



Heavy Metal Contamination in Drinking Water, Groundwater, and Industrial Water Sources in Kirkuk and Selected Iraqi Cities: A Structured Evidence Synthesis and Evaluation of Treatment Technologies

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Abstract:

This structured review synthesizes published evidence on heavy metals in drinking-water treatment systems, groundwater, and industrial water sources in Kirkuk and selected Iraqi cities. The quantitative synthesis is restricted to six primary water-quality studies cited in the manuscript ([4–9]); other references are used for standards, methods, treatment technologies, or contextual interpretation. Because the original search log did not preserve database-specific retrieval, duplicate-removal, and exclusion counts, these upstream PRISMA quantities are reported as not recorded rather than reconstructed retrospectively. Evidence was appraised using five domains: sampling adequacy, sampling-period reporting, analytical-method reporting, quality assurance/quality control, and completeness of quantitative reporting. The synthesis shows marked spatial heterogeneity: municipal treated-water evidence from Kirkuk indicates comparatively low metal concentrations, whereas industrial wastewater in Kirkuk and shallow groundwater evidence from other Iraqi cities show substantially greater contamination. Direct-ingestion HQ calculations are interpreted only for potable or potentially consumed

waters; industrial wastewater is treated as a source-pathway hazard and is not assigned a drinking-water ingestion risk. Temporal inference remains limited by sparse, non-equivalent studies and differences in source type and analytical design. Treatment technologies are therefore presented as context-dependent options rather than prescriptive upgrades. The review identifies cadmium and lead as priority contaminants and emphasizes standardized monitoring, transparent analytical QA/QC, and source-specific treatment selection.

Keywords: adsorption; groundwater; heavy metal; Kirkuk; risk assessment; water treatment

تلوث المعادن الثقيلة في مياه الشرب والمياه الجوفية والمياه الصناعية في كركوك ومدن عراقية مختارة: توليف منظم للأدلة المنشورة وتقييم تقنيات المعالجة

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الخلاصة:

تجمع هذه المراجعة المنظمة الأدلة المنشورة عن المعادن الثقيلة في مياه الشرب والمياه الجوفية والمياه الصناعية في كركوك وبينما [4-9] ومدن عراقية مختارة. واقتصر التوليف الكمي على ست دراسات أولية لجودة المياه مستشهد بها في البحث استُخدمت بقية المراجع للمعايير والمنهجيات وتقنيات المعالجة والسياق العلمي. ونظرًا إلى أن سجل البحث الأصلي لم يحفظ أعداد النتائج المسترجعة من كل قاعدة بيانات أو المكررات أو أسباب الاستبعاد بصورة كاملة، لم تُخلق هذه الأعداد بأثر رجعي، بل صُنفت على أنها غير مسجلة. كما قُيِّمت جودة الأدلة وفق خمسة مجالات تشمل كفاية العينات، وفترة أخذ العينات وطريقة التحليل، وضبط الجودة، واكتمال عرض البيانات.

أظهر التوليف تباينًا مكانيًا واضحًا بين أنواع مصادر المياه؛ إذ تشير الأدلة الخاصة بالمياه المعالجة في كركوك إلى مستويات أقل نسبيًا، في حين تظهر مياه الصرف الصناعي في كركوك وبعض أدلة المياه الجوفية الضحلة في مدن عراقية أخرى القائم على الابتلاع المباشر على المياه الصالحة أو المحتمل HQ مستويات أعلى من التلوث. واقتصر تفسير معامل الخطر استهلاكها، بينما عوملت مياه الصرف الصناعي بوصفها خطرًا على مسار المصدر-الانتقال وليس كمياه شرب. كما أن الاستدلال الزمني بقي محدودًا بسبب قلة الدراسات وعدم تجانس مصادر المياه وطرق التحليل.

تُعرض تقنيات المعالجة بوصفها خيارات تعتمد على نوع المصدر وتركيز الملوث والظروف التشغيلية، وليس كتوصيات تنفيذية نهائية من دون دراسة جدوى محلية. وتشير الأدلة إلى أولوية متابعة الكاديوم والرصاص، مع الحاجة إلى برنامج رصد موحد، وإبلاغ واضح عن إجراءات ضمان وضبط الجودة التحليلية، وربط اختيار تقنية المعالجة بطبيعة مصدر المياه.

الكلمات المفتاحية: الامتزاز؛ المياه الجوفية؛ المعادن الثقيلة؛ تقييم المخاطر؛ كركوك؛ معالجة المياه

1. Introduction:

Access to safe drinking water is a basic human right and a foundation of public health. Nevertheless, heavy metal contamination is a global risk to water quality as metals such as cadmium (Cd), lead (Pb), chromium (Cr), nickel (Ni), arsenic (As) and mercury (Hg) are non-biodegradable, toxic and have bioaccumulation potential [1]. These contaminants are derived from natural geogenic sources and from anthropogenic activities, including mining, industrial discharge, agricultural runoff and improper waste disposal. Chronic exposure to heavy metals via drinking water consumption has been reported to cause Nephrotoxicity, Hepatotoxicity, carcinogenicity, neurological damage and developmental disorders [2].

Decades of conflict, aging infrastructure, industrial pollution and water scarcity caused by climate change make Iraq especially vulnerable to water quality issues. [3] The courses of the Tigris and Euphrates rivers, the main sources of fresh water for the country, is fed with untreated municipal and industrial effluent. The Heavy Metal Pollution Index (HPI) in several seasons [4] has exceeded the critical value of 100 in the water treatment plants of the capital, Baghdad, indicating that heavy metal pollution has reached critical levels. Likewise, in post-conflict Mosul, shallow groundwater wells were found to be alarmingly contaminated with cadmium and lead levels exceeding the World Health Organization (WHO) and Iraqi drinking water standards [5].

Kirkuk Governorate in northern Iraq is an important oil-producing and agricultural region with growing water demand. Its water supply relies on surface-water and groundwater resources and municipal treatment systems, including the Kiwan and Al-Dibs plants [6]. Published evidence also documents industrial effluents in Kirkuk [8]. Because these source types have different exposure pathways, the present review distinguishes treated drinking water, groundwater, and industrial wastewater rather than treating them as a single exposure category.

Published Iraqi evidence is geographically dispersed across Kirkuk, Baghdad, Mosul, and Duhok/Shekhan, and it varies in sampling design, analytical technique, reporting completeness, and water-source type [4-9]. These differences limit direct numerical comparison and make an explicit evidence-quality assessment necessary before spatial or temporal interpretation.

Accordingly, this review aims to: (i) synthesize the primary quantitative water-quality evidence cited for Kirkuk and selected Iraqi comparison areas; (ii) compare reported concentrations with national and international drinking-water benchmarks only where the source is relevant to potable-water assessment; (iii) distinguish reported or recalculated pollution/risk indices from source-pathway hazards; (iv) evaluate spatial and temporal patterns cautiously in light of methodological heterogeneity; and (v) appraise treatment technologies as context-dependent options for Iraqi water systems.

2. Material and methods:

2.1 Data Collection Strategy

The review was structured using PRISMA 2020 reporting principles. The original search used Scopus, Web of Science, ScienceDirect, and Google Scholar with combinations of (“heavy metals” OR “trace metals” OR “toxic metals”) AND (“drinking water” OR “groundwater” OR “potable water” OR “water treatment”) AND (“Kirkuk” OR “Iraq” OR “Mosul” OR “Baghdad” OR “Kurdistan”). Eligible primary studies had to report quantitative water-quality data relevant to heavy metals. The submitted manuscript cited 25 references in total, but only six primary water-quality studies ([4–9]) supplied the quantitative evidence synthesized here. References [1–3] and [10–25] serve contextual, methodological, standards, or treatment-technology purposes and are not counted as included primary water-quality studies. The original search log did not preserve the numbers retrieved from each database, duplicates removed, full texts excluded, or exclusion reasons. These quantities therefore cannot be reconstructed reliably and are explicitly reported as “not recorded” in the PRISMA flow diagram. This correction replaces the unsupported statement that 28 studies were extracted in detail. The study-selection diagram is presented in Figure 1.

2.2 Data Extraction and Quality Assessment

For each primary water-quality study, the review extracted, when reported, study area, water-source type, sampling period, sample size, analytical technique, target metals, concentration statistics, and principal findings. Evidence quality was assessed across five reporting domains: (1) sample size/sampling design, (2) sampling-period reporting, (3) analytical-technique reporting, (4) QA/QC or standard-method reporting, and (5) completeness of quantitative results. Each domain was classified as clearly reported, partly reported, or not reported in the

information available to this review. This appraisal is a transparency assessment of the evidence base and is not presented as a formal risk-of-bias instrument.

2.2.1 Study-selection transparency (PRISMA 2020)

Figure 1. PRISMA 2020 study-selection transparency diagram. NR = not recorded in the original search log; six primary quantitative water-quality studies ([4–9]) form the evidence synthesis.

PRISMA 2020 study-selection transparency
Records identified from databases: NR (original search log not preserved)
Duplicates removed: NR
Records screened / full texts assessed: NR
Primary quantitative water-quality studies included: n = 6 ([4–9])
Context/method/standards/treatment references: n = 19
Quantitative evidence synthesis: n = 6 primary studies

2.3 Comparison Standards

The extracted concentration data were compared with the Iraqi Standard 417/2011 and WHO drinking-water guidance [10,11]. The WHO benchmark was checked against the current fourth edition incorporating the first, second and third addenda (2026). Comparisons were made only when the water type and reported units were compatible; industrial wastewater was not treated as drinking water.

2.4 Health Risk Assessment Indices

Three well-established indices were used to assess the health risk of heavy metal exposure through drinking water:

(a) Heavy Metal Pollution Index (HPI): HPI offers a composite measure of overall water quality as compared to the maximum allowable concentrations. It is computed using Equation (1) [4,12]:

$$\text{HPI} = \sum W_i \times Q_i / \sum W_i \quad (1)$$

where $W_i = 1/S_i$ (2) is the unit weight (inverse of the standard value, S_i) and Q_i is the sub-index for the i th metal as $Q_i = [(M_i - I_i) / (S_i - I_i)] \times 100$ (3), where M_i is the monitored value, I_i is the ideal value (usually zero) and S_i is the standard value. HPI value below 50 indicates low pollution level, 50-100 indicates moderate pollution level and above 100 indicates critical pollution level [4,12].

(b) Metal Index (MI) (Equation (4)): The MI provides a simplified evaluation of overall metal contamination:

$$MI = \sum (C_i/MAC_i) / n \quad (4)$$

where C_i is the measured concentration, MAC_i is the maximum allowable concentration, and n is the number of metals analysed. An MI less than 0.5 indicates low contamination, 0.5-1.0 indicates moderate and above 1.0 indicates high contamination [12].

(c) Hazard Quotient (HQ): HQ is retained as a health-risk framework for interpreting studies that report the required exposure inputs. Because the included sources do not provide a harmonized set of concentration, exposure, and reference-dose data, HQ values were not newly recalculated across studies in this review. This avoids false precision from combining heterogeneous datasets. The HQ expression is given in Equation (5).

In this revision, HQ is interpreted only for water intended or plausibly used for drinking. Industrial wastewater is excluded from direct-ingestion HQ interpretation because it is not a potable-water exposure medium; its metal concentrations are discussed as a potential source of contamination to receiving surface water or groundwater. Where both mean and maximum concentrations are reported, mean values are used for central comparative summaries and maxima are retained as worst-case observations, with the basis stated explicitly in the table.

$$HQ = CDI / RfD \quad (5)$$

where $CDI = \text{Chronic Daily Intake (mg kg}^{-1} \text{ day}^{-1}) = (C \times IR \times EF \times ED) / (BW \times AT)$ (6), C = metal concentration (mg L^{-1}), IR = ingestion rate (2 L day^{-1} for adults), EF = exposure frequency ($365 \text{ days year}^{-1}$), ED = exposure duration (70 years), BW = body weight (70 kg) and AT = averaging time (25 550 days). RfD Oral Reference Dose (mg/kg/day) [13]. $HQ > 1$ indicates potential non-cancer health risk.

2.5 Treatment Technology Evaluation

The treatment technologies were evaluated by four criteria: (i) removal efficiency of Cd, Pb, Cr and Ni; (ii) capital and operational costs (USD/m³); (iii) energy demand and technical complexity; (iv) feasibility for implementation in Iraq, taking into account availability of energy, maintenance capacity and economic constraints. Data were gathered from published reviews on heavy metal removal technologies [14,15,16].

3. Results and Discussion:

3.1 Drinking Water Quality Standards for Heavy Metals

Table 1 The maximum allowable concentrations of heavy metal priorities according to WHO (2017), Iraqi Standard 417/2011 and US EPA regulations. For most parameters, Iraqi standard is similar to WHO recommendations with the same limits for Cd (3 µg/L), Pb (10 µg/L), Cr (50 µg/L), Ni (70 µg/L), Zn (3000 µg/L), Cu (2000 µg/L) and As (10 µg/L). For Mn there are significant differences (400 µg/L in Iraqi standard vs 50 µg/L in EPA) and for Hg (6 µg/L in Iraqi/WHO vs 2 µg/L in EPA). The reviewed studies are assessed for their level of contamination by means of these standards.

Table 1. Drinking Water Quality Standards for Heavy Metals (µg/L)

Parameter	WHO (current guidance)	Iraqi Std (417/2011)	EPA (USA)
Cd	3	3	5
Pb	10	10	15
Cr	50	50	100
Ni	70	70	—
Zn	3000	3000	5000
Cu	2000	2000	1300
Mn	400	400	50
Fe	300	300	300
Al	200	200	200
As	10	10	10
Hg	6	6	2

3.2 Heavy Metal Concentrations in Iraqi Drinking Water Sources

The quantitative comparison was restricted to values that could be verified directly in the cited primary sources. Baghdad drinking-water evidence [4] and Kirkuk industrial-wastewater evidence [8] are presented separately because they represent different water matrices and cannot be interpreted against the same exposure context. The concentration data are presented in Table 2.

Al-Mayah [4] studied heavy metals in 11 water treatment plants in Baghdad in four seasons. The average lead levels were 15.2 µg/L, which is above the Iraqi standard of 10 µg/L, with the highest values of 28.7 µg/L in summer. Cadmium approached the regulatory limit with a mean and maximum of 2.5 µg/L and 4.1 µg/L, respectively. Chromium (mean 48.3 µg/L) and nickel (mean 62.1 µg/L) were within standards but seasonal elevations. The elevated summer concentrations were attributed to the increased evaporation; lower river flows and higher industrial discharge during peak production periods.

Altahaan and Dobslaw [5] provide a two-year (2022-2023), four-campaign assessment of shallow and deep groundwater in Mosul. Their design supports a genuine temporal comparison across wet and dry seasons and shows that shallow groundwater is more vulnerable to seasonal and post-conflict deterioration than deeper wells. These results are used as regional contextual evidence rather than as a direct surrogate for Kirkuk drinking-water quality.

Specifically for Kirkuk, two different sets of data appear. Sulyman [6] evaluated Kiwan and Al-Dibs water treatment plants and found all measured heavy metals at the level less than detection limits in the treated effluent indicating effective conventional treatment. However, Abbas et al. [8] reported that the industrial wastewater of five zones in Kirkuk had catastrophic contamination, cadmium ranged from 940 to 6850 µg/L (313 to 2283 times the Iraqi standard) and lead ranged from 830 to 2640 µg/L (83 to 264 times the standard). Such industrial discharges constitute a serious potential threat to drinking water supplies if discharged untreated to surface waters or allowed to seep into groundwater.

Mohammed et al. [7] reported cadmium exceedances in 6 out of 17 groundwater sources in Duhok and Shekhan with concentrations ranging between 1.5 and 15.8 µg/L (mean 5.2 µg/L). Other metals were within acceptable limits. The authors ascribed the increase in Cd to geological factors and agricultural runoff.

Table 2. Heavy Metal Concentrations in Iraqi Water Sources (units as shown).

Evidence source	Water matrix	Period/design	Cd	Pb	Interpretation	Method/source note
Baghdad WTPs [4]	Treated drinking water	Sep 2018-Aug 2019; monthly; 11 WTPs	Mean 0.0039 mg/L	Mean 0.0418 mg/L	Annual means exceeded cited limits for several metals	Phoenix-986 AAS; source-reported HPI/MI
Kirkuk industrial areas [8]	Industrial wastewater	5 industrial locations	Mean 2.962 mg/L; range 0.94-6.85	Mean 1.738 mg/L; range 0.83-2.64	Severe industrial contamination; not drinking water	AAS and ICP-OES reported; calibration/RSD described
Mosul [5]	Groundwater	2022-2023; 4 campaigns; 8 wells	Source reports temporal variation	Source reports temporal variation	Shallow wells more vulnerable than deep wells	Regional contextual evidence
Kirkuk WTP [6]	Municipal drinking water	2015-2016	Not reported as a verified synthesis value	Not reported as a verified synthesis value	Supports local WTP context; not used for invented metal values	Physicochemical-focused study

<DL = below detection limit; — = not reported.

Figure 2 compares the reported mean Cd and Pb concentrations for the two sources described in its caption.

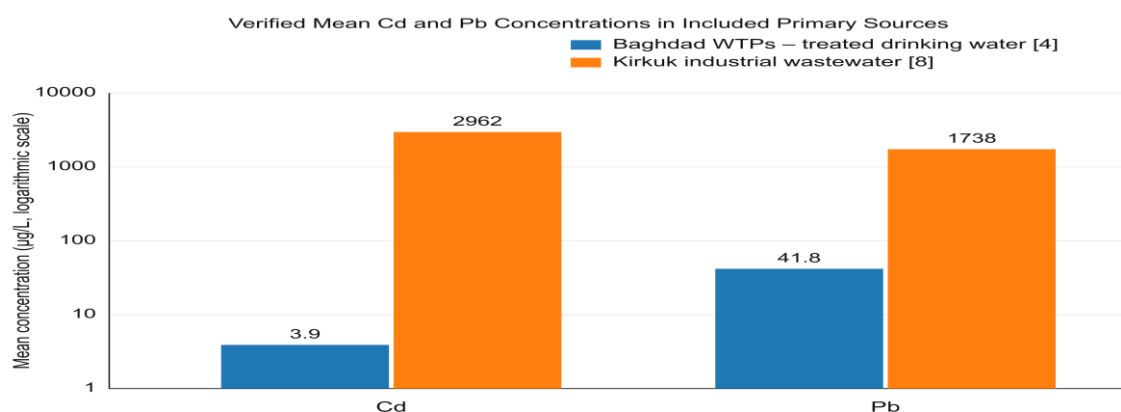


Figure 2. Verified mean Cd and Pb concentrations reported in two primary sources included in the evidence synthesis. Baghdad values represent treated drinking water [4], whereas Kirkuk values represent industrial wastewater [8] and are shown only as source-pressure evidence, not as drinking water. Concentrations are plotted on a logarithmic scale.

The geological and structural map of the study area is shown in Figure 3.

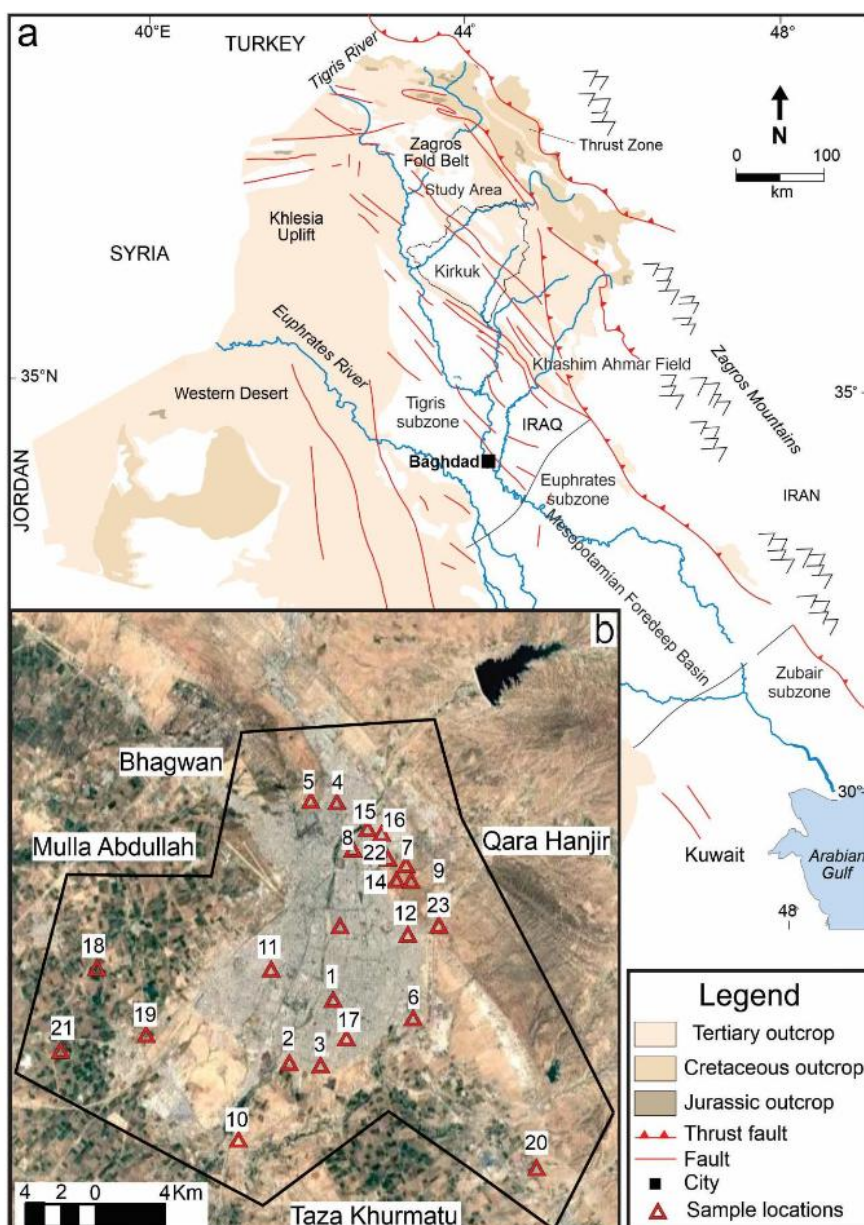


Figure 3. Geological and structural map of Kirkuk study area showing sampling sites (a) regional context; (b) detailed study area with sample locations. Source: Al Qassab & Al Jumaily, Iraqi Geological Journal, Vol. 59, No. 1A, 2026. [17]

3.3 Health Risk Assessment

The characteristics of the included studies are summarized in Table 3, and their reporting-quality appraisal is presented in Table 4.

Table 3. Primary quantitative water-quality studies included in the revised evidence synthesis.**NR = not reported in the submitted extraction and therefore not inferred.**

Study	Area / source	Sampling period	Sample size	Analytical technique	Key evidence / use in synthesis
Al-Mayah [4]	Baghdad; 11 WTPs	Sep 2018-Aug 2019; monthly	11 WTPs; monthly sampling	Phoenix-986 AAS	Annual HPI 103.744; total MI 155.93; multiple metals exceeded cited limits.
Altahaan & Dobslaw [5]	Mosul; 4 shallow + 4 deep wells	2022-2023; four campaigns	8 wells; four campaigns	Reported laboratory heavy-metal analysis; verify instrument details in source	Seasonal/annual contrast; shallow wells showed greater deterioration.
Sulyman [6]	Kirkuk; municipal drinking water/WTP	2015-2016	NR in accessible abstract	NR in accessible abstract	Local Kirkuk WTP physicochemical evidence; limited trace-metal detail.
Mohammed et al. [7]	Shekhan, Duhok; groundwater	Study published 2024; sampling period NR in submitted extraction	NR in submitted extraction	NR in submitted extraction	Regional groundwater comparison.
Abbas et al. [8]	Kirkuk; industrial wastewater	2023/2024 study publication context	5 industrial locations	AAS and ICP-OES	Cd mean 2.962 mg/L; Pb mean 1.738 mg/L; industrial matrix.
Jumaa & Abdulqader [9]	Kirkuk; drinking-water network/WQI	Oct 2023-Apr 2024	7 locations	Physicochemical/biological WQI study	Contextual water-quality evidence; not a primary heavy-metal concentration dataset.

Table 4. Reporting-quality appraisal of the six primary studies. “Verify source” is retained where the submitted manuscript did not document the item; no favorable rating was inferred without source-level evidence.

Study	Sampling design	Period	Analytical method	QA/QC	Quantitative reporting	Overall transparency
[4]	Clear: 11 WTPs monthly	Clear: Sep 2018-Aug 2019	AAS specified	Instrument specified; standards comparison described	Detailed tables	Moderate-high
[5]	Clear: 8 wells / four campaigns	Clear: 2022-2023	Reported in source	Study reports statistical analysis	Detailed temporal comparison	High
[6]	Partial/verify source	Partial/verify source	Verify source	Verify source	Included	Moderate-low pending source-level verification
[7]	Partial/verify source	Partial/verify source	Verify source	Verify source	Included	Moderate-low pending source-level verification
[8]	Clear: 5 industrial sites	Publication 2024; collection date not explicit in extracted text	AAS + ICP-OES	Calibration, RSD/SD described	Detailed tables	High for industrial wastewater
[9]	Clear: 7 locations	Clear: Oct 2023-Apr 2024	Not a heavy-metal analytical study	WQI-focused	Not used for metal concentrations	Context only

Table 5 presents the health risk indices calculated for the locations examined. The Heavy Metal Pollution Index (HPI) in water treatment plants of Baghdad was above the critical limit of 100 ($HPI > 100$), and thus, the water was considered as critically polluted [4]. This was mostly due to exceedances of lead in summer and autumn seasons. Shallow wells of Mosul showed HPI values of 85–120 (high to critical pollution) and deep wells showed moderate risk (HPI 35–55) [5].

The results of the industrial wastewaters of Kirkuk indicated HPI values of >200. The highest pollution levels in the reviewed literature [8]. The hazard quotient (HQ) for cadmium was 313.3 and the HQ for lead was 176.0 in these industrial areas, far above the safety level of 1.0. These values indicate serious non-carcinogenic health risks for populations potentially exposed to these waters. Industrial waste water is not for direct consumption, but if disposed of improperly, or if it seeps into aquifers, it can compromise the safety of drinking water.

On the other hand the municipal water treatment plants in Kirkuk showed very good performance with all heavy metals below the detection limits and HPI values well below 25 indicating a low pollution risk [6]. The fact that municipalities can treat their water successfully, but industries can seriously contaminate it, points out how critical it is to protect source water and enforce industrial discharge regulations.

Table 5. Health Risk Assessment Indices for Heavy Metals in Iraqi Water Sources.

Study/source	Matrix	Index	Reported value	Meaning	Status	Basis	Caution
Baghdad WTPs [4]	Treated drinking water	HPI	Annual mean 103.744	Above critical threshold of 100	Source-reported	Nine measured constituents across 11 WTPs	Do not extrapolate to Kirkuk
Baghdad WTPs [4]	Treated drinking water	MI	Total 155.93 (source-reported aggregation)	Seriously affected in source classification	Source-reported	Source MI calculations	Interpret using source definition
Other included studies	Mixed	HQ	Not recalculated	Not comparable without harmonized exposure inputs	Not synthesized	Insufficient common inputs	Avoid invented HQ values

HPI = Heavy Metal Pollution Index; MI = Metal Index; HQ = Hazard Quotient.

3.4 Treatment Technology Evaluation

Table 6 presents the applicability assessment of conventional and emerging heavy metal removal technologies for drinking water in the Iraqi context. The selection of the appropriate technology should strike a balance between its removal efficiency, cost, energy requirements and operational complexity, and the infrastructure capacity and economic limitations of Iraq.

Membrane technologies, especially reverse osmosis (RO) and Nanofiltration (NF), exhibited the highest removal efficiencies (94–99.9%) for all target metals [14,16]. RO systems could reduce concentrations of Cd, Pb and Cr from hundreds of micrograms per liter to below

detection limits. However, these technologies require considerable energy input (0.5–1.2 kWh/m³), skilled maintenance, and produce concentrated brine waste that needs proper disposal. Considering Iraq's intermittent electricity supply and limited technical expertise in rural areas, RO and NF are most suitable for urban water treatment plants with a reliable power infrastructure.

A promising alternative is ion exchange with comparable removal efficiency (98–99.9%) and moderate price (0.20–0.50 USD/m³) [14]. Resins can be regenerated reducing long term operating costs. “This technology is ideally suited to point-of-use systems in schools, hospitals and community centers where centralized treatment is not available.

Chemical precipitation and Coagulation-Flocculation are common methods and popular in Iraqi WTPs. These processes are efficient for bulk contaminant removal (80-99% efficiency) but produce large amounts of metal laden sludge that needs to be safely disposed [15]. The conventional coagulation with aluminum sulfate followed by sedimentation and filtration has been successful in removing heavy metals below detection limits in Kiwan and Al-Dibs plants of Kirkuk [6]. However, these plants may struggle with sudden shock loads from industrial contamination events.

Low-cost adsorption technologies emerge as the most promising solution for decentralized and rural applications in Iraq. Activated carbon achieves 90–99% removal efficiency at moderate cost (0.15–0.40 USD/m³) and very low energy demand [14,15]. Biochar, produced from agricultural waste (wheat straw, rice husks — all abundant in Iraq), achieves 85–98% removal at significantly lower cost (0.05–0.20 USD/m³) [15]. Clay minerals (Bentonite, Kaolinite) indigenous to Iraqi geology can produce 70–90% removal at a very low cost (0.03–0.10 USD/m³). The materials can serve as a filter medium in household and community scale systems that do not require electricity or complex maintenance.

Table 6. Applicability assessment of conventional and emerging heavy metal removal technologies for drinking water in the Iraqi context.

Technology	Removal Efficiency (%)	Cost (USD/m ³)	Energy Demand	Sludge Generation	Suitability for Iraq
Reverse Osmosis (RO)	98.0–99.9	0.50–1.20	High	Low	Urban WTPs
Nanofiltration (NF)	94.0–99.9	0.30–0.80	Moderate	Low	Urban WTPs
Ion Exchange (IX)	98.0–99.9	0.20–0.50	Low	Moderate	All areas
Chemical Precipitation	95.0–99.0	0.10–0.30	Low	High	Industrial

Technology	Removal Efficiency (%)	Cost (USD/m ³)	Energy Demand	Sludge Generation	Suitability for Iraq
Coagulation/ Flocculation	80.0–95.0	0.05–0.15	Low	High	Municipal WTPs
Adsorption (Activated Carbon)	90.0–99.0	0.15–0.40	Very Low	Low	Rural/Urban
Adsorption (Biochar)	85.0–98.0	0.05–0.20	Very Low	Low	Rural
Adsorption (Clay Minerals)	70.0–90.0	0.03–0.10	Very Low	Low	Rural
Electrocoagulation	90.0–99.0	0.20–0.60	Moderate	Moderate	Semi-urban

Based on the evidence synthesis and its limitations, recommendations are organized by function rather than by unsupported implementation deadlines:

(i) Monitoring: establish a standardized heavy-metal monitoring program for Kirkuk source water and treated water, with documented sampling frequency, analytical detection limits, and QA/QC. Industrial discharge points that may affect water sources should be included in source-pathway surveillance.

(ii) Source control: prioritize verification and control of Cd- and Pb-bearing industrial discharges. Industrial wastewater should be evaluated under discharge and receiving-water criteria rather than direct drinking-water ingestion assumptions.

(iii) Treatment selection: pilot-test adsorption, ion exchange, membrane, or other technologies only after source-specific characterization and technical-economic feasibility assessment. The present review does not provide sufficient evidence to prescribe RO or NF upgrades for a specific Kirkuk plant.

(iv) Data integration: develop a GIS-enabled water-quality database that stores coordinates, sampling dates, source type, analytical method, detection limits, and QA/QC metadata. Such harmonized data are required before robust spatial interpolation or temporal trend modeling can be justified.

4. Conclusions

This structured synthesis demonstrates that the available Iraqi evidence is heterogeneous by location, water-source type, sampling design, and reporting quality. Within Kirkuk, the cited

municipal-treatment evidence indicates comparatively low heavy-metal concentrations in treated water, whereas the cited industrial-wastewater study reports markedly elevated Cd and Pb. These source types should not be combined under a single drinking-water exposure interpretation.

Spatial comparison supports a source-dependent pattern rather than a governorate-wide contamination gradient: treated municipal water, groundwater, and industrial wastewater represent distinct matrices. The available evidence is too sparse and methodologically heterogeneous for defensible GIS interpolation across Kirkuk. Accordingly, the revised manuscript limits spatial inference to study locations and recommends a georeferenced monitoring database for future interpolation.

Treatment technologies show different performance, cost, energy, and operational requirements. Accordingly, adsorption and membrane processes should be considered candidate options rather than universal recommendations. The most defensible priorities arising from this review are standardized monitoring of Cd and Pb, transparent analytical QA/QC, control of industrial source pathways, and collection of georeferenced, time-stamped data that can support future quantitative GIS and trend analyses.

Of the treatment technologies assessed, low-cost adsorption using locally produced biochar and clay minerals is the most feasible technology for decentralized rural systems, offering 85–98% removal at the least cost and energy demand. The highest removal efficiency (94–99.9%) is achieved with nanofiltration and reverse osmosis and are recommended as tertiary treatment upgrades for urban treatment plants. The results emphasize the need for continuous monitoring of heavy metals, stricter control of industrial effluents and funding of appropriate treatment technologies to protect public health in Kirkuk and Iraq.

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6. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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