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Article

Environmental Pollution in Iraq: A Biomarker-Based Assessment and a Proposed Bio-Nanomarker Index for Integrated Remediation Policy

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Abstract: The Iraqi environment faces increasing and diverse pressures stemming from industrial development, unregulated urban sprawl, the consequences of armed conflict, and the widespread open burning of municipal waste. Among the combined effects are increased concentrations of heavy metals in urban and semi-industrial soils, persistent seasonal pollution of the Tigris and Euphrates river systems, deteriorating air quality in urban areas, and a marked rise in pollution-related diseases. This narrative review brings together peer-reviewed Iraqi and regional literature, primarily from 2024 to 2026, along with previous foundational studies, along four analytical axes: (a) primary sources, spatial distribution, and relative intensity of soil, water, and air pollution in Baghdad, Mosul, and Najaf; (b) measurable human health burden associated with this exposure; (c) biological monitoring methods, including algal, microbial, fish, and zooplankton biomarkers, that can detect sublethal environmental stress that is indistinguishable by conventional chemical analysis alone; (d) Emerging treatment technologies, particularly nanoparticle-assisted phototherapy and nanomaterial-based wastewater treatment, are evaluated against the costs of conventional treatment and the documented results of similar river restoration initiatives abroad. Based on this research, the paper proposes a composite nanobiomarker (BNI) index that combines standardized biological response data, Nano-treatment performance metrics, and existing chemical pollution indicators to create a unified, site-specific, and policy-relevant index. The study indicates that Iraq's main challenge is not a lack of scientific or technological resources, but rather the absence of a comprehensive, long-term national monitoring system capable of translating fragmented data into coherent policy measures. To implement the BNI framework, the analysis concludes with targeted institutional and financial recommendations.

Keywords: Biomarkers, Nano-phytoremediation, Heavy-metal pollution, Wastewater treatment, Bio-Nanomarker Index, Iraq

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1. Introduction

Iraq's environmental burden has intensified markedly since the beginning of the twenty-first century, driven by industrial expansion, largely unplanned urban growth, chronic underinvestment in wastewater and solid-waste infrastructure, and the cumulative legacy of successive conflicts. Evidence of this burden is now extensive rather than anecdotal: concentrations of lead, cadmium, nickel, and chromium exceeding international and World Health Organization (WHO) safety thresholds have been repeatedly documented in the Tigris and Euphrates rivers and in the soils of major urban centers [1]. This is not a historical or abstract concern. Contemporary health-risk modeling indicates that exposure to fine particulate matter (PM2.5) in Baghdad is associated with a relative risk of lung-cancer mortality of 1.61 a 61% elevation relative to populations in less polluted areas, and the highest value recorded among the Iraqi cities

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Widespread soil, surface water, and wastewater contamination [3]. Complementing biological-indicator responses [4]. and promising remediation efforts. have all been reported in a sizable and growing body of Iraqi research, the majority of which has been published in the last 20 years. An integrated synthesis that (i) places pollution intensity across Iraq's major urban centers on a common, comparable footing; (ii) systematically links that pollution intensity to documented health outcomes; and (iii) assesses emerging remediation technologies not only on removal efficiency but also on economic feasibility relative to conventional treatment and to the long-term results of comparable river-rehabilitation programs elsewhere is still largely lacking. Even methodologically sound Iraqi research run the danger of not being properly contextualized to be used as policy evidence in the absence of this integration. This review is structured to address that gap. Section 2 characterizes the principal sources and spatial extent of soil, water, and air pollution in Iraq and the associated health burden, with a comparative summary for Baghdad, Mosul, and Najaf. Section 3 examines biomarker-based monitoring approaches that complement conventional chemical analysis. Section 4 reviews emerging remediation technologies, with emphasis on Nano-phytoremediation and nanomaterial-based wastewater treatment. Section 5 benchmarks these technologies against conventional remediation costs and against the institutional lessons of comparable international river-restoration programs [4]. Section 6 introduces the proposed Bio-Nanomarker Index (BNI) as a mechanism for consolidating these heterogeneous data streams into a single, actionable, site-level metric for decision-makers, and Section 7 sets out the resulting policy recommendations.

1.1. Sources and Extent of Environmental Pollution in Iraq

1.1.1. Heavy-Metal Contamination of Industrial and Urban Soils:

Spatial assessments combining Geographic Information Systems (GIS) with soil sampling along both banks of the Tigris River in Baghdad have identified cadmium concentrations above established safety thresholds, with spatial distribution patterns pointing to irrigation with untreated wastewater and the application of cadmium-bearing pesticides and fertilizers as the principal sources. A peer-reviewed comparison across three land-use categories in Baghdad residential, commercial, and industrial reported mean soil concentrations of 18.6 mg/kg for cadmium, 30.7 mg/kg for nickel, and

23.7 mg/kg for zinc, with a composite pollution index ranging from 0.98 to 2.15 (mean 1.28); industrial zones showed consistently the highest contamination , Lead and cadmium concentrations above natural background levels were found in Baghdad's soils and surrounding vegetation in earlier research, which was mostly attributable to industrial activity and traffic emissions. Higher metal concentrations were found in leafy vegetables than in fruit tissue [5]. Outside of Baghdad, contamination is particularly noticeable in vicinity of phosphate-mining operations in southern Iraq, where geochemical surveys show an overall pollution load index of 2.85 and cadmium and lead contamination factors of 9.14 and 3.50, respectively.

1.1.2. *Surface-Water Pollution in the Tigris and Euphrates Rivers*

The state of the Tigris River as it flows through Mosul and its surroundings demonstrates how conflict-induced destruction exacerbates existing infrastructure weaknesses. Seasonal assessments of cadmium, lead, chromium, and nickel levels in the water and riverbed sediments have exceeded World Health Organization safe limits, a consequence of both direct combat operations and the chronic inadequacy of a drainage system that fails to meet the needs of the city’s approximately 3.75 million inhabitants [6]. Heavy metal pollution affects a much wider area of the river, extending far beyond Mosul, based on monitoring conducted downstream between Baghdad and Kut**.** Similar trends are evident in the Euphrates River, where recent phytoplankton assessments near Ramadi indicate deteriorating water quality and changes in the structure of algal communities, reflecting ongoing environmental stress [7]**.**

1.1.3. Air Pollution from Open Burning and Waste Accumulation: The largely unregulated open burning of municipal solid waste remains a major contributor to air pollution in Iraq, emitting methane, particulate matter, and black carbon. Local health authorities in various regions report that respiratory symptoms are more prevalent during periods of intense burning. Eight Iraqi cities have shown particulate matter (PM2.5) levels exceeding the World Health Organization's annual limit of 5 μg/m³ using the WHO AirQ+ model. Baghdad recorded the highest concentration at 54 μg/m³, nearly eleven times the permissible limit [8]. Water and air pollution are closely linked to poor solid waste management rather than being considered separate problems, as uncollected waste leach’s harmful substances into adjacent surface and groundwater used for irrigation and drinking.

2. Materials and Methods

2.1 Associated Health Outcomes

Public-health analyses reinforce the urgency suggested by the environmental data. Application of the WHO AirQ+ model to Baghdad PM2.5 measurements indicates a 61% higher relative risk of lung-cancer mortality (95% CI 1.23–2.00) and a 40% higher relative risk of death from acute lower respiratory infection in children under five (95% CI 1.27–1.57) the highest risk estimates recorded among the Iraqi cities assessed to date. These modeled risks are consistent with national surveillance data: Iraq's cancer registries recorded 46,320 cancer cases nationwide in 2024, with Baghdad accounting for 3,763 cancer-related deaths, the highest of any governorate, a pattern that health officials have partly attributed to air pollution, traffic congestion, and the loss of urban green space. Because these figures derive from health-sector surveillance and epidemiological modeling rather than from the environmental-monitoring literature reviewed in Sections 2.1–2.3, they constitute independent, converging evidence for the same underlying exposure pathways documented at the soil, water, and air levels reinforcing the case, developed further in Section 6, for a monitoring framework that links pollution data to health outcomes rather than treating the two literatures separately.

2.2 Comparative Overview: Baghdad, Mosul, and Najaf

Table 1 consolidates the quantitative indicators presented in Sections 2.1–2.4 for the three most extensively studied urban and wetland ecosystems in Iraq. The comparison is deliberately asymmetric: Baghdad has the most extensive air-quality and health-outcome literature, Mosul has the most extensive post-conflict sedimentation literature, and Najaf through the Bahr Al-Najaf depression has the most extensive biological-indicator literature. This disparity is itself part of the argument developed in Section 6 for a monitoring framework capable of generating comparable chemical, biological, and health data at every site rather than relying on whichever domain happens to have attracted local research attention.

3. Results and Discussion

Table 1. Comparative pollution indicators for Baghdad, Mosul, and Najaf, drawn from the peer-reviewed and health-sector sources reviewed in Sections 2.1–2.4.

Indicator	Baghdad	Mosul	Najaf (Bahr Al-Najaf)
Dominant soil-metal signal	Mean soil Cd 18.6 mg/kg; composite pollution index 0.98–2.15 (mean 1.28); industrial zones highest	Sediment Cd in the severe contamination-factor category; Pb moderate at all monitored sites	Not separately soil-surveyed in the reviewed literature; catchment affected via inflow water quality
Surface-water heavy metals	Cd, Pb, Cr, Ni measured along the Tigris reach to Kut; contamination persists beyond the urban core	Cd, Pb, Cr, Ni exceed WHO limits seasonally in water and sediment; conflict debris implicated	Zn, Pb, Cd, Mn, Fe monitored in depression reservoir water; used to interpret biotic stress
Air quality (PM2.5)	Mean 54 μg/m³ — highest of eight Iraqi cities studied, ≈11× the WHO guideline	Not separately quantified in the PM2.5 studies reviewed; conflict-debris dust a contributing factor	Not separately quantified in the PM2.5 studies reviewed
Health-risk signal	Lung-cancer mortality RR 1.61 (95% CI 1.23–2.00) attributable to PM2.5 — highest nationally	Elevated cadmium/lead ecological-risk classification based on sediment contamination factors	No PM2.5-based relative risk reported; biological stress inferred from invertebrate community structure
Principal biological-indicator finding	Not separately reported; chemical and health data dominate the reviewed literature for this city	Not separately reported; chemical and sediment data dominate the reviewed literature for this city	48 zooplankton taxa identified; Copepoda dominant (54.2%); low evenness signaling dominance of pollution-tolerant taxa
Principal attributed	Vehicular and industrial emissions;	War-related debris and munitions residue; destroyed	Diffuse agricultural and municipal inflow to a semi-closed

Indicator	Baghdad	Mosul	Najaf (Bahr Al-Najaf)
driver	irrigation with untreated sewage; open urban waste burning	wastewater infrastructure serving ≈3.75 million residents	depression system

3.1 Biomarker-Based Monitoring Approaches

Chemical analysis alone cannot reveal how a given pollutant loads translate into physiological stress, bioaccumulation, or altered community structure within an ecosystem. A growing segment of Iraqi environmental research has therefore adopted biomarker-based monitoring as a complementary and in several respects more sensitive layer of assessment.

3.1.1 Algal and Microbial Biomarkers

Unicellular green algae of the genus *Chlorella* are among the most widely applied biomarkers for water-pollution monitoring, owing to their short generation time, measurable growth-inhibition response, and the relative ease with which antioxidant enzyme activity catalase, superoxide dismutase, and glutathione peroxidase can be quantified under pollutant-induced stress. Beyond their indicator function, algal populations also participate directly in the remediation of hydrocarbon-contaminated sediments, making algal biomarkers a dual-purpose tool for both monitoring and passive bioremediation in oil-affected Iraqi wetlands and marshlands [9]. This dual role has not yet been the subject of a dedicated Iraqi field study identified in the present review and is flagged here as a priority for future empirical work.

3.1.2 Fish and Food-Web Bioaccumulation

Heavy metals entering sediments and surface water in the Tigris and Euphrates do not remain confined to those compartments. Environmental risk assessments of the Tigris River near Mosul explicitly incorporate bioaccumulation potential into their risk profiles, consistent with the known capacity of cadmium and lead to transfer through aquatic food webs from sediment and primary producers to fish tissue. Because fish occupy a higher trophic position and constitute a direct human food source, this bioaccumulation pathway represents one of the most policy-relevant links between the chemical contamination documented in Section 2 and the risk of human dietary exposure [10].

3.1.3 Zooplankton and Aquatic-Invertebrate Diversity Indices

In Iraq, zooplankton assemblages are sensitive biological indicators of the state of wetlands. Copepods were the most prevalent group (54.2%), followed by rotifers (35.4%) and other crustaceans (10.4%) in a twelve-month survey conducted at five locations in the Bahr Al-Najaf depression, Najaf Governorate.Researchers can determine when a small number of pollution-tolerant taxa take over a degraded community using diversity metrics like the Shannon–Wiener index, taxon richness, and evenness derived from this and similar Iraqi wetland studies. This is an early indicator of ecological stress that may occur before observable changes in chemical water-quality parameters [11]. A similar strategy has been employed to monitor trends in water quality in the Euphrates near Ramadi, using changes in phytoplankton composition.

3.2 Innovative Remediation Technologies

3.2.1 Nano-Phytoremediation of Heavy-Metal-Contaminated Soil

Among the most promising remediation advances reported in Iraq is the combination of nanoparticle-based metal stabilization with conventional phytoremediation. In a 90-day controlled trial using representative Iraqi calcareous soils, curcumin-functionalised nanoparticles were applied alongside sunflower cultivation

(*Helianthus annuus*) in a combined protocol designed to immobilize cadmium and lead while reducing metal-induced phytotoxic stress. This combined strategy outperformed either nanoparticle treatment or sunflower phytoremediation when used separately, resulting in a 70% decrease in bioavailable soil cadmium [12]. The suggested mechanism, as shown in Figure 1, entails nanoparticles immobilizing a portion of the mobile metal fraction within the root zone, thereby lowering the contaminant burden that would otherwise impair root function. This protective effect, in turn, enables the sunflower to absorb a higher pollutant load than would be feasible in the absence of assistance.

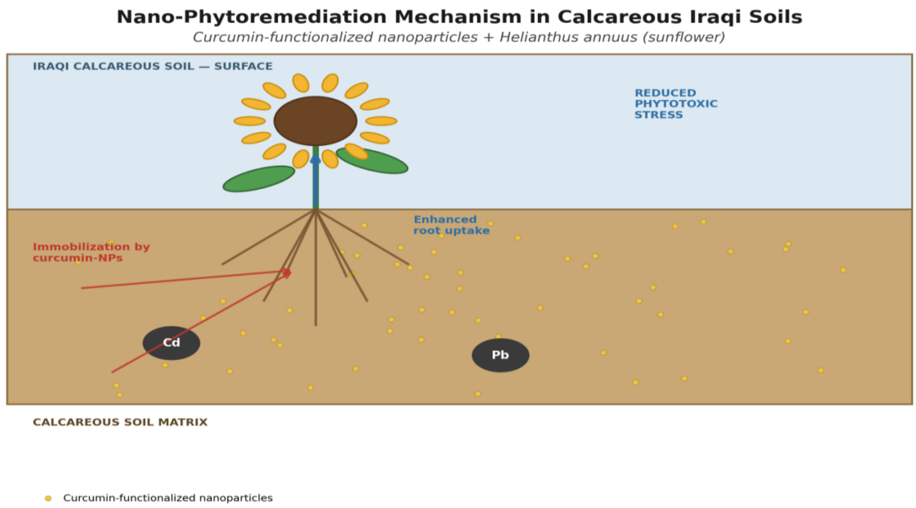

Figure 1. Schematic mechanism of curcumin-nanoparticle-assisted phytoremediation using sunflower (Helianthus annuus) in cadmium/lead-contaminated Iraqi calcareous soils.

3.2.2 *Microbial Bioremediation of Hydrocarbon-Contaminated Sites*

In-situ bacterial bioremediation provides a low-cost alternative to excavation and off-site disposal for the hydrocarbon-contaminated soils that Iraq's vast petroleum infrastructure has left behind. Twelve species of black-oil-degrading bacteria, including Pseudomonas aeruginosa, Bacillus cereus, Burkholderia species, and Acinetobacter species, were found in a recent isolation study of workshop soils in the Tarmiya district north of Baghdad. Bacillus cereus showed the highest oil-degradation efficiency, closely followed by Pseudomonas aeruginosa. The realistic possibilities for scaling bioremediation at locations next to refineries and auto workshops across the country are improved because these strains are native to the contaminated sites and have already adapted to local soil chemistry and temperature regimes.

3.2.3 *Nanomaterial-Based Wastewater Treatment*

Beyond soil applications, engineered nanomaterial's metal oxides, magnetic nanoparticles, and carbon-based compounds have demonstrated removal efficiencies of 50–98% for organic pollutants and 80–99% for inorganic pollutants in wastewater treatment, substantially outperforming many conventional treatment methods of comparable operating scale [13]. As quantified in Section 5, the principal barrier to wider deployment of these materials in Iraq is economic rather than technical.

3.3 Economic and Institutional Challenges

Several structural constraints limit the translation of the science reviewed above into sustained environmental improvement. A number of these constraints can now be quantified rather than only qualitatively described.

3.3.1 *Cost Comparison: Nanotechnology versus Conventional Remediation*

Table 2 juxtaposes published cost ranges for conventional remediation with the available performance data for nanotechnology-based approaches. Conventional excavation and off-site disposal costs range from US$35 to US$150 per cubic meter for routine contamination, rising to US$300–400 per ton where thermal treatment of persistent organic matter is required. Unassisted phytoremediation is considerably cheaper, at US$11–30 per cubic meter, but typically requires three to ten years to achieve remediation targets. Per-hectare costs for Iraqi Nano-phytoremediation trials have not yet been published, but the 90-day timeframe of the curcumin-nanoparticle/sunflower protocol, which achieved a 70% reduction in bioavailable cadmium, compares favorably in duration with the multi-year timelines reported for unassisted phytoremediation elsewhere [14]. This suggests that, once the cost of nanoparticle production at scale is accounted for, Nano-phytoremediation could occupy an intermediate position between slow, low-cost phytoremediation and rapid, high-cost excavation. For wastewater treatment, the removal efficiencies achieved by engineered nanomaterial's (50–98% organic; 80–99% inorganic) have not yet been benchmarked against the costs of conventional Iraqi treatment in the literature reviewed here a data gap that the BNI framework proposed in Section 6 is explicitly designed to help close by requiring cost and performance reporting alongside removal-efficiency claims.

Table 2. Indicative cost and timeline comparison between conventional and Nano-based remediation approaches.

Remediation approach	Typical cost (USD)	Typical timeline / notes
Excavation and off-site disposal (conventional)	US$35–150 per m³; up to US$300–400 per ton for thermal treatment/incineration of persistent organics	2–12 weeks on site, but with landfill liability and transport costs
Phytoremediation (unassisted)	US$11–30 per m³	3–10 years; low cost but slow, and effective only in shallow contamination zones
Nano-phytoremediation (curcumin nanoparticles + sunflower; Iraqi trial)	No formal per-hectare cost yet published for Iraqi conditions	90-day trial achieved a 70% reduction in bioavailable Cd — markedly faster than unassisted phytoremediation
Engineered nanomaterials — wastewater treatment	Cost driven by nanomaterial synthesis; not yet benchmarked against conventional treatment at Iraqi scale	Removal efficiencies of 50–98% (organics) and 80–99% (inorganics) reported

3.3.2 Lessons from Comparable International River-Restoration Programs

Large-scale river restoration experience from other countries provides Iraq both positive examples and cautionary tales. The Rhine Action Program, which was started in 1987 in reaction to a major chemical spill in 1986, is generally regarded as a successful case: between 1985 and 2000, emissions of major pollutants, including heavy metals, decreased by 70–100% from documented sources, and the percentage of the Rhine basin population connected to municipal wastewater treatment increased from roughly 60% to 96% during the same period. For nearly 40 years, the International Commission for the Protection of the Rhine (ICPR) has consistently released standardized monitoring data, mandatory connection to treatment systems, enforceable discharge limits, and institutional and regulatory design were more responsible for this outcome than technological advancement. A different lesson can be learned from India's experience with the Ganges: a later initiative that began in 2015 had only completed 43% of its 341 planned projects by 2021, and the original Ganga Action Plan, which began in 1986 and cost approximately nine billion Indian rupees, was formally closed in 2000 without accomplishing its goals. When taken as a whole, these cases show that, under enforceable regulation and nearly universal treatment coverage, heavy-metal contamination of the magnitude reported for Iraq in Section 2 can be reduced approximately tenfold within ten years, as the Rhine experience demonstrates; the Ganges case equally clearly shows that financial investment alone does not consistently translate into measurable improvements in water quality without ongoing regulatory oversight and institutional continuity[15].

3.3.3 Potential Routes and Structural Obstacles

In Iraq, infrastructure deficiencies continue to be the biggest obstacle to development. Because contaminated water cannot consistently reach treatment facilities in the first place, the lack of a working wastewater-collection network in Mosul is a reflection of a larger national deficiency that undermines both basic and sophisticated treatment. Iraq also lacks a permanent, coordinated national environmental-monitoring program comparable to the ICPR model that underpinned the Rhine's recovery: the individual studies reviewed here are, for the most part, methodologically sound, but they remain geographically and temporally dispersed, and none currently links pollution data systematically to the health outcome data reviewed in Section 2.4. Against these constraints, three opportunities identified in earlier assessments of this literature remain valid and are reinforced by the comparative evidence above. First, locally available treatment inputs indigenous bacterial strains, regionally cultivated sunflowers reduce the capital barrier relative to imported technology. Second, the growing volume of internationally published Iraqi environmental research since 2024 indicates a domestic scientific capacity sufficient, in principle, to staff and operate a monitoring body along the lines of the ICPR, provided it is granted a comparable institutional mandate. Third, the cost-performance gaps identified and quantified in Table 2 point to a specific and immediately actionable Iraqi research and funding priority: cost-explicit, pilot-scale field trials of nano-phytoremediation and nanomaterial-based wastewater treatment, rather than a further round of open-ended exploratory studies.

3.4 Proposed Framework: The Bio-Nanomarker Index (BNI)

To convert the disparate evidence reviewed above into a single, policy-usable metric, this review proposes a composite Bio-Nanomarker Index (BNI), calculable at the level of an individual monitoring site a riverbed reach, an urban soil parcel, or an artificial catchment from three weighted components, as illustrated in Figure 2:

Biological Response Score (B) — a standardized composite of algal growth-inhibition and antioxidant-enzyme response, zooplankton or phytoplankton diversity indices (e.g., the Shannon–Wiener index), and fish-tissue bioaccumulation data where available, each rescaled to a 0–1 range relative to a reference, minimally affected site [16].

Chemical Pollution Index (C) — a standardized composite of established pollution indices already applied in Iraqi studies, such as the contamination factor, the pollution load index, and the heavy-metal pollution index, derived from inductively coupled plasma mass spectrometry (ICP-MS) or atomic absorption spectrometry measurements of soil, sediment, or water samples.

Nanoremediation Performance Index (N) — where a nanotechnology-based intervention has been applied or piloted at the site, the documented removal percentage or bioavailability-reduction efficiency (for example, the 70% reduction in cadmium bioavailability reported for curcumin-nanoparticle/sunflower co-treatment, or the 50–98% organic and 80–99% inorganic removal efficiencies reported for engineered nanomaterials in wastewater treatment [12,13]), standardized to a 0–1 scale.

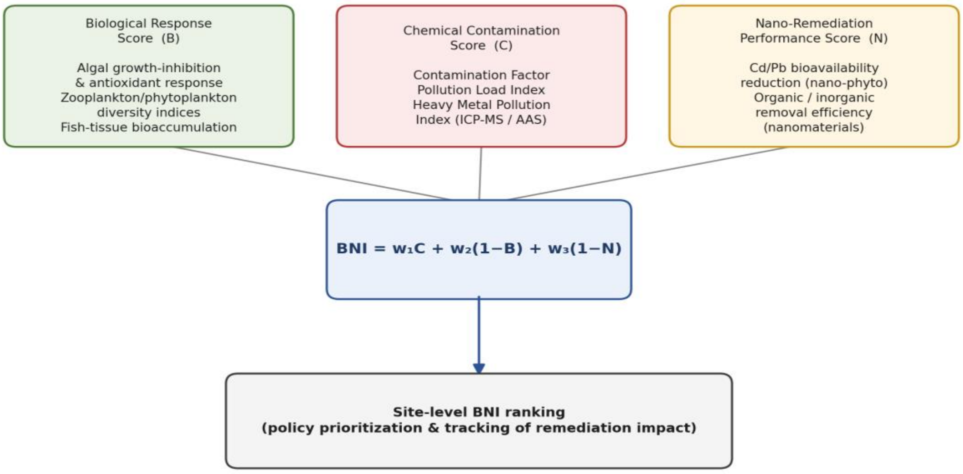

Figure 2. Structure of the proposed Bio-Nanomarker Index (BNI), showing the three weighted component scores and their combination into a single, site-level policy metric.

The composite index is defined as:

$$\mathbf{BNI = w_1\,C + w_2\,(1 - B) + w_3(1 - N)}$$

Where the weights w_1, w_2, and w_3 are set by an expert panel according to local monitoring priorities and sum to one. A higher BNI value identifies a site of greater combined chemical, biological, and remediation priority, whereas sites with effective, high-performance nanoremediation interventions in place receive correspondingly lower scores [17]. Unlike the single-domain indices currently in use, the BNI is explicitly designed to reward the joint presence of biological monitoring and cost-effective remediation, giving Iraqi environmental authorities a unified tool for prioritizing intervention sites and for tracking the measurable impact of remediation investment over time the same coordinating function that standardized ICPR reporting has performed for the Rhine basin. The index is presented here as a prototype rather than a finalized instrument: its component weights and standardization thresholds require calibration against a nationally representative baseline dataset before formal adoption, a step that is itself contingent on establishing the standardized, ongoing monitoring system identified in Section 5 as Iraq's most critical structural deficiency.

4. Conclusion

The available evidence indicates that environmental pollution in Iraq is well documented at the level of individual studies. Recent, methodologically sound Iraqi research has recorded heavy-metal contamination in urban and industrial soils, persistent seasonal pollution of the Tigris and Euphrates, long-term decline in urban air quality, and rising rates of pollution-associated cancer and respiratory disease. What remains absent is systematic synthesis across cities, across data types — chemical, biological, and health-related — and against the benchmarks established by comparable international programs. Converting this evidence base into effective policy will require progress on three fronts.

First, an Iraqi environmental authority plausibly affiliated with or adjacent to the Ministry of Health and Environment could adopt the BNI, or a comparable composite index, as the basis for a permanent, site-level national monitoring registry, prioritizing the Tigris and Euphrates corridors and the three cities summarized in Table 1 for an initial baseline survey. Second, remediation funding should be explicitly linked to the cost evidence assembled in Table 2: given the multi-year timelines associated with unassisted phytoremediation and the high per-ton cost of conventional excavation and disposal, cost-explicit, pilot-scale trials of nano-phytoremediation and nanomaterial-based wastewater treatment at two or three Iraqi sites represent the most immediately actionable research investment identified in this review, and would, for the first time, generate Iraq-specific cost data currently absent from Table 2. Third, the institutional design of any Iraqi program should be guided by the central lesson of the Rhine Action Program: that binding discharge regulation and near-universal connection to wastewater treatment, supported by a standing inter-agency or international monitoring commission, contributed more to measurable outcomes than budget size alone a lesson that, if applied, would help new Iraqi treatment investment avoid the sustainability shortfalls that have constrained comparable efforts on the Ganges. Taken together, these three steps offer a practicable pathway from Iraq's current evidence base methodologically robust but fragmented toward a coordinated, monitorable, and financially sustainable national environmental management strategy.

REFERENCES

[1] M. B. Musa, S. A. A. Albakri, and M. A. Sultan, "Spatial analysis of heavy metals in soil at east and west areas of the Tigris River in Baghdad using GIS and remote sensing techniques," *Iraqi Journal of Physics*, vol. 23, no. 1, 2025. [Online]. Available: https://ijp.uobaghdad.edu.iq/index.php/physics/article/view/1288

[2] A. H. M. J. Al-Obaidy and A. A. M. Al-Mashhadi, "Heavy metal contaminations in urban soil within Baghdad City, Iraq," *Journal of Environmental Protection*, vol. 4, no. 1, pp. 72–82, 2013, doi: 10.4236/jep.2013.41008.

[3] R. H. Habib, S. M. Awadh, and M. Z. Muslim, "Toxic heavy metals in soil and some plants in Baghdad, Iraq," *Journal of Al-Nahrain University Science*, vol. 15, no. 2, pp. 1–16, 2012.

[4] F. K. Shandookh and Z. M. Abbas, "Assessment of heavy metal contamination and environmental risk in soils and surface waters adjacent to phosphate mining areas, southern Iraq," *Journal of Degraded and Mining Lands Management*, vol. 13, no. 3, pp. 10543–10554, 2026, doi: 10.15243/jdmlm.2026.133.10543.

[5] A. Altahaan and D. Dobslaw, "Assessment of the impact of war on concentrations of pollutants and heavy metals and their seasonal variations in water and sediments of the Tigris River in Mosul, Iraq," *Environments*, vol. 11, no. 1, Art. no. 10, 2024, doi: 10.3390/environments11010010.

[6] S. S. Alzaidi and M. A. Hassan, "Assessment of heavy elements' pollution in surface water of Tigris River between Baghdad and Kut cities, Iraq," *Iraqi Journal of Science*, vol. 66, no. 4, pp. 1632–1640, 2025, doi: 10.24996/ijs.2025.66.4.21.

[7] Climate & Clean Air Coalition, "Iraq advances pollution reduction through smarter waste management and green jobs," 2026. [Online]. Available: https://www.ccacoalition.org/news/iraq-advances-pollution-reduction-through-smarter-waste-management-and-green-jobs

[8] B. M. Hashim *et al.*, "Estimating respiratory and cardiovascular health risks associated with PM2.5 concentration in major populated areas of Iraq with examining its correlation to COVID-19," *Iraqi Geological Journal*, vol. 58, no. 1B, 2025. [Online]. Available: https://igj-iraq.org/igj/index.php/igj/article/view/2587

[9] Iraqi News, "Cancer rates surge in Iraq amid pollution, climate change, and urban overcrowding," Feb. 7, 2026. [Online]. Available: https://www.iraqinews.com/health/cancer-rates-surge-iraq-pollution-climate-change/

[10] A. A. Tsear, "Biodiversity study of zooplankton in selected Bahr Al-Najaf depression, Najaf governorate, Iraq," *Bulletin of the Iraq Natural History Museum*. [Online]. Available: https://jnhm.uobaghdad.edu.iq/index.php/BINHM/article/view/310

[11] M. M. Sharq, A. N. A. Al-Tamimi, and O. M. Hassan, "Evaluation of Euphrates river water quality on phytoplankton biodiversity in Ramadi, Iraq," *Borneo Journal of Resource Science and Technology*, vol. 14, no. 2, pp. 19–30, 2024, doi: 10.33736/bjrst.5724.2024.

[12] S. A. Altai and M. F. Mohammed, "Nano-phytoremediation of heavy metals in Iraqi soils: An integrated strategy using curcumin nanoparticles and sunflower (*Helianthus annuus*)," *South Asian Research Journal of Biology and Applied Biosciences*, 2026, in press.

[13] S. Q. Aziz, S. O. Ismael, and K. K. M. Salih, "Nanotechnology in wastewater treatment: Efficiency review, cost analysis, and reusing," *Polytechnic Journal*, vol. 15, no. 2, Art. no. 5, 2025, doi: 10.59341/2707-7799.1863.
[14] Z. G. Faisal, M. M. Jameel, and O. A. Abdullah, "Isolation and identification of black oil-degrading bacteria from lubricant-contaminated soil in northern Baghdad, Iraq," *The Scientific World Journal*, vol. 2025, Art. no. 4009105, 2025, doi: 10.1155/tswj/4009105.
[15] International Commission for the Protection of the Rhine (ICPR), "Rhine Action Programme (1987–2000)." [Online]. Available: https://www.iksr.org/en/icpr/predecessor-programmes/rhine-action-programme. [Accessed: Aug. 18, 2026].
[16] A. Majumdar and K. Avishek, "Assessing heavy metal and physiochemical pollution load of Danro River and its management using floating bed remediation," *Scientific Reports*, vol. 14, Art. no. 9885, 2024, doi: 10.1038/s41598-024-60511-x.
[17] NVES Environmental, "Cost of soil remediation in 2026: Complete pricing guide," 2026. [Online]. Available: https://northvanenvironmental.com/blog/soil-remediation-cost-guide-2026?lang=en. [Accessed: Aug. 18, 2026].