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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 is under mounting and varied stress from industrial development, uncontrolled urban expansion, the impact of armed conflict and 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. Water and riverbed sediments have consistently exceeded the World Health Organization's maximum allowable levels of cadmium, lead, chromium and nickel on a seasonal basis. This is due to direct combat operations, as well as the chronic inadequacy of a drainage system unable to cater to the needs of the city's 3.75 million inhabitants *6+. Monitoring downstream, between Baghdad and Kut, indicates that heavy metal pollution is impacting a much wider area of the river, well beyond Mosul. Similar trends are observed in the Euphrates River where recent phytoplankton assessments near Ramadi have shown decreasing water quality and changes in algal assemblage composition, indicative of ongoing environmental stress [7]**.**

1.1.3. 1.1.3. Air pollution from open burning and waste piling-up: In Iraq, the open burning of municipal solid waste is largely unregulated and remains a major source of air pollution, emitting methane, particulate matter and black carbon. In some areas, health authorities say heavy burning brings more respiratory symptoms. Eight Iraqi cities have PM2.5 levels higher than the World Health Organization's annual limit of 5 $\mu g/m^3$, according to the WHO AirQ+ model. The highest concentration was recorded in Baghdad with 54 $\mu g/m^3$, which is almost eleven times the permissible limit [8]. Poor solid waste management, not separate problems, is intimately associated with water and air pollution. Uncollected waste is leaching harmful substances into adjacent surface and ground water being used for irrigation and drinking.

2. Materials and Methods

2.1 Associated Health Outcomes

Environmental data underline the urgency suggested by public health analyzes. 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

The heavy metals that are introduced into the sediments and surface water of the Tigris and Euphrates do not stay there. In the risk profiles of the environmental risk assessments of the Tigris River near Mosul, the bioaccumulation potential is explicitly considered, in line with the known ability of cadmium and lead to transfer through aquatic food webs from sediment and primary producers to fish tissue. The bioaccumulation pathway is one of the most policy-relevant links between the chemical contamination described in Section 2 and risk of human dietary exposure because fish are a higher trophic position and are a direct source of human food [10].

3.1.3 Zooplankton and Aquatic-Invertebrate Diversity Indices

Zooplankton assemblages in Iraq as sensitive biological indicators of the health of wetlands. The dominant group was copepods (54.2%), followed by rotifers (35.4%) and other crustaceans (10.4%) in a twelve-month survey carried out in five localities of the Bahr Al-Najaf depression, Najaf Governorate.From these and similar Iraqi wetland studies, researchers can use diversity metrics like the Shannon-Wiener index, taxon richness and evenness to determine when a degraded community is dominated by a small number of pollution tolerant taxa. This is an early indicator of ecological stress prior to changes in chemical water quality parameters [11]. Similar methods have been used to monitor trends in water quality in the Euphrates River near Ramadi, using changes in the composition of phytoplankton.

3.2 Innovative Remediation Technologies

3.2.1 Nano-Phytoremediation of Heavy-Metal-Contaminated Soil

Combining traditional phytoremediation with nanoparticle-based metal stabilization is one of the most promising remediation innovations documented in Iraq. Curcumin-functionalized nanoparticles were used in conjunction with sunflower cultivation in a 90-day controlled study utilizing typical Iraqi calcareous soils.

Helianthus annuus) in a combination strategy intended to lessen metal-induced phytotoxic stress while immobilizing lead and cadmium. This combination approach

reduced bioavailable soil cadmium by 70%, outperforming either nanoparticle treatment or sunflower phytoremediation when applied independently [12]. In order to reduce the pollutant burden that would otherwise impair root function, the proposed method, as seen in Figure 1, involves nanoparticles immobilizing a portion of the mobile metal component within the root zone. . This protective effect, in turn, enables the sunflower to absorb a higher pollutant load than would be feasible in the absence of assistance.

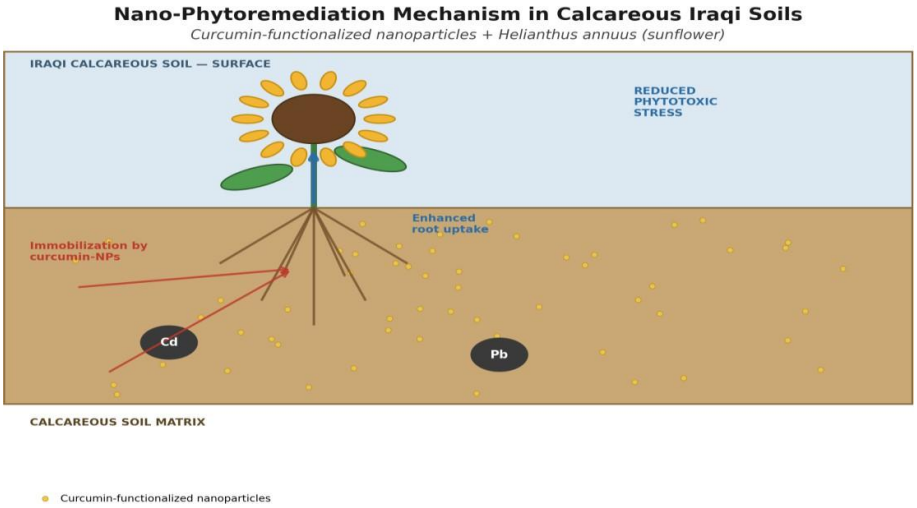


Figure 1. Schematic mechanism of curcumin-nanoparticle-assisted phytoremediation using sunflower (Helianthus annuus) in cadmium/lead-contaminated Iraqi calcareous soils.

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]. The main obstacle to the broader use of these materials in Iraq is economic rather than technological, as measured in Section 5.

3.3 Institutional and Economic Difficulties

The application of the knowledge discussed above to long-term environmental improvement is constrained by a number of structural issues. Many of these limitations may now be quantified instead of only expressed intuitively.

3.3.1 Cost Comparison: Conventional Remediation versus Nanotechnology

Table 2 compares the existing performance statistics for nanotechnology-based methods with published cost ranges for conventional cleanup. 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 m^3; 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 m^3	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 considered collectively, these cases demonstrate that heavy-metal contamination of the magnitude reported for Iraq in Section 2 can be reduced roughly tenfold within ten years under enforceable regulation and nearly universal treatment coverage, as the Rhine experience shows; the Ganges case equally clearly demonstrates 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.

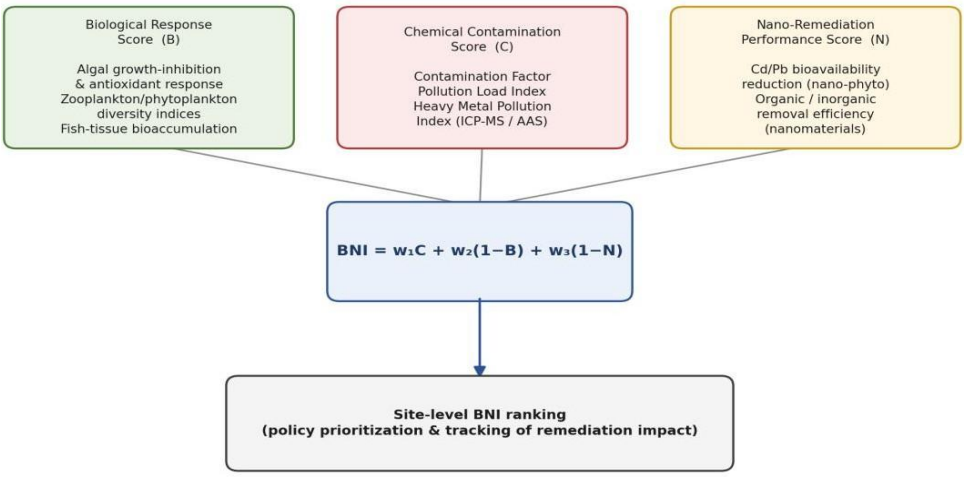


Figure 2. Structure of the proposed Bio-Nanomarker Index (BNI), showing the three weighted component scores and their combination into a single, site-level policy metric.

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]. The BNI provides Iraqi environmental authorities with a unified tool for prioritizing intervention sites and tracking the quantifiable impact of remediation investment over time the same coordinating function that standardized ICPR reporting has performed for the Rhine basin unlike the single-domain indices currently in use. It is specifically designed to reward the joint presence of biological monitoring and cost-effective remediation. Since the index's component weights and standardization thresholds must be calibrated against a nationally representative baseline dataset prior to formal adoption a step that is itself dependent on the establishment of the standardized, continuous monitoring system identified in Section 5 as Iraq's most critical structural deficiency it is presented here as a prototype rather than a finalized instrument.

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.

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