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Dominant Heavy Metal Contaminants in Groundwater in the Vicinity of Municipal Solid Waste Sites: A Global Synthesis of Studies from 2015 to 2025

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ABSTRAK

Pencemaran air tanah oleh logam berat yang berasal dari lindi tempat pembuangan akhir (TPA) merupakan ancaman serius bagi kesehatan manusia dan kelestarian lingkungan. Masalah ini seringkali diperparah oleh lemahnya sistem pengelolaan lindi, keterbatasan kapasitas pemantauan, serta keragaman karakteristik limbah padat yang diterima oleh TPA. Penelitian ini bertujuan untuk mengidentifikasi logam berat yang paling sering terdeteksi dan paling dominan dalam mencemari air tanah di sekitar TPA. Melalui pendekatan *Systematic Literature Review* (SLR), sebanyak sepuluh artikel ilmiah primer yang terbit antara tahun 2015 hingga 2025 dianalisis secara menyeluruh. Proses pemilihan artikel ilmiah dilaksanakan berdasarkan kriteria inklusi dan eksklusi yang cermat, mencakup lokasi studi, jumlah logam yang dianalisis, aksesibilitas data, serta kesesuaian konteks dengan fokus kajian. Data disintesis untuk mengevaluasi lokasi TPA, prosedur pengambilan sampel, jenis logam berat yang diuji, standar kualitas air yang digunakan, dan kejadian status pencemaran melampaui ambang batas aman. Hasil analisis menunjukkan bahwa kromium (Cr), timbal (Pb), dan kadmium (Cd) merupakan kontaminan yang paling sering terdeteksi sekaligus paling banyak melampaui baku mutu. Besi (Fe) juga menunjukkan kecenderungan melampaui ambang batas aman meskipun frekuensi deteksinya tidak setinggi Cr dan Pb. Sementara itu, seng (Zn) ditemukan di seluruh studi namun jarang melebihi batas aman. Lima logam berat ini dikategorikan sebagai prioritas dalam pemantauan kualitas air tanah serta perencanaan mitigasi berbasis risiko. Temuan ini diharapkan dapat menjadi dasar ilmiah dalam perumusan strategi pengelolaan lindi yang lebih efektif, penguatan kebijakan lingkungan, dan perlindungan kesehatan masyarakat secara berkelanjutan.

***Kata kunci*:** baku mutu air tanah, dominasi logam berat, pencemaran air tanah, pengelolaan lindi TPA, risiko kesehatan lingkungan, strategi pemantauan terfokus, SDGs, Systematic Literature Review

ABSTRACT

Groundwater contamination by heavy metals originating from Municipal Solid Waste (MSW) landfill leachate poses a significant threat to human health and environmental sustainability. This issue is often exacerbated by inadequate leachate management systems, limited monitoring capacity, and the heterogeneous composition of solid waste entering landfills. This study aims to identify the most frequently detected and dominant heavy metals that pollute groundwater near MSW landfill sites. Employing a Systematic Literature Review (SLR) approach, ten primary research articles published between 2015 and 2025 were thoroughly analyzed. Article selection followed strict inclusion and exclusion criteria, including landfill location, number of metals analyzed, data accessibility, and relevance to the study context. The synthesized data evaluated study sites, sampling procedures, types of heavy metals tested, water quality standards applied, and regulatory exceedance status. The findings proves that chromium (Cr), lead (Pb), and cadmium (Cd) are the most frequently reported and most commonly exceeding safe limits. Iron (Fe) also shows a notable tendency to exceed standards, despite being analyzed less frequently. Zinc (Zn), on the other hand, appeared in all studies but rarely surpassed regulatory thresholds. These five metals—Cr, Pb, Cd, Fe, and Zn—are classified as priority contaminants in groundwater quality monitoring and risk-based remediation planning. This study contributes important scientific evidence for strengthening landfill leachate management strategies, improving regulatory frameworks, and enhancing long-term public health protection through focused groundwater monitoring initiatives.

***Keywords*:** dominance of heavy metals, environmental health risk, focused monitoring strategy, groundwater contamination, landfill leachate management, groundwater quality standards, SDGs, Systematic Literature Review

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1. INTRODUCTION

Rapid population growth, urbanization, and industrial development have significantly increased municipal solid waste (MSW) generation worldwide by altering consumption patterns and elevating daily waste production (Supangkat & Herdiansyah, 2020). Currently, the annual generation of municipal solid waste exceeds 2 billion tons, with forecasts indicating an increase to 3.4–3.88 billion tons by 2050. However, waste management practices vary considerably across countries. In high-income nations, only close to 2% of waste is disposed of without proper control, whereas in low-income countries, up to 93% is either dumped or incinerated without adequate treatment. Although some waste is disposed of in engineered landfills, a substantial portion remains unmanaged or poorly treated, posing severe environmental risks. Much of this waste ends up in municipal landfills that lack engineered containment systems or leachate treatment facilities, leading to uncontrolled leachate production with a high potential to contaminate surrounding groundwater (Yatoo et al., 2024).

Groundwater is a crucial source for both human and ecological systems, providing approximately 36% of domestic use, 42% of agricultural needs, and 27% of industrial water consumption worldwide. In many regions, it represents the only perennial source of freshwater, essential for drink, agriculture, sanitation, and maintaining ecosystem balance (Nanda et al., 2022; Taylor et al., 2012). Given this reliance, heavy metal contamination of groundwater originating from landfill leachate has emerged as main public health and environmental concern. Numerous studies have reported elevated levels of toxic heavy metals, such as; cadmium (Cd), chromium (Cr), lead (Pb), iron (Fe), and manganese (Mn), in landfill leachate, that are non-biodegradable and present enduring threats not only to human health but also to ecosystems (Boateng et al., 2019). For instance, groundwater near the Ghazipur Landfill in Delhi, India, was discovered to be polluted with Cd, Fe, and Cr (Sharma et al., 2025); around the Solous Landfill in Lagos, Nigeria, with Fe and Pb (Ojo-Awo et al., 2018); and around the Banyuurip Landfill in Magelang, Indonesia, with Mn and Fe (Budihardjo et al., 2018). Human contact to these metals occurs primarily through ingestion and dermal absorption. Once in the body, they can bioaccumulate and hinder cellular processes by inducing reactive oxygen species (ROS), impairing antioxidant enzymes, and damaging biomolecules such as deoxyribonucleic acid (DNA), proteins, and lipids—leading to severe health issues, including kidney dysfunction, neurological disorders, reproductive toxicity, cardiovascular complications, and elevated risks of cancer (Zhang et al., 2023; Balali-Mood et al., 2021). Consequently, such contamination will compromise the Sustainable Development Goals (SDGs), not only SDG 6 (clean water and sanitation), by limitating access to safe and clean water, but also SDG 3 (good health and well-being), by intensifying the disease burden on communities (Dermatas, 2017; Baldassarre et al., 2019)

Despite widespread acknowledgment of these risks, a significant knowledge gap remains regarding which specific heavy metals are the most dominant and persistent in groundwater impacted by landfill leachate. The composition of landfill leachate is highly heterogeneous, shaped by factors such as landfill age, waste characteristics, degradation stages, and climatic conditions, resulting in broad variability in heavy metal concentrations (Kjeldsen et al., 2002; Renou et al., 2008). This variability presents major challenges for monitoring, risk assessment, and management. Leachate treatment systems often fail to reduce heavy metal concentrations to meet regulatory discharge standards, and even when some metals are removed, others often persist at hazardous levels (Butt et al., 2016). Furthermore, the lack of accurate knowledge about contaminant dominance and speciation often leads to inappropriate treatment technology selection and ineffective mitigation efforts (T. A. Kurniawan et al., 2006). Thus, systematically identifying the most frequently detected and dominant heavy metals in landfill-affected groundwater is highly essential for advancing treatment strategies, enhancing pollution modeling, and achieving regulatory compliance all of which safeguard human well-being and environmental integrity.

Identifying dominant heavy metals in landfill-contaminated aquifers enables targeted, site-specific mitigation strategies. It facilitates the prioritization of risk assessments by considering toxicity, persistence, and bioaccumulation potential. For instance, Cd and Pb are associated with several severe diseases such as; nephrotoxicity, neurotoxicity, and carcinogenic effects, requiring urgent intervention (Popa et al., 2021; Ali et al., 2019). Such information also enables pollution severity classification, guides public health advisories, and supports location-specific policy decisions. Moreover, spatial-temporal data on heavy metal concentrations are essential for simulating subsurface contaminant transport and evaluating long-term risks. Numerical models software support high-resolution predictions of groundwater flow and solute transport. Models such as MODFLOW, HYDRUS 2D, and FEFLOW have been applied across diverse hydrogeological settings, each incorporating different mechanisms including; advection-dispersion, non-equilibrium sorption, and geochemical interactions. (Nyika et al., 2024; Chotpantarat & Sutthirat, 2011; Bincy et al., 2025). These simulations help forecast plume behavior, delineate contamination zones, and assess long-term risks. Furthermore, understanding the dominant heavy metals informs the best selection and design of remediation process. For instance, phytoremediation strategies can be optimized using hyperaccumulator species such as *Brassica juncea* for Cd or *Vetiveria zizanioides* for Pb (Yadav et al., 2018; Ali et al., 2013). Understanding the redox behavior and solubility characteristics also informs whether in-situ immobilization, adsorption barriers, or ex-situ treatment is the most suitable. Finally, groundwater monitoring systems benefit substantially from such knowledge, enabling more strategic well placement, focused detection protocols, and optimized sampling frequencies. Without clear and comprehensive data on contaminant dominance, mitigation efforts risk being misaligned, generic, or insufficient—ultimately threatening both environmental protection and public health outcomes.

The present study aims to systematically review and synthesize worldwide findings from 2015 to 2025 regarding the most commonly detected and dominant heavy metals in groundwater around municipal solid waste disposal sites. This article also aims to assess their exceedance levels based on regulatory standards and highlight the implications for environmental modeling, risk assessment, and targeted remediation planning.

2. METHODOLOGY

The methodological framework adopted in this article is a Systematic Literature Review (SLR), which is a structured approach for identifying, evaluating, and synthesizing pertinent studies to answer targeted research questions transparently (Siddaway et al., 2019). SLR offers methodological strengths such as minimized bias, enhanced transparency, replicability, and comprehensive coverage, leading to evidence-based conclusions (Gurevitch et al., 2018; Turk, 2021). SLR has been implemented in various environmental studies, such as in evaluating forest fire mitigation policies and exploring trends in green supply chain management and green innovation (Gusmira et al., 2025; Kurniawan & Hartini, 2025). In this research, the SLR process entails defining research questions using Population-Concept-Context (PCC) framework, determining eligibility criteria, conducting systematic searches, screening and selecting studies, extracting data, and synthesizing findings clearly and rigorously.

2.1. PCC Framework

Population-Concept-Context (PCC) framework was employed in this SLR to explicitly structure the research question and eligibility criteria. The PCC framework is particularly recommended for scoping and systematic reviews that seek to map existing evidence comprehensively and transparently within defined boundaries, without necessarily focusing on comparison or interventions (Pollock et al., 2023). The population refers to who or what is specifically targeted and included in the review, the concept refers to the specific phenomena or themes that the review intends to examine and understand, and at last the context defines the boundaries that frame and focus the research question and the literature review (Peters et al., 2020). The detailed practice of the PCC framework elements specifically in the present study is presented in Table 1.

Table 1. PCC Framework

Framework element	Application in this study
Population (P)	Groundwater in the vicinity of municipal solid waste sites.
Concept (C)	Types of heavy metals commonly detected as contaminants, for instance; chromium (Cr), lead (Pb), cadmium (Cd), iron (Fe), zinc (Zn), manganese (Mn), copper (Cu), nickel (Ni), aluminum (Al), arsenic (As), mercury (Hg), cobalt (Co), among others.
Context (C)	Municipal solid waste sites globally.

2.2. Research Question

Formulating a well-defined research question is essential as it guides the review by defining eligibility criteria, shaping the search strategy, and directing data extraction and synthesis processes. Based on the PCC framework that has been formulated previously, a clear and specific research question was developed to direct this review. Therefore, the guiding research question for this study is: "What types of heavy metals are most commonly detected in groundwater in the vicinity of municipal solid waste sites globally?"

This research question is intended to provide a systematic identification and mapping of both the types and categories of heavy metal contaminants that are frequently found and reported in groundwater in the vicinity of landfill sites. The findings derived from this study will provide a comprehensive perspective on dominant heavy metal contamination, as a critical foundation to support the selection of representative parameters for environmental risk assessment and groundwater modeling.

2.3. Eligibility Criteria

The eligibility criteria were developed according to the previously formulated research question and PCC framework to ensure that only pertinent studies were comprised in this systematic literature review. Both Inclusion and exclusion criteria were formulated systematically to ensure a focused scope, enhancing transparency, consistency, and rigor while reducing bias in systematic evidence syntheses (Haddaway et al., 2018). The details of eligibility criteria are clearly provided in Table 2.

2.4. Information Sources and Search Strategy

Information sources and search strategies were systematically formulated to ensure comprehensive identification of relevant studies for this review. Several reputable academic databases and publisher platforms were selected as primary sources—Scopus, MDPI, Springer, etc. These databases and platforms were chosen due to their extensive coverage of peer-reviewed journals in environmental engineering and waste management, thereby ensuring that the review captures the most relevant and high-quality literature. All of these information sources were accessible using the institutional email provided by Universitas Gadjah Mada, facilitating full access to subscription-based journals and supporting a comprehensive literature search.

Table 2. Study Eligibility Criteria

Criteria	Inclusion	Exclusion
Population	Studies investigating groundwater samples collected from areas surrounding municipal landfill sites	Studies focusing exclusively on surface water, river water, leachate alone, rainwater, or soil contamination without groundwater component
Concept	Studies reporting the types, categories, and/or levels of heavy metals in groundwater (e.g., Cr, Pb, Cd, Fe, Zn, Mn, Cu, Ni, Al, As, Hg, Co, etc.), specifically those that analyzed more than five heavy metals	Studies reporting only organic pollutants (e.g., PAHs, PCBs, etc.), microbiological contaminants, radionuclides, or those analyzing five or fewer heavy metals without relevant data
Context	Studies related to municipal solid waste landfill sites globally, including both active and inactive landfills	Studies unrelated to landfill contamination or conducted in non-landfill contexts
Type	Original peer-reviewed journal articles presenting primary research findings	Review articles, conference proceedings, book chapters, editorials, commentaries, symposium results, and theses/dissertations
Language	Publications written in English or Indonesian	Publications written in languages other than English or Indonesian
Date	Publications published between 2015 and 2025	Publications published outside this range
Accessibility	Full open-access publications with downloadable texts available for screening and extraction	Closed-access publications articles without full-text availability

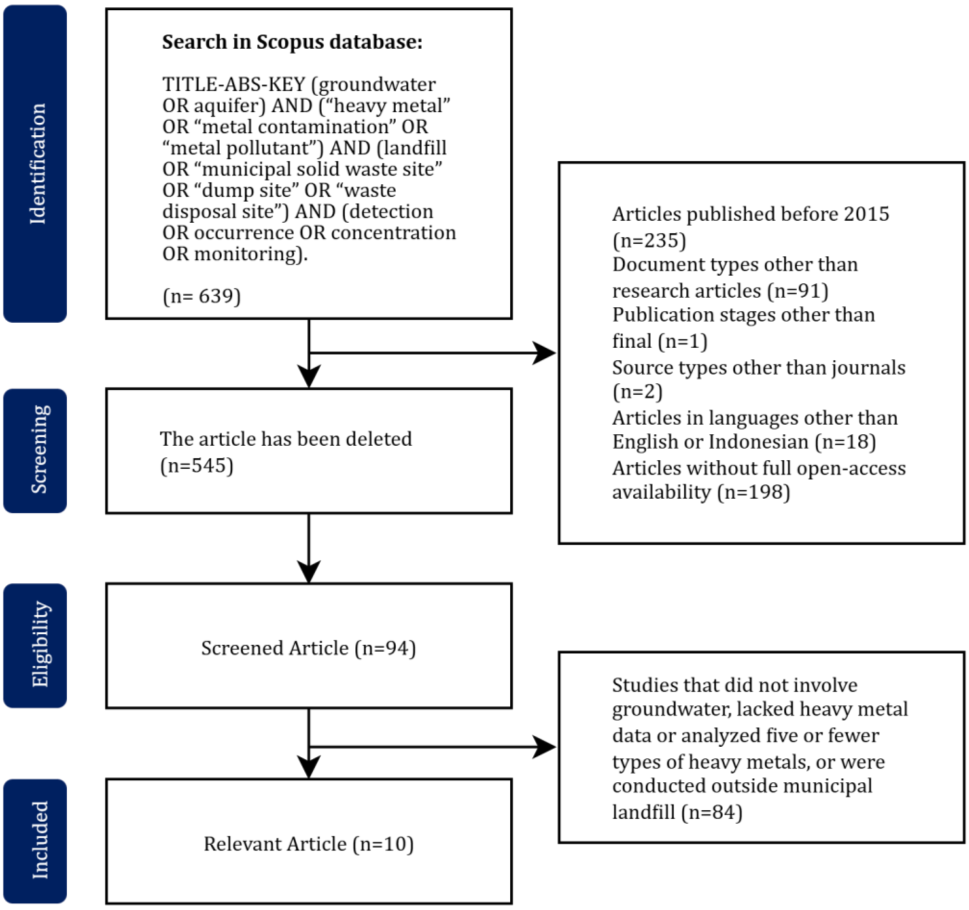

Figure 1. PRISMA Diagram of the Study Selection Process

A Boolean search strategy was developed based on the research question, combining keywords and their synonyms related to population (groundwater), concept (heavy metals), and context (landfill). The search strategy implemented combinations of terms, including "(groundwater OR aquifer) AND ("heavy metal" OR "metal contamination" OR "metal pollutant") AND (landfill OR "municipal solid waste site" OR "dump site" OR "waste disposal site") AND (detection OR occurrence OR concentration OR monitoring)." The search terms were systematically adapted to meet the syntax specifications of individual databases, thereby facilitating the effective retrieval of relevant literature.

2.5. Study Selection Process

The process of article selection was guided by the preferred reporting items for systematic reviews and meta-analyses (PRISMA) diagram, which provides a transparent and standardized method for reporting the counts of records identified, screened, excluded, and included in the review. The complete screening process, including reasons for exclusion at each stage, is illustrated in Figure 1.

3. RESULT AND DISCUSSION

This section reveals the results of the systematic literature review and provides a critical discussion of selected studies. The analysis is organized to highlight key patterns, methodological approaches, and major findings associated to heavy metal contamination in groundwater near municipal solid waste disposal sites. Comparisons are made across different study locations and contexts to identify dominant trends, regional characteristics, and research gaps. This part synthesizes implications for environmental modeling, risk assessment, and policy development.

3.1. Literature Identity in the Study

This subsection presents the identity of the ten selected studies included in this systematic literature review. Table 3 briefly presents key information for each study, including the authors, year of publication, research title, journal name, and publisher. This initial profiling intends to provide an outline of the academic sources analyzed and serves as a basis for further thematic synthesis and comparative analysis in the subsequent sections.

The studies span a publication range from 2015 to 2025 and were published in international journals, including those from Springer, Elsevier, MDPI, and other reputable academic publishers. These studies encompass diverse geographical contexts, covering landfill sites in three continents, including Asia (Laos, India, Iraq, and China), Africa (Egypt, Nigeria, Zambia, and Ghana), and Europe (Poland and Czech Republic). This variation enhances the representativeness of the review by capturing region-specific characteristics of landfill leachate effect on groundwater. The selected studies serve as foundation for the thematic synthesis and comparative analysis presented in the following sections.

a. Summary of Selected Studies

This subsection synthesizes ten selected studies that have investigated heavy metal contamination in groundwater in the vicinity of municipal solid waste landfill sites. These studies demonstrate considerable variation in geographic setting, landfill properties, sampling frameworks, and the analytical techniques employed. Although their methodologies vary, the studies still provide valuable empirical evidence on contamination patterns, regulatory exceedances and exposure risks. The essential attributes of each study, including landfill location, sample collection process (covering when, where, and how), and key findings, are comprehensively summarized in Table 4.

Tabel 3. Literature Identity Overview

No	Author	Year	Title	Journal	Publisher
1	Magda M. Abd El-Salam, Gaber I. Abu-Zuid	2015	Impact of landfill leachate on the groundwater quality: A case study in Egypt	Journal of Advanced Research	Cairo University & Elsevier
2	Noudeng Vongdala, Hoang-Dung Tran, Tran Dang Xuan, Rolf Teschke, Tran Dang Khanh	2019	Heavy Metal Accumulation in Water, Soil, and Plants of Municipal Solid Waste Landfill in Vientiane, Laos	International Journal of Environmental Research and Public Health	MDPI
3	Daniel Abiriga, Live S. Vestgarden, Harald Klempe	2020	Groundwater contamination from a municipal landfill: Effect of age, landfill closure, and season on groundwater chemistry	Science of the Total Environment	Elsevier
4	Francis Chizoruo Ibe, Alexander Iheanyichukwu Opara, Collins Emeka Amaobi, Bridget Onyekachi Ibe	2021	Environmental risk assessment of the intake of contaminants in aquifers in the vicinity of a reclaimed waste dumpsite in Owerri municipal, Southeastern Nigeria	Applied Water Science	Springer
5	Anna Podlasek, Aleksandra Jakimiuk, Magdalena Daria Vaverková, Eugeniusz Koda	2021	Monitoring and Assessment of Groundwater Quality at Landfill Sites: Selected Case Studies of Poland and the Czech Republic	Sustainability	MDPI
6	James Nyirenda, Philip Mwamba Mwansa	2022	Impact of leachate on quality of ground water around Chunga Landfill, Lusaka, Zambia and possible health risks	Heliyon	Cell Press (an imprint of Elsevier)
7	Piu Saha, Kundil Kumar Saikia, Manoj Kumar, Sumi Handique	2023	Assessment of health risk and pollution load for heavy and toxic metal contamination from leachate in soil and groundwater in the vicinity of dumping site in Mid-Brahmaputra Valley, India	Total Environment Research Themes	Elsevier
8	Fatin F. Aziz, Entessar Kareem Hussain	2023	Spatiotemporal Variation of Heavy Metals and Pollution Indices in Groundwater Around Al-Diwaniyah Open Dump	Journal of Ecological Engineering	Polish Society of Ecological Engineering
9	Daniel Gyabaah, Esi Awuah, Richard Amankwah Kuffour, Prince Antwi-Agyei, Samuel Wiafe, Samuel Boamah Asiedu	2024	Assessment of dumpsites leachate, geotechnical properties of the soil, and their impacts on surface and groundwater quality of Sunyani, Ghana	Environmental Advances	Elsevier
10	Juan Du, Wenbing Yang, Qi Yang, You Li, Xiang Wan, Anan Zhu, Zhenzhu He, Rajendra Prasad Shrestha, Amar Razzaq	2025	Assessment and Seasonal Monitoring of Groundwater Quality in Landfill-Affected Regions of China: Findings from Xiangyang	Water	MDPI

Table 4. Study Summary: Sites, Sampling, and Findings

No	Reference	Object Study	Sampling Procedures	Key Findings
1	Abd El-Salam & Abu-Zuid, 2015	Borg El-Arab Landfill and El-Hammam Landfill, Alexandria, Egypt	Leachate and groundwater samples were collected from Borg El-Arab and El-Hammam landfills in Alexandria, Egypt. Sampling was conducted bimonthly over a year, yielding an altogether of six leachate and twelve groundwater samples. At each site, leachate was collected during the landfill's active operational season, while groundwater was sampled from monitoring wells surrounding the landfill cells. All samples were preserved and analyzed according to the Standard Methods for the Examination of Water and Wastewater (American Public Health Association, 2005). Heavy metals, such as; Ni, Pb, Cu, Mn, Cr, Cd, Zn, and Fe, were quantified using Atomic Absorption Spectrophotometry (Shimadzu AA-6650 flame system).	The landfill leachate exhibited high levels of organic and inorganic pollution, with significant mean concentrations of conductivity (40,921 µS/cm), total dissolved solids (27,452 mg/L), chloride (11,387 mg/L), BOD (10,824 mg/L), and COD (15,629 mg/L). Heavy metals were present in varying concentrations, with elevated levels of Fe (6.314 mg/L), Mn (0.839 mg/L), and Zn (0.749 mg/L). Although groundwater near the landfill showed no severe contamination, several parameters—namely conductivity, TDS, chloride, sulfate, Mn, and Fe—exceeded WHO and EPA limits. Organic groundwater contamination was negligible. The BOD/COD ratio (0.69) pointed out that the landfill was in the initial stabilization phase. These findings emphasize the need for continuous groundwater monitoring, enhanced anaerobic degradation, and pre-treatment of municipal waste to reduce leachate impact.
2	Vongdala et al., 2019	Municipal Solid Waste Landfill, Vientiane, Laos	Water, soil, and plant samples were taken from the municipal solid waste landfill in Vientiane, Laos, during both wet and dry seasons in 2017. Surface water was sampled at three points along a wetland stream, while groundwater was collected from two wells located inside and 70 meters outside the landfill. A total of five water samples were obtained each season. Additionally, 48 composite soil samples were taken from 0-25 cm depth near leachate canals and 60 meters beyond the landfill. Twenty-four plant samples, including *Ipomoea aquatica* and *Pennisetum purpureum*, were gathered from leachate ponds and surrounding areas. All samples were digested using HNO_3 and HCl and examined for six heavy metals (Cd, Cr, Cu, Ni, Pb, and Zn) utilizing Inductively Coupled Plasma Emission Spectrometry (ICP-ES, Shimadzu ICPE-9000) following standardized protocols	The landfill in Vientiane, Laos, showed significant deposition of heavy metals, particularly cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), and zinc (Zn), across water, soil, and vegetation matrices. Although surface water remained within permissible limits, groundwater samples exceeded WHO and ANESs standards for Cr (up to 0.08 mg/L) and Pb (up to 0.06 mg/L). Soil samples inside the landfill exhibited Cd (3.73-3.76 mg/kg) and Cu (54.06-66.82 mg/kg) levels surpassing Dutch target values, indicating eco-toxicological risk. The edible plant *Ipomoea aquatica* accumulated Cr, Pb, Cu, and Zn in concentrations 5-86 times higher than WHO safety limits, posing serious health risks. These findings highlight the landfill's unlined, open-dumping status and emphasize the urgent need for phytoremediation, strict leachate control, and continuous environmental monitoring.
3	Abiriga et al., 2020	Revdalen Landfill, Bø, Norway	Groundwater samples were taken from the Revdalen Landfill site in Norway, spanning a 24-year monitoring period (1992-2015). Sampling was conducted four times annually from 1992 to 2002 and twice per year thereafter, targeting five wells positioned along a 324-meter downgradient transect from the landfill. Multilevel sampling systems were employed at selected wells to capture vertical variation, with samples extracted using nitrogen pressure or suction pumps. All samples were analyzed for 28 physicochemical parameters, including heavy metals (Fe, Mn, Cd, Cr, Cu, Pb, Ni, Zn, and Hg) and organic pollutants, using standard laboratory techniques such as the Winkler method and Inductively Coupled Plasma Spectrometry (ICP)	The leachate from Revdalen Landfill exhibited moderate to high contamination with both inorganic and heavy metal pollutants, notably elevated levels of bicarbonate (mean: 213 mg/L), iron (mean: 19.0 mg/L), manganese (mean: 4.4 mg/L), ammonium (9.2 mg/L), and chloride (36 mg/L). Groundwater samples also contained detectable levels of cadmium, lead, and PAHs, although most remained below Norwegian drinking water standards. However, concentrations of Fe, Mn, Pb, and Cd exceeded upstream reference values, indicating clear pollution. Over the 24-year monitoring period, contaminant levels declined significantly with landfill age, nearing reference values after 21 years. Landfill closure led to notable reductions in solutes, while seasonal effects were minimal. These findings suggest the landfill was entering its final stabilization phase, and highlight the efficacy of aquifer-based natural attenuation, although groundwater use was prohibited due to residual health risks, underscoring the importance of long-term monitoring and post-closure management.
4	Ibe et al., 2021	Oweri Municipal, Imo State, Nigeria	Groundwater samples were taken in July 2018 from five boreholes located within a repurposed municipal waste dumpsite along Akachi Road, Owerri, Southeastern Nigeria. An additional control sample was obtained from a housing zone with no history of waste disposal. A total of six samples were collected using pre-cleaned plastic containers, following on-site rinsing procedures. Physicochemical parameters	Groundwater near the reclaimed waste dumpsite in Owerri, Nigeria, exhibited notable contamination, particularly elevated levels of nitrate (up to 36.8 mg/L), aluminium (up to 0.26 mg/L), and chromium (up to 0.06 mg/L), exceeding WHO drinking water standards. Although zinc, iron, manganese, copper, and sulphate remained within permissible limits, the hazard quotient and carcinogenic risk values for chromium surpassed safety thresholds (HQ > 1; CR > 10^{-6}), pointing to

No	Reference	Object Study	Sampling Procedures	Key Findings
			and anions were analyzed using a Hanna H1 83200 photometer, while heavy metals, such as; Al, Cr, Cu, Fe, Mn, and Zn, were digested with HNO_3 and quantified using Atomic Absorption Spectrophotometry (AAS, Agilent 240FS AA), adhering to standard analytical protocols.	serious health hazards affecting adults as well as children. The landfill, which had been reclaimed without proper remediation, showed persistent leachate influence on aquifer quality. The site can be classified as an unlined, reclaimed landfill with ongoing contamination risks. These findings highlight the pressing need for groundwater treatment, continuous monitoring, and policy enforcement before any residential use or further borehole development in such areas.
5	Podlasek et al., 2021	Radiowo Landfill, Warsaw, Poland and Zdounky Landfill, Kroměříž District, Czech Republic	Groundwater samples were collected semiannually, during spring and autumn from 2008 to 2018, at two municipal solid waste landfills; Radiowo in Warsaw, Poland, and Zdounky in the Zlín Region, Czech Republic. The monitoring involved a total of eleven piezometers at Radiowo and six at Zdounky, including upstream and downstream locations. Sampling followed ISO standards (PN-EN ISO 5667-3:2013-05 and PN-ISO 5667-11:2004). Samples were stored at 1-5°C and investigated immediately for physicochemical parameters and heavy metals (Cr, Zn, Pb, Cd, and Hg) using standard methods in accordance with national and WHO drinking water guidelines.	The study revealed that groundwater around the Radiowo (Poland) and Zdounky (Czech Republic) landfills exhibited low concentrations of heavy metal pollution due to effective landfill engineering and protection systems. The levels of Cr, Zn, Pb, Cd, and Hg in groundwater were generally within WHO and EPA permissible limits, with only occasional exceedances observed for Cr and Pb near Zdounky, attributed to runoff from nearby industrial and agricultural activities rather than direct landfill leakage. The HEI and HPI indices confirmed low contamination levels (HEI < 10; HPI < 100), indicating the groundwater was suitable for consumption. The landfills were in post-closure or reclaimed states, and the Radiowo site benefited from vertical bentonite barriers and recirculation systems. The findings emphasize the critical role of continuous groundwater monitoring and robust sealing systems in mitigating long-term environmental risks from landfill leachate.
6	Nyirenda & Mwansa, 2022	Chunga Landfill, Lusaka, Zambia	Groundwater and leachate samples were collected in and surrounding Chunga Landfill, Lusaka, Zambia, during two distinct durations, August to September and November to December 2019, representing the dry and wet seasons. Fourteen sampling sites within a 1,700 m radius from the landfill's leachate pond were selected. At each location, six grab samples were taken and composited, yielding a total of 84 samples per period. Samples were preserved in HDPE bottles under cooled conditions and later analyzed at the Zambia Agriculture Research Institute using MP-AES (Agilent MP4210) for heavy metals (Cu, Pb, Cr, Cd, and Zn), while physical parameters were examined at the University of Zambia. Analyses followed APHA (1998) protocols and were benchmarked against ZABS (2010) and WHO (2011) standards.	The Chunga landfill leachate exhibited high concentrations of both organic and inorganic pollutants, notably with COD reaching 10,378.5 mg/L, BOD 1,569.6 mg/L, TDS 39,166 mg/L, and electrical conductivity up to 78,328 μS/cm. Heavy metals were also significantly elevated, particularly lead (2.591 mg/L), cadmium (1.149 mg/L), and chromium (2.699 mg/L), exceeding WHO permissible limits. Groundwater samples revealed widespread contamination, especially for lead and cadmium, with maximum values of 0.660 mg/L and 0.089 mg/L, respectively. The leachate pollution index (LPI) was 30.17 and the heavy metal pollution index (HPI) reached 3,938.92, indicating substantial contamination potential. These findings confirm that the landfill has entered the methane fermentation phase and highlight the urgent need for improved leachate collection systems and continuous groundwater quality monitoring to mitigate health and environmental risks.
7	Saha et al., 2023	Tezpur Dumping Site, Mid-Brahmaputra Valley, India	During the pre-monsoon season of 2022, leachate, soil, and groundwater samples were collected from a municipal landfill site located near the Morabharali River in Tezpur, Assam, India. A total of 12 soil and multiple groundwater samples were taken from areas surrounding residential and roadside locations using manual drilling and deluge pumps, respectively. Leachate samples were preserved with nitric acid and refrigerated prior to analysis. Heavy metals (Pb, Cd, Ni, Mn, Zn, Cu, Cr, and Co) in all samples were quantified using ICP-MS (iCAPQnova Series) and AAS (Thermo Scientific ICE-3500), following EPA Method 3051A and APHA (1995) protocols. Quality assurance included triplicate analyses and use of certified reference materials.	The study revealed that landfill leachate from an unstable municipal solid waste site in Tezpur, India, contained high levels of heavy metals, with particularly elevated concentrations of Mn (mean: 125.93 mg/L), Cr (20.89 mg/L), and Cu (9.05 mg/L). Groundwater exhibited contamination with Mn (up to 639.52 mg/L), Cr (1.97 mg/L), and Pb (6.91 mg/L), exceeding WHO and US EPA drinking water standards. The groundwater pollution index (HPI) and contamination index (CI) identified several sites with high pollution levels, with Mn contributing most significantly. Despite some locations showing acceptable risk, hazard index (HI) values for Cr, Cd, and Pb indicated substantial non-carcinogenic and carcinogenic risks, notably for children. The landfill was classified as unstable based on a high Leachate Pollution Index (LPI = 18.39), necessitating urgent treatment measures and continuous groundwater monitoring to mitigate health and environmental risks.
8	Aziz & Hussain, 2023	Al-Diwaniyah Open Dump, Al-Qadisiyyah	Samples of groundwater were obtained from three traditional dug wells located at varying spatial intervals (100 m, 500 m, and 750 m)	Groundwater samples near the Al-Diwaniyah open dumpsite exhibited elevated concentrations of heavy metals, especially Zn (up to 0.921 mg/L), Fe

No	Reference	Object Study	Sampling Procedures	Key Findings
		Governorate, Iraq	from the Al-Diwaniyah open dump in Al-Qadisiyah Governorate, Iraq. Sampling was carried out periodically from August 2022 to March 2023, covering both dry and rainy seasons. A total of six groundwater samples were obtained using sterile 1-liter plastic bottles, stored at 4°C, and assessed within 48 hours. The levels of seven heavy metals (Cd, Cr, Cu, Fe, Ni, Pb, and Zn) were analyzed using flame Atomic Absorption Spectrophotometry (Shimadzu AA-7000) following the Standard Methods for the Examination of Water and Wastewater (APHA, 2019).	(0.772 mg/L), Cu (0.641 mg/L), Pb (0.373 mg/L), Cr (0.324 mg/L), Ni (0.172 mg/L), and Cd (0.066 mg/L), with concentrations generally highest at site W1, closest to the dumpsite. While Zn and Fe levels were mostly under WHO/IQS limits, Pb, Ni, and Cd exceeded permissible drinking water standards at several points. Pollution indices (HPI, HEI, and Cd) identified site W1 as heavily polluted and unfit for consumption, while W2 and W3 remained within acceptable ranges. The site, lacking engineered leachate controls, appears to contribute significantly to subsurface contamination, underscoring the urgency for regular monitoring, heavy metal treatment, and engineered landfill development to prevent further groundwater degradation.
9	Gyabaah et al., 2024	Sunyani Municipal and Nsoate Community Dumpsite, Bono Region, Ghana	Leachate, groundwater, and surface water samples were collected from urban and peri-urban dumpsites in Sunyani, Ghana. Sampling occurred during three distinct seasons—minor rainy (August 2021), dry (February 2022), and major rainy (June 2022)—to capture seasonal variation. In total, six leachate samples, eleven triplicate groundwater samples from urban areas, eight triplicate groundwater samples from peri-urban areas, and three surface water samples were collected. Groundwater was sampled from boreholes and wells within a 1 km radius after pumping for 3 minutes. Physicochemical parameters were measured in situ, while heavy metals (As, Cd, Cr, Cu, Fe, Pb, Ni, and Zn) were analyzed using ICP-MS and Atomic Absorption Spectrophotometry, following USEPA (2006) protocols. All samples were preserved in HDPE bottles, acidified with HNO_3, stored below 4°C, and analyzed in triplicate to ensure quality control.	The landfill leachate at the Sunyani dumpsite exhibited severe contamination, with exceptionally high concentrations of chlorides (up to 106,340 mg/L), BOD (up to 820 mg/L), ammonium (up to 267.6 mg/L), and cadmium (up to 5.73 mg/L), resulting in leachate pollution loads (LPL) exceeding 2,500, far above the disposal standard (LDS > 100). Although the leachate was heavily polluted, most groundwater samples (79%) showed excellent quality (WQI < 25), with only those located within 75-155 m of the dumpsite exceeding WHO limits for iron (2.4 mg/L) and nickel (0.18 mg/L), indicating localized contamination. Surface water, however, was severely impacted, particularly mid- and downstream sections of Sunyani stream, with cadmium (1.88 mg/L) and iron (14.68 mg/L) greatly surpassing WHO standards. The site is considered mature, with declining LPL by waste age. The study emphasizes the critical need for leachate treatment, reclamation of the dumpsite, and rigorous monitoring of nearby water sources.
10	Du et al., 2025	13 Landfill Sites, Xiangyang City, Hubei Province, China	Groundwater sampling was conducted near 13 landfill sites in Xiangyang City, China, during both dry and wet seasons in 2025. Altogether, 178 samples were collected from 89 piezometer wells, strategically sited to capture upstream and downstream contamination gradients. Sampling followed the Technical Specifications for Groundwater Environmental Monitoring (HJ164-2020) using low-flow submersible pumps and other devices, with pre-washing, on-site parameter testing, and standard preservation methods. Laboratory analyses covered 62 parameters, including heavy metals, organics, and conventional ions, using ICP-MS, atomic fluorescence spectrometry, ion chromatography, GC-MS, and HPLC, in accordance with GB/T 14848-2017 and GB3838-2002 standards.	The landfill leachate in Xiangyang City led to widespread groundwater contamination, with over 73% of samples falling into the poor (Class IV) or extremely poor (Class V) based on the Chinese GB/T 14848-2017 standard. Key pollutants included nitrate (up to 4.75× above limit), manganese (up to 18.6×), lead (up to 7.6×), and arsenic (up to 3.13×), while organic contaminants such as polychlorinated biphenyls (4.76×) and hexachlorobenzene (3.84×) were also detected. Groundwater near landfills in Zaoyang City and Gucheng County (sites L4 and L5) was most severely affected. Seasonal monitoring confirmed higher leachate impact during wet periods, while persistent pollutants like nitrate and manganese indicated chronic contamination. The landfills were largely unlined, lacking proper leachate management. These findings underscore the urgent need for modern liners, advanced leachate treatment, and continuous groundwater quality

While Table 4 provides a general overview of the selected studies, Table 5 presents detailed synthesis focusing on analytical aspects. Specifically, it outlines the water quality standards referenced in each study, the types of heavy metals analyzed, and those found to exceed regulatory thresholds. Those informations are vital for recognizing pollution trends, identifying high-risk contaminants, and informing priority setting in groundwater monitoring and mitigation strategies.

Table 5. Comparison of Standards Used, Heavy Metals Analyzed, and Exceedance Observed in Reviewed

No	Reference	Standard Used	Heavy Metals Investigated	Heavy Metals Exceeding Standard
1	El-Salam & Abu-Zuid (2015)	WHO (1993), EPA (2003)	Ni, Pb, Cu, Mn, Cd, Cr, Zn, and Fe	Mn and Fe
2	Vongdala et al. (2019)	WHO (2011), ANEs (2009)	Cd, Cr, Cu, Ni, Pb, and Zn	Cr and Pb
3	Abiriga et al. (2020)	Norwegian Drinking Water Stadard	Fe, Mn, Cd, Cr, Cu, Pb, Ni, Zn, and Hg	Fe, Mn, Cd, and Pb
4	Ibe et al. (2021)	WHO (2004a)	Zn, Mn, Cr, Al, Fe, and Cu	Al and Cr
5	Podlasek et al. (2021)	WHO (2017)	Cr, Zn, Pb, Cd, and Hg	Cr and Pb
6	Nyirenda & Mwansa (2022)	WHO (2011), ZABS (2010)	Cu, Pb, Cr, Cd, and Zn	Pb, Cr, and Cd
7	Saha et al. (2023)	WHO (2018), US EPA, India CPCB	B, Cr, Mn, Co, Ni, Cu, Pb, Cd, Ba and Zn	Cr, Mn, and Pb
8	Aziz & Hussain (2023)	WHO (2022), IQS (2014), FAO (1985)	Cd, Cr, Cu, Fe, Ni, Pb, and Zn	Cd, Cr, Pb, Ni, and Fe
9	Gyabaah et al. (2024)	WHO (2004)	As, Cd, Cr, Cu, Fe, Pb, Ni, and Zn	Cd and Fe
10	Du et al. (2025)	Groundwater Quality Standard (GBIT 14848-2017)	Pb, As, Cd, Cr, Fe, Mn, Zn, Hg, Cu, Se, Tl, and Al	Pb, As, Fe, Zn, and Al

Table 6. Ranking of Heavy Metals Based on Detection Frequency and Regulatory Exceedance across Reviewed Studies

No	Heavy Metal	Detection Frequency	Exceedance Frequency	Average Score
1	Cr (Chromium)	9	7	8.0
2	Pb (Lead)	9	7	8.0
3	Cd (Cadmium)	8	5	6.5
4	Fe (Iron)	6	6	6.0
5	Zn (Zinc)	10	1	5.5
6	Mn (Manganese)	5	4	4.5
7	Cu (Copper)	8	0	4.0
8	Ni (Nickel)	6	2	4.0
9	Al (Aluminums)	2	2	2.0
10	As (Arsenic)	2	2	2.0
11	Hg (Mercury)	2	1	1.5
12	Co (Cobalt)	1	0	0.5

b. Ranking of Dominant Heavy Metals

Subsequent to the identification of regulatory standards, types of heavy metals analyzed, and those found to exceed permissible limits in each study, a ranking framework was established to determine the most dominant and environmentally concerning heavy metals in landfill-impacted groundwater. This ranking is derived from two key indicators: detection frequency, which reflects how often a particular metal was analyzed and reported in the selected studies, and exceedance frequency, which reflects how frequently the observed concentrations of that metal surpassed the applicable regulatory thresholds. The detection frequency illustrates the monitoring priorities of the researchers, while the exceedance frequency captures the real-world severity of contamination and potential threats to human and ecological health. By combining both key indicators into a weighted average score, this approach ensures a more balanced and meaningful assessment—highlighting contaminants that are not only reotinely monitored, but also consistently exceed safety limits. Such a dual-metric strategy is essential for identifying major pollutants, guiding groundwater quality monitoring efforts, and informing the design of targeted, risk-based remediation strategies. The rank is provided in Table 6.

The ranking presented in Table 6 reveals a clear hierarchy of heavy metal contaminants based on their detection frequency and regulatory exceedance across the selected studies. The two highest-ranked contaminants, chromium (Cr) and lead (Pb), stand out as the most dominant pollutants in landfill-impacted groundwater. Both contaminants were identified in nearly 90% of the studies and surpassed regulatory limits in approximately 70% of those instances. The combination of frequent detection and exceedance indicates their widespread presence and persistent hazardous properties, reinforcing their classification as priority pollutants in both the WHO guidelines and most national drinking water standards.

Cadmium (Cd) also emerges as a heavy metal of major concern. Although it was detected in slightly fewer studies than Cr and Pb, its concentrations frequently exceeded regulatory limits, highlighting its persistence and toxicological significance. Cd is well recognized for its high toxicity even at low levels, with bioaccumulation risks that affect renal and skeletal systems. Its relatively frequent exceedance in the reviewed studies indicates that it poses a significant environmental and public health risk, especially in regions where the landfill containment is inadequate or groundwater monitoring is infrequent.

Iron (Fe) occupies the fourth position. Although Fe is considered as an important element, its high frequency of exceedance relative to its detection frequency suggests that when it is present, it often appears in concentrations that surpass safe drinking water concentrations. This trend may reflect specific geochemical conditions around the landfill sites or the presence of waste with high iron content. The elevated Fe concentrations may also correlate with anaerobic leachate conditions that promote the dissolution of iron-bearing minerals.

Zinc (Zn), while detected in all ten studies, only exceeded quality standards in one, placing it lower in the risk profile despite its ubiquity. A comparable pattern is observed for Copper (Cu), which had a high detection frequency but zero exceedance. This case indicates that although these elements are commonly monitored their concentrations remain within safe ranges. This finding is insightful for optimizing future monitoring programs by helping distinguish between metals of concern and those of lower priority.

Both manganese (Mn) and nickel (Ni) occupy the middle tier of the ranking. Mn, in particular, shows a notable exceedance rate despite a moderate detection frequency, pointing to possible under-monitoring in some studies. Mn has been increasingly recognized for its neurotoxic effects, especially in children, and its presence in landfill-impacted groundwater should not be underestimated.

Lower-ranked elements such as aluminum (Al), arsenic (As), and mercury (Hg) were detected in fewer studies, but when reported, those elements frequently exceeded permissible limits. Their placement in the ranking reflects both limited inclusion in study designs and localized contamination scenarios rather than widespread occurrence. Nevertheless, given their high toxicity and regulatory importance, the presence of these elements justifies more consistent inclusion in monitoring protocols, particularly in regions characterized by geological or anthropogenic susceptibilities.

The metal at the bottom of the ranking, Cobalt (Co), was detected in only one study each and showed no exceedance. While this suggests a relatively low concern in the current body of literature, it is also possible that these elements are underrepresented due to analytical limitations, lack of prioritization, or regional regulatory perspective. Their ecological or toxicological importance of these findings suggests the need for more exploration in targeted assessments or extended longitudinal studies.

This ranking framework supplies a reliable, evidence-based foundation for determining priority heavy metals in groundwater monitoring in landfill-impacted regions. It helps inform regulatory attention, guide the selection of indicator parameters in leachate and groundwater analyses, and tailor treatment strategies to the most critical metal contaminants. Moreover, the ranking contributes to the development of risk-based remediation approaches that are both cost-effective and health-protective. Ultimately, the synthesis reinforces the urgent priority for improved landfill site management, standardized monitoring practices, and context-specific policy interventions to address the threat of heavy metal contamination in groundwater systems.

4. CONCLUSION

This systematic literature review synthesized evidence from ten primary studies published between 2015 and 2025 concerning heavy metal contamination in groundwater near municipal solid waste disposal sites. Within this limited evidence base, chromium (Cr) and lead (Pb) showed the highest combined detection and regulatory exceedance frequencies, followed by cadmium (Cd) and iron (Fe). Zinc (Zn) was investigated in all reviewed studies but rarely exceeded the applicable regulatory thresholds. These results indicate recurring contamination patterns across the included studies rather than establishing a universally applicable ranking of heavy metals in landfill-affected groundwater.

The findings should be interpreted in light of several limitations. First, only ten studies met the eligibility criteria, limiting the statistical robustness and generalizability of the synthesis. Second, the studies were unevenly distributed geographically, with evidence concentrated in Asia, Africa, and Europe and no eligible studies representing the Americas or Oceania. Third, comparisons of regulatory exceedance were affected by differences in national and international water-quality standards, including variations in threshold values and publication years. Additional heterogeneity in landfill conditions, groundwater sampling designs, analytical methods, monitoring periods, and hydrogeological settings further restricted direct comparison among studies. Moreover, no formal study-quality or risk-of-bias assessment was conducted; therefore, all included studies contributed equally to the synthesis regardless of their methodological rigor.

Accordingly, Cr, Pb, Cd, Fe, and Zn may be considered candidate parameters for site-specific groundwater monitoring rather than universal priority contaminants. Their inclusion in remediation planning or contaminant-transport modeling should be treated as a preliminary hypothesis that requires validation using local background concentrations, metal speciation, landfill characteristics, hydrogeological conditions, and temporal monitoring data. Similarly, remediation technologies should not be selected solely from the ranking presented in this review but should be evaluated through source identification, site characterization, feasibility assessment, and pilot-scale testing. Future reviews should include a broader and more geographically balanced evidence base, apply a formal study-quality assessment, and improve comparability by reassessing reported concentrations against a consistent reference standard where sufficient data are available.

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