scope and structure, both characterised by a range of landscape features that may include stagnant pond water, mine water, waste rocks, tailings impoundments, areas impacted by smelter plumes, abandoned equipment, and structures. Many mining companies ceased operations before environmental regulations governing the management of mines came into force in their respective jurisdiction. Hence, governments are often left with the legacies of abandoned mines and responsibility for their rehabilitation (Coelho, Teixeira, and Gonçalves 2011; Hasheela et al. 2015). Globally, over a million abandoned mines (Figure 1) have been identified, including shafts, adits, and alluvial surface mines (Coelho, Teixeira, and Gonçalves 2011).

Abandoned mines are significant sources of persistent contamination, primarily due to heavy metals, polycyclic aromatic hydrocarbons (PAHs), and natural radionuclides (Gopinathan et al. 2023). These pollutants are released through mine waste, tailings, acid mine drainage (AMD), and other environmental processes (Iatan 2021). Heavy metals such as arsenic, lead, cadmium, and chromium persist in these sites, accumulating in waste and tailings, with increased mobility under acidic conditions (Wolkersdorfer and Mugova 2022; Han et al. 2023). PAHs are carcinogenic and mutagenic, partially persistent in anaerobic or low oxygen conditions, and bind strongly to sediments and soil (Li et al. 2019; Bukowska, Mokra, and Michałowicz 2022; Venkatraman et al. 2024). Natural radionuclides, including uranium, thorium, and radon, pose radiotoxic risks through inhalation or ingestion, depending on the environmental conditions (Momčilović et al. 2013; Paul et al. 2022). These contaminants migrate through soil, water, and air, influencing surrounding ecosystems and necessitating detailed environmental and health assessments to guide remediation efforts.

AMD is a major source of contamination, affecting watercourses globally. Many specific sites have been described in the literature e.g., Tinto-Odiel rivers in southern Spain (Grande et al. 2003), surface waters of Gujiao and Gyama valley in China (Huang et al. 2010; Ping et al. 2017), and Blyde river catchment in South Africa (Selebalo, Scholes, and Clifford-Holmes 2021). Over 23,000 km of contaminated rivers have been recorded in the United States (Cravotta et al. 2010; Gammons et al. 2010). Additionally,

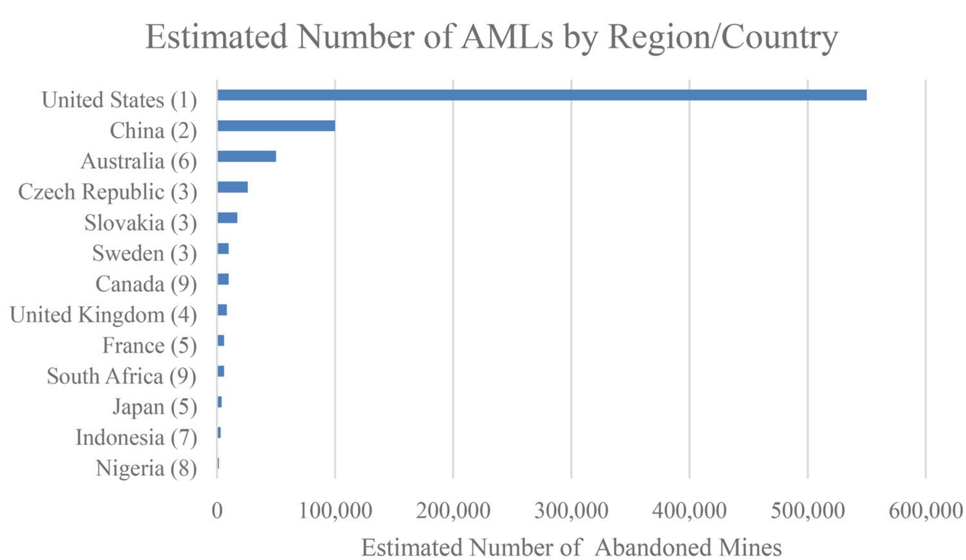

Figure 1. Estimated number of AMLs in some regions and countries 1. (BLM 2017); 2. (Ashby and van-Etten 2021); 3. (EEA 2004); 4. (Hughes 2024a); 5. (Martínez-López, Martínez-Sánchez, and Pérez-Sirvent 2021); 6. (Tyson 2020); 7. (Hans 2021); 8. (MECD 2022); 9. (Venkateswarlu et al. 2016).

the release of heavy metals and PAHs into surrounding soils and sediments can cause extensive pollution, with high contamination levels recorded in rivers and soils (Han et al. 2023; Hughes 2024a; Sartorius 2024; Wolkersdorfer and Mugova 2022). In coal AMLs, PAHs contribute to environmental and health risks, with severe implications for aquatic ecosystems (Li et al. 2019). Moreover, the dispersion of pollutants through surface runoff, groundwater leaching, and sediment transport exacerbates the contamination of water and soil resources (Candeias et al. 2015; Patel et al. 2024).

The persistence of pollutants such as heavy metals and organic contaminants in the environment poses ongoing risks to both humans and ecosystems (Sartorius 2023), especially when combined, leading to the loss of plant and animal species (Coelho, Teixeira, and Gonçalves 2011; Venkateswarlu et al. 2016; Worlanyo and Jiangfeng 2021). Studies of abandoned lead-zinc mines reveal their long-term health effects (US EPA 2000b; Obiora, Chukwu, and Davies 2016; Son et al. 2019; Sartorius et al. 2022; Chukwu and Obiora 2023), highlighting the need for targeted remediation and risk management (Naidu et al. 2019; Rouhani, Skousen, and Tack 2023).

Assessing these risks is critical to preventing long-term environmental damage and protecting public health. Risk can be defined as the product of the impact and the probability of that event occurring. In this context, risk is the potential for harmful impacts resulting from exposure to environmental stressors that could be physical, geological, biological, or chemical entities (US EPA 1998; Bartell 2008). Chemical risk assessment (CRA) typically consists of the comparison of an exposure level, the concentration of the chemical of interest in a given compartment (exposure assessment), with the corresponding safety threshold, derived from knowledge of the toxicity of that chemical (hazard assessment). CRA for AMLs essentially aligns with frameworks used in contaminated land assessment and follows a structured four-step evaluation involving hazard identification, hazard assessment, exposure assessment, and risk characterisation (WHO 2010; ISO 2017; UK EA 2020; OECD 2021; US EPA 2022). Whilst they may vary according to contextual environmental factors, the hazardous properties of a chemical, such as mobility, toxicity, persistence, and bioaccumulation are intrinsic to a substance's chemical structure and physico-chemical properties. CRA in AMLs typically use existing safety thresholds from regulatory hazard evaluation. Whilst a reference for that safety threshold is given, the process to select it is rarely reported. Accordingly, for this systematic evidence map, we will capture the sources of the hazard thresholds and, when available, the process and rationale for their selection. CRA in AMLs typically begins with site characterisation, involving a desk study to review historical data, including Earth Observation data, and a walkover survey to develop an initial Conceptual Site Model (CSM). This model identifies potential contaminant sources, exposure pathways, and receptors at risk. This informs the sampling strategy, sample preparation, and laboratory analysis to identify and quantify contaminants in line with established standards and procedures (US EPA 2000a; ISO 2018; UK EA 2020). We aim to capture exposure assessment methods specific to the AML context. Risk characterisation of AMLs is necessary to evaluate individual sites, prioritise those requiring remediation, and develop sustainable, site-specific mitigation plans to protect affected receptors. This risk management stage is beyond the scope of this systematic evidence map (SEM).

Rationale

This evidence map aims to identify and synthesise methods used to assess and evaluate chemical risks from AMLs. This study seeks to identify current practices as reported in the peer-reviewed literature. Although many national and international guidelines are available (e.g. US EPA 2000a; ICMM 2007; WHO 2010; NEPM 2014; CCME 2016; ICMM 2016; ISO 2017; UK EA 2020), most are general (for contaminated lands overall) and not tailored to AML-specific complexities. In contrast, academic research frequently applies more tailored and nuanced, site-specific assessments.

AMLs present unique challenges due to their diverse contaminant sources, multiple pathways, diffuse pollution, and persistent environmental legacies. The complex interactions of physical, chemical, and environmental hazards (Fields 2003; Lottermoser 2010; DEP 2015; Venkateswarlu et al. 2016; BLM 2017) are associated with the nature of mining operations, the type of mine structures, and longterm legacy impacts (Jain et al. 2016; Hufty 2019), which amplify overall risk. As recognised by ICMM (2007), traditional RA and guidance fail to consider the specificities of metals, a major problem in AMLs (ICMM 2007).

They require additional layers of considerations, such as mine infrastructure, waste repositories, geotechnical instability of hillslopes and tailings dams, river mobility, and the chronic effects of AMD. Consequently, the scope of contaminants studied, the sampling strategies, analytical methods, exposure models, specific sources, multiple pathways, contaminant fate and transport models, and specific receptors typically considered in CRAs of AMLs may differ from guidance that applies to contaminated land more generally.

Furthermore, CRA methods for AMLs need to be able to cope with increased complexity resulting from climate change and increased anthropogenic pressures. Accounting for multiple chemical stressors, mixture risk assessment, and considering the effects of changing magnitude and/or frequency of extreme events, sea-level rise, and other consequences of climate change, is required as these factors may modify exposure and therefore risks (Marras et al. 2022). For instance, extreme rainfall and rising temperatures can accelerate AMD formation, enhance contaminant mobility, and widen pollutant dispersion (Anawar 2013; Jacqueline et al. 2021; Li et al. 2024). Additionally, climate-driven impacts, including erosion, permafrost thaw, altered hydrology, and land instability (Palma et al. 2019; Santos et al. 2019; Bulovic, McIntyre, and Trancoso 2024), threaten ecosystems and human health (Grajal-Puche, Driver, and Propper 2024; Hughes 2024a). A case from Kam Kotia AML in Canada highlights that in 2012, rapid snowmelt caused a tailings dam breach, releasing contaminated water and sediment into the surrounding environment (MacMillan et al. 2021).

Some regulatory updates now reflect these emerging concerns. For example, the UK's updated guidance (UK EA 2020) mandates that climate change impacts be considered from project inception through long-term monitoring of contaminated land.

A bibliographic search for literature reviews synthesising methods of risk assessment specific to chemical contamination from AMLs yielded no comprehensive results. This suggests a notable gap in efforts to consolidate guidance in relation to risk from legacy mine contamination. A SEM can help synthesise current methods, and highlight where guidance is lacking, and how current practice deviates from established guidance.

This SEM aims to provide a foundational tool for improving AML-specific risk assessments and guiding future research, policy, and remediation efforts. Consolidating key insights, it seeks to provide a valuable reference for organisations, policymakers, researchers, and practitioners involved in addressing chemical risks from AMLs.

The literature search timeframe encompasses developments over the past two decades, capturing recent advances in AMLs risk assessment methods.

Systematic evidence map (SEM)

Evidence maps follow transparent and replicable methods, including the formulation of structured research questions, comprehensive and reproducible literature searches, and standardised data extraction procedures (James, Randall, and Haddaway 2016; Wolffe et al. 2019). This ensures consistency and reliability, making evidence maps particularly valuable for informing environmental policy, prioritising future research, and guiding mitigation strategies (James, Randall, and Haddaway 2016; Miake-Lye et al. 2016).

They are used to systematically catalogue and visualise the breadth and characteristics of research in a given field (Miake-Lye et al. 2016). In the context of environmental risk assessment, particularly in complex domains such as chemical contamination from abandoned mines, evidence maps help organise diverse sources of information across geographic regions, contaminant types, pathways, and receptors, amongst other factors (James, Randall, and Haddaway 2016). Unlike traditional systematic reviews that aim to synthesise outcomes, evidence maps focus on providing a high-level overview of the existing evidence, its areas of concentration, and significant gaps (Snilstveit et al. 2016). They do not necessarily include or necessitate a critical appraisal of individual studies, and such a step has not been included in the proposed work.

Scope

Globally, the most mined minerals by weight are coal, iron ore, aluminium (bauxite), copper, chromium, zinc, titanium, and lead (Casey 2018; LePan 2020; Venditti 2023) with over 7 billion tonnes of coal (IEA News 2023) and 17 million tonnes of lead-zinc mined each year (Venditti 2023). Among these, coal and lead mines are of particular concern due to the significant and well-documented severe health risks, especially those linked to exposure associated with legacy contamination from AMLs (Li and McDonald-Gillespie 2020; US EPA 2000a, 2000b; Sartorius 2023; Hughes 2024b). Hence, given their substantial toxic legacies, and the environmental persistence, and the health and ecological impacts of associated metals, lead-zinc mines are valuable case studies within the broader global context of AMLs contamination (Wani, Hammad Ahmad Shadab, and Afzal 2021; Tozsin et al. 2022; Rouhani, Skousen, and Tack 2023; Sartorius 2023, 2024; Morgan 2024). Accordingly, this evidence map will focus on methods of assessing risks from abandoned coal and lead-zinc mines as representative examples of AML cases.

Pb/Zn and coal AMLs may not fully capture the impacts of other abandoned metal and mineral mines, such as abandoned gold mines. As a result, all relevant methods may not be fully captured by focusing on Pb/Zn metals and coal mines. For example, because of the complex transformation processes of mercury (Alpers et al. 2005), abandoned mercury mines may require specific methods of risk assessment, which our approach would miss. This limitation is acknowledged, as reviewing all abandoned minerals/metal mines is impractical due to time and resource constraints. Nonetheless, this protocol has been carefully designed and may be adaptable to other types of AMLs.

This SEM seeks to answer the following question: What are the current methods for evaluating chemical risks from abandoned coal and lead-zinc mines? This has been articulated using a Population, Intervention, and Outcome (PIO) statement (Table 1).

Here, the Population refers to the types of AMLs being assessed, the Intervention refers to the chemical risk assessment methods applied, and the Outcome refers to the types of risks or effects identified as impacting ecological and/or human receptors.

Materials and methods

This protocol was developed giving due consideration to the recommendations of the Conduct of Systematic Reviews in Toxicology and Environmental Health Research (COSTER) (Whaley et al. 2020). Deviations from the COSTER recommendations are documented in the supplementary material 2.1. This protocol is reported following the Preferred Reporting Items for Systematic Review and MetaAnalysis Protocols (PRISMA-P) guidelines (Moher et al. 2015; Shamseer et al. 2015). The checklist is provided in the supplementary material 2.2 (PRISMA-P Checklist).

Eligibility criteria

The PIO statement in Table 1 was used as the starting point to articulate the eligibility criteria for inclusion in the SEM, with the following considerations:

Population: The focus is on abandoned coal and lead-zinc mines, as they represent an enduring toxic legacy with significant environmental and public health risks. Studies on other types of mines will be excluded, although the protocol may be adaptable for application to other abandoned mine types.

Table 1. Population, Intervention, and Outcome (PIO) statement of assessment practices relating to chemical risk from Abandoned Mine Lands.

What are the current methods for evaluating chemical risks from abandoned coal and lead-zinc mines?	
Population (types of AMLs)	Abandoned mine lands (mines that are no longer active, have been shut down, closed, forgotten, or have ceased operation). Only coal and lead-zinc mines; all other former mining activities are out of scope.
Intervention (methods of chemical risk assessment)	Chemical risk assessment practices; studies must include an evaluation of the chemical risks (comparing exposure levels with a safety threshold). Intermediary interventions include exposure assessment and/or modelling, and risk assessment and characterisation. Studies in which actual effects (realised risks) are monitored are within scope, while studies limited to exposure or hazard assessment or characterisation will not be considered.
Outcome (types of risk and effects identified for ecological and human receptors)	Risks and effects of chemicals associated with AMLs on ecological and human receptors.
Time frame	Peer-reviewed studies or grey literature published between the years 2000 to 2024.

Intervention: This refers to the chemical risk assessment methods applied to evaluate risk. Initial pilot activities revealed that there is a large body of literature documenting chemical contamination in AMLs, but many studies stop short of conducting a chemical risk assessment. Including these studies, which primarily focus on analytical methods reporting concentrations of chemical contaminants, would add little value as they have already been extensively researched and reported over the years, and the effort required would exceed the resources available for this project. The scope was therefore refined and limited to studies that report or conduct a chemical risk assessment. Consequently, studies focusing solely on exposure or hazard assessments will be excluded. However, studies that evaluate actual impacts or harm, i.e., realised risks due to exposure to toxic chemicals from AMLs will be considered eligible while not specifically targeted by our search strategy.

Outcome: Types of risks and impacts identified for ecological and human receptors. Studies investigating quantitatively measurable toxicological effects on reproduction, growth, behaviour, or development on ecological and human receptors at the community, population, or individual level will be included. Studies focusing on physical injury from engineering failures, hazards due to subsidence, or structural failures of tailings dams will be excluded. Studies focusing solely on exposure measurement, contaminant fate, transport, bioavailability, and bioaccumulation.

Study design: this evidence map is concerned with primary studies and reviews and meta-analyses will be excluded.

Timeframe: To comprehensively capture advances, applications, and persistent gaps in chemical risk assessment methods for AMLs, studies published between 2000 and 2024 will be included. This timeframe reflects a period of significant methodological development across international contexts (Table 2).

Information sources

The following six bibliographic databases will be searched for peer-reviewed articles using search algorithms adequate for each database:

- Web of Science
- PubMed

Table 2. Eligibility criteria.

Element	Statement	Inclusion	Exclusion
Population (types of AMLs)	Abandoned mine lands	Coal and lead-zinc mines. Abandoned open-pit or surface mines. Abandoned underwater and underground mines	Other types of AMLs, such as mercury and arsenic. Active mines, surface, open pit, underground, or underwater mines undergoing reclamation, rehabilitation, remediation, or restoration Other types of activities, such as active or abandoned quarries and smelting sites.
Intervention (methods of chemical risk assessment)	Chemical risk assessment practices	Process: evaluation of the actual effects or potential impacts due to chemical exposures	Process: Studies focusing on inventory, prioritisation of sites, and chemical contamination without assessing the risk of such contamination.
		Agents: organic and inorganic chemicals Exposure via water, sediment, soil, dust, air, biota (including food) Receptors: living organisms (humans and non-humans including microorganisms, plants, vertebrate and invertebrate animals), and their systems (populations, communities, ecosystems).	Agents: nanominerals, macrominerals, microplastics, or organometallics Receptors: studies focusing on environmental media as endpoints without assessing associated risks to humans and non-human organisms.
Outcome (types of risk and effects identified for ecological and human receptors)	Chemical risks and effects on ecological and human receptors	Evaluation of chemical/toxicological risks and impacts on reproduction, growth, behaviour, survival, or development in ecological and human receptors.	Physical injury due to natural or engineering hazards (subsidence), structural failure of tailing dams, hydrogeochemical behaviour, rock-water interaction.
Time frame	Peer-reviewed studies and grey literature	Studies published between 2000 and 2024	Studies published before the year 2000

- Academic Search Complete and Business Source Premier (via EBSCOhost)
- ScienceDirect
- Scopus

In addition, manual searches of grey literature not indexed in the selected databases will be conducted, targeting specific websites of government agencies, institutes, and other platforms, including:

- International Council on Mining and Metals (ICMM)
- US Environmental Protection Agency (US EPA)
- UK Environment Agency (UK EA)
- The International Organization for Standardization (ISO)
- Canadian Council of Ministers of the Environment (CCME)

Search strategy

Pilot searches were conducted to iteratively develop the search strategy, with the assistance of an information specialist (JMP) and insights from other systematic evidence maps related to environmental studies. Initially, we planned to include all types of mines in our mapping. However, after conducting preliminary searches, we realised this approach was unmanageable. We refined our focus to coal and lead-zinc mines. During the piloting phase, we noticed many studies simply reported chemical concentrations without contributing significantly to the research question. As a result, we decided to specify our focus on studies assessing risk.

This approach addressed the challenge of identifying manuscripts specifically related to chemical risk assessment methods from AMLs, as unspecific terms like “assessment” and “risk” yielded much irrelevant research. The number of hits for synonyms related to the elements of the PIO statement was recorded and combined using Boolean operators to ensure the search strategy maintained sensitivity while achieving some level of specificity.

A general approach is shown in Table 3. This was tested across all listed databases, adjusting the search strings to ensure appropriateness in retrieving relevant literature, except for ScienceDirect, which only supports eight Boolean operators, restricting long, complex search algorithms. Truncation of words was used with care. Proximity searches were run to find combined forms of terms. For example, Web of Science uses the proximity operator NEAR/3 while Scopus’s is w/3. A simplified search algorithm was developed for ScienceDirect as follows:

(Abandoned OR inactive) AND (coal OR lead OR zinc) AND Mine AND (Contaminant OR Pollution) AND “Risk Assessment”

The use of adequate filters, such as article type and publication year, was also explored and applied. The results from piloting the search strategy, the complete search algorithms for each database, the compiled search strings, and the number of articles retrieved from each database are included in the supplementary material 2.3 (search strategy). The sensitivity of the search strategy was assessed using a set of relevant articles identified during an initial review of the impacts of abandoned coal and leadzinc mines. All selected articles were successfully retrieved using Web of Science, while 90% were also captured by Scopus and PubMed. This confirmed that our core search terms would be effective in retrieving key literature relevant to the evidence mapping.

Table 3. General search strategy combined with Boolean operators.

S/N	Keywords	Synonym
#1	Abandoned mines	(inactive OR historic OR orphan OR derelict OR forgotten OR disused OR deserted OR abandoned) NEAR/3 (Coal OR Lead OR Zinc OR mine* OR exploitation OR site OR land)
#2	Contamination	Pollut* OR contamin* OR chemical
#3	Risk	Risk
Total	#1 AND #2 AND #3	(inactive OR historic OR orphan OR derelict OR forgotten OR disused OR deserted OR abandoned) NEAR/3 (Coal OR Lead OR Zinc OR mine* OR exploitation OR site OR land) AND (Pollut* OR contamin* OR chemical) AND (Risk)

The term “historic” was initially omitted from the pilot search. To ensure that relevant articles were not missed, this term was later searched separately in combination with other key terms, as shown below:

(Historic) NEAR/3 (Coal OR Lead OR Zinc OR mine OR exploitation OR site OR land) AND (Pollut* OR contamin* OR chemical) AND (Risk)*

Details of this additional pilot search and database-specific retrieval are provided in the supplementary material 2.3, and a flow diagram of the literature search results is presented in Suplementary materials

Data management

The screening of the literature is managed using CADIMA, a user-friendly, free online tool established by the Julius Kühn Institut and the Collaboration for Environmental Evidence (Julius Kühn Institut 2017). The Mendeley Reference Manager (Elsevier 2013) is used to manage manual searches while Citavi (Swiss Academic Software GmbH 2024) is used for automatic retrieval of full-text that are accessible.

Selection process/screening

The defined eligibility criteria are applied to screen the merged list of references retrieved from each literature source after the duplicates have been removed. Screening is carried out in two stages. In the first stage, titles and abstracts are examined for relevance to the formulated question, with studies deemed irrelevant excluded. In the second stage, the full texts of the remaining studies from the first stage will be assessed for inclusion. The reasons for excluding studies at the full-text stage will be documented.

CADIMA facilitates a consistency check as a method of piloting the screening stage. Any disagreements between screeners were resolved through discussion, and agreed outcomes of these discussions were used to revise and clarify the eligibility criteria and ensure a consensus on their interpretation. The eligibility criteria were applied to 15% (randomised by CADIMA) of the merged reference list at the title and abstract level by two reviewers, OVM and URE, the outcome was assessed as “poor” by Cadima, mainly because differences between ‘included’ and ‘unclear’ decisions for each eligibility criterion at the title–abstract screening stage are recorded as discrepancies, though they do not materially affect the selection process. Additionally, URE first applied a stricter interpretation of the exclusion criteria, leading to some articles being marked as “excluded” when they should have been rated “unclear”. A common example was when the title or abstract referred to AML without specifying the type of mine. All discrepancies from this pilot stage were resolved through discussion.

URE will screen the remaining articles independently, with an overlap of 20% of retrieved articles screened independently in duplicate by OVM as a quality control step. Any disagreements will be discussed as soon as they arise and resolved by consensus to ensure a consistent interpretation of eligibility criteria and avoid drift. If the rate of discrepancies in inclusion-exclusion decisions becomes too high (>1%), this will trigger duplicate screening of previously screened literature.

Data extraction

A data extraction template was developed and piloted to ensure consistency in the data extraction process. The pilot extraction was conducted independently by two reviewers, URE and OVM. Discrepancies in the extraction process were resolved through discussion and used to refine the data extraction template and ensure that a consensus understanding of the process was reached. The piloted data extraction sheet is available in supplementary material 2.5 (Data Extraction Sheet-Pilot 1 and 2). The data will be extracted from all included studies by a single reviewer (URE), and a sample of 25% of the extracted data will be independently checked by OVM. The data extraction template is designed to facilitate identification, documentation, and validation by a second reviewer. The finalised data extraction template is included in supplementary material 2.6 (Finalised data extraction template). A coding strategy combining both deductive and inductive approaches was developed to guide the data extraction process and is provided in the supplementary material 2.7 (Code Book for Data Extraction). This dual approach was selected to ensure both consistency and flexibility in capturing relevant information across studies. The deductive component involved the predefined categorisation of commonly encountered data types to standardise data recording. In parallel, the inductive component was designed to allow for the identification and categorisation of emerging terms or concepts, during the extraction process.

In brief, the following data will be extracted from all studies included during the full-text screening stage:

- Bibliographic metadata: Author(s), year, journal name, journal details (volume, issue, page), article title and abstract, and source of funding.
- Abandoned mined land details: study location (country, state, or county where the study was carried out), mine name, information about the type of mine, method of mining, duration of operation, and year of abandonment.
- Exposure measurement (if relevant): Sample medium, sampling strategy, sample storage, and preparation, sample volume (unit), method of chemical analysis, the limit of detection (including unit), precision, accuracy, contaminant or pollutant name, CAS number, information about the reported concentrations including the unit in the article, and other contextual measurements.
- Exposure modelling (if relevant): Source medium, pathway, target media, modelling method, and reference used to model the exposure, chemical name, CAS number, and outcome.
- Effect monitoring (if relevant): Taxonomic group, species, sampling strategy/method, sample storage and preparation, sample size (unit), type and level of observed effect, measurement methods, statistical significance, statistical methods, reported outcomes.
- Risk characterisation: source, exposure pathway, receptor, risk characterisation method, reference for the method used, the source of reference dose used (as well as notes on the selection of the reference dose when this is reported), uncertainty factors, risk category, outcome, consideration of mixtures.

This data extraction process is designed to systematically capture key components relevant to chemical risk assessment at AMLs.

First, bibliographic metadata will be extracted to organise the studies included in this evidence map. This information helps establish the context for teh conduct of each study, including its authorship, source of funding, publication details, abstract, and DOI.

The details of the abandoned mine lands, such as the location, type of mine, mining method, and duration of abandonment, are crucial for evaluating environmental impacts. These factors influence the pollution pathways and long-term risks associated with AMLs. Information about the mining history, waste characteristics, and local geology is fundamental to predicting and assessing site-specific environmental risks. The data from this section will help evaluate the applicability of different risk assessment methods across specific contexts and support subset analyses of methodological differences.

Exposure assessment methods include details on the sampling strategy, storage and preparation of samples, and the chemical analysis techniques used. Parameters such as the medium of exposure, contaminant(s), and limit of detection data will help inform the applicability and performance of the methods described. Exposure modelling is often essential for extrapolating measured concentrations of contaminants in environmental media to concentrations in relevant pathways of exposure. Information such as the exposure pathways, target media, and modelling methods helps to document current methods used to predict human and ecological receptor exposure to chemical contaminants from AMLs.

Effect monitoring data, such as the taxonomic group, species involved, and the type and level of effects observed, provide crucial evidence of the actual risks faced by receptors exposed to AML contaminants. These data are particularly important for identifying realised risks and understanding the ecological and human health consequences of chemical exposure.

Finally, data from risk characterisation methods, including references to the guidelines or method used, and the incorporation of uncertainty factors, will help document the range of risk assessment methods and applications across various exposure sources and routes. Also, information on whether mixture risks are considered, along with the range of methods used, will be recorded.

The extraction of these data types will ensure that the evidence map captures a comprehensive overview of current practices, which will allow us to query and document advancements, applications, and any gaps in methods related to risk from AMLs. Piloting the data extraction has helped to establish guidelines for maintaining a consistent format to extract data from included studies. The use of dropdown menus also allows for categorisation, which will facilitate the data analysis. Following the extraction process, the data will be cleaned, such as removing irrelevant symbols, units, or numbers, before analysis and revisiting categorisation, as appropriate.

Data analysis and reporting

The outcome will address our objectives: identifying procedures, extracting relevant information for evaluating chemical risks, and establishing current best practices related to chemical risk assessment of AMLs.

The key characteristics of abandoned mines that have undergone risk assessment will be summarised in tabular format, accompanied by a map visualising their geographic locations. Information related to exposure measurement, exposure modelling, effect monitoring, and risk characterisation will also be summarised in tables. This analysis aims to provide insights into both the diversity and frequency of various methodologies and practices used to characterise chemical risks from AMLs. This will be complemented by a critical narrative synthesis of the elements researchers identified as necessary in the included studies.

The visualisation software Tableau (Salesforce Inc. 2025) allows for the creation of interactive dashboards, enabling users to select subsets of data and easily view all relevant references and sources of information. Tableau will be employed to illustrate quantitatively the use of categories of methods from each risk assessment step and generate summary findings, highlighting key insights.

We will address the "current method" question for each risk assessment step through narrative analysis and trend evaluation from the database. Tableau will help track changes over time, illustrating how methods have evolved. This will be compared with guidance documents from organisations such as the US EPA, UK EA, ICMM, and ISO to assess alignment and deviations. Through the data analysis, we aim to identify scientific advancements in AML chemical risk assessment methods and highlight improvements made over recent years. Identified gaps and limitations will also be documented.

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Author contributions

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Disclosure statement

Authors have no competing interests. Complete declarations of interest for all co-authors are provided.

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Data availability statement

Supplementary materials relating to this protocol can be found here: https://doi.org/10.5281/zenodo.14246187.

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