Environment and Social Psychology (2025) Volume 10 Issue 9 ISSN: 2424-8975 (O)
doi: 10.59429/esp.v10i9.3949 2424-7979 (P)

Research Article

Regulatory approaches to soil contamination and agricultural sustainability

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ABSTRACT

Soil contamination poses a serious threat to agricultural sustainability, driven by heavy metals, pesticide residues, nutrient imbalances, and weak governance. Despite extensive research on soil degradation, few studies have systematically integrated scientific diagnostics with regulatory evaluation. This study addresses that gap by combining composite indices—Contaminant Load Index (CLI), Weighted Residue Risk Index (WRRI), Nutrient Deviation Score (NDS), and Adjusted Cation Exchange Capacity (ACE) with a Multi-Criteria Regulatory Score (MCRS) to assess both ecological and institutional dimensions of soil health. Data were collected from ten major agricultural regions, using stratified sampling and validated laboratory methods, and supported by enforcement records. Results reveal that contamination hotspots align with industrial proximity, intensive agrochemical use, and weak regulatory enforcement, while regions with higher MCRS values showed healthier soil indicators. Field validation demonstrated that integrated remediation strategies, combining phytoremediation and organic amendments, significantly reduced contaminant loads and improved fertility, highlighting the feasibility of cost-effective, nature-based solutions. By integrating diagnostics with governance, this study significantly deepens our theoretical understanding of soil sustainability and delivers tangible tools for prioritizing interventions and shaping regulatory frameworks. The results highlight that soil remediation is not solely a technical matter; it is also shaped by ecological and institutional dynamics. Ultimately, the framework proposed here is highly relevant for policymakers aiming to safeguard soil health and bolster agricultural resilience, particularly in regions grappling with similar environmental and governance challenges.

Keywords: Soil contamination; heavy metals; nutrient imbalance; pesticide residues; phytoremediation; soil health indicators; environmental governance; regulatory frameworks; soil governance; sustainable agriculture

1. Introduction

Soil pollution is fast becoming a major concern for global agricultural sustainability. Recent studies highlight just how urgent this issue is contamination doesn't just lower crop yields; it also disrupts ecosystem

ARTICLE INFO
Received: 29 July 2025 | Accepted: 08 September 2025 | Available online: 15 October 2025

CITATION
Zuhair M, Mohammed H E E, Bajjay R T A. Regulatory approaches to soil contamination and agricultural sustainability. *Environment and Social Psychology* 2025; 10(9): 3949. doi:10.59429/esp.v10i9.3949

stability and poses risks to human health [1, 2]. here's growing recognition that effective solutions will require combining stricter regulatory measures with advanced soil health diagnostics. This integrated approach is now seen as a key direction for future research [3, 4]. With the progress of modern agricultural practices, the dependence on chemical fertilizers, pesticides and byproducts of industrial waste has heightened, sometimes causing the ingress of toxic materials in soil. This can alter the physical and chemical properties of the soil and poses a risk to the ecosystem, crop yield, and human health. The stability of the global food supply chain is increasingly threatened by ongoing soil degradation, as fertile land remains essential for agricultural productivity. Identifying and addressing soil contamination is, therefore, a critical priority if we intend to sustain agriculture safely and effectively in the future. Failure to do so could compromise food security on a significant scale [5]. This aligns with findings that sustainable food systems depend on continuous monitoring and remediation of toxic elements [5-7]. Current gaps include insufficient regulatory enforcement and limited multi-scalar assessments, which this study seeks to address.

Since then, different regulatory methods have evolved, focusing on both preventing soil contamination and supporting sustainable agricultural practices. For example, integrated nutrient management [7-9] and bioremediation techniques [10-12] have shown promise, but their success depends on policy frameworks and institutional capacity [13, 14]. This dual scientific–regulatory lens is often missing in prior literature. These involve putting in place rules that limit the use of hazardous chemicals, promote sustainable farming practices, and provide data on measures of soil health. Nevertheless, efforts to govern soil management have been fragmented globally, with inconsistent regulatory enforcement, differing national policies and the absence of a coordinated global effort. Scholars emphasize that governance fragmentation undermines soil sustainability and creates inequalities across regions [15-17]. Therefore, our study aims to fill this gap by combining contamination indices (CLI, WRRI, NDS, ACE) with a regulatory scorecard (MCRS), thereby linking science and governance. Furthermore, the issue of soil governance requires urgent attention. Soil management shouldn't be constrained by national borders; instead, it ought to be recognized as a matter of transnational importance. Local initiatives must be effectively integrated with international frameworks to ensure cohesive and impactful action on a global scale, without this alignment, isolated efforts are unlikely to produce meaningful, lasting results [8].

The contamination of soil is a complicated and multidimensional problem — not one with a one-size-fits-all solution, to be sure. The pool of contaminants is large and diverse: from heavy metals, like lead, mercury and cadmium (all of which have a long history of chronic toxicity to crops, livestock and humans) to those pesky organic pollutants, such as pesticide residues. They can persist for months or longer in the environment, building higher up the food chain to suffocate entire ecosystems. Even with the air and waste regulation structures we have, the challenge is still enormous.

This issue is also not just about yesteryear's toxins. Overuse fertilization with a soil amendment can cause a nutrient imbalance in the soil. On balance, these nutrient surpluses are less immediately toxic than, say, heavy metals, but they can sterilize soil, suppress biodiversity and degrade the long-term productivity of food systems. Soil pollution is a very mixed and fragmented bag of sector specific problems that would need sector specific legal and scientific response[1]

There is perhaps no environmental problem more immediate and serious to food security, the life support system, and human existential condition, than soil pollution, and on the farms, the cost of money lost to soil pollution is incalculable. Decrease in crop harvest, and added production cost, which makes the farm more unprofitable, also poses the risk of food shortage, food and agro-products quality and safety risk. As far as soil pollution, it is like air and water pollution, the devastation of the environment more broadly, and ecosystems then we should certainly make an attempt to measure those as well. This less than ideal situation provides the impetus for a new soil-crop management method – one that truly addresses the causes as opposed to the symptoms, rooting out the true source of soil contamination while shifting from a profit to sustainability focus[18].

Regulations at best can give better governance to the soiling practice will not even make that much soiling since they would part section of it only be soiling monitoring, discipline and enforcement to enforced the way current rule is. The uptake of new methodologies implemented in agriculture: precision farming and soil test value basis help to reduce the application of input and with that pollution. It would allow governments, academia and even farmers on those kinds of things to come almost to a common location and develop policy space around you could do some role of, I can't think of the right words, what is based from the science but also very practical on the ground advice. This in turn would be able to create momentum towards best practice, sensitize everybody and further promote action through a positive incentive towards sustainable agriculture [9].

Soil is heavily contaminated and there are problems in several factions and departments. Globally accepted indicators of soil degradation due to pollution, the causes of soil degradation and the implications of degradation for the potential for sustainable agriculture and self-renewal. And it's a more comprehensive and in-depth look at regulation that is actually getting things done as we continue on the path toward a healthier, more sustainably produced food system. Our study also has theoretical implications (to the best of our knowledge, we are the first to translate the composite indexes of soil contamination into governance [2, 19]; and practical implications, providing evidence for regulatory systems and sustainable farming policies policy making [18, 20, 21]. Its dual focus will be of interest to policy makers, academics and sustainable practitioners alike.

1.1.The aim of the article

This article covers the new rules around soil contamination and what that means in terms of sustainable practices for farmland. Soil poisoning is the biggest agricultural crisis of our age not only for what our land can produce now, but for the health of our land now and into the future and ours with it. As the human population grows, the climate changes, and industry transforms, the question of how best to understand what it means to say that regulation may best ameliorate the adverse effects of human insertions into the environment is increasingly diagnostic.

The article draws together research and data from a broad range of disciplines, including ecology and environmental science, and shows how enlightened policy that takes into consideration what farmers need from a productive environment, along with what society needs, has been the general rule. Through a cross-jurisdictional survey of case law and policy, this Article seeks to identify best practices, to map the landscape of loopholes in the rulemaking and to create incremental doctrinal interventions that can challenge and chip away at interspecies surrogacy's broader legal framework and institutional structure. That's the logic of the study below too, since we live more in the natural habitat than in the forest, and long-term agriculture is dependent on fertile soil, not just for growing food, but increasingly for storing some of its lost value as carbon, and hopefully for retaining some of its lost potential in supporting biodiversity.

This article is not a review of the regulatory tools available for soil but an acknowledgement that if we are to be more integrative and proactive about soil management, we need to be thinking about what that all looks like in the future. It should be making us think about one potential pathway for how international co-operation, technological innovation and community action can be combined to ensure regulation is enacted and strengthened in times of challenge. Finally, it looks at the extent to which the assumption that regulation will help to reduce 'soil degradation' in the lower-mid North Island is conjectural, by promoting the uptake of environmentally-beneficial farm practices.

1.2. Problem statement

Contamination of soils is one of the largest issues facing sustainable agricultural systems around the world. The bad news is that ground pollution is on the rise and this creates more industrial growth, more industrial-farm growth opportunity to hammer the land for all it is worth. As well as resulting in a loss of agricultural output and the quality of food products, pollution is having health implications for humans and biodiversity. Rather, countries have adopted it in different ways, some more or less globally applicable, but in general there exists no industry-wide guidance for the watchdogs and they have a patchwork of approaches and schemes.

What is fascinating is that we spend a lot of our regulatory time trying to address problems after they have happened rather than trying to avoid them from happening in the first place. Well of course they don't care that much for cleaning the laundry. There are also a host of federal and state laws on top of that, making it even more unclear. Some systems are stringent with complicated, rigid surveillance, and some allow for almost anything. The reality is we are in a food, water and energy crisis; and we are all in it together, with distribution patterns of these goods that have forced us off a sustainable trajectory and pushed too many of the weakest among us past the point of no return under existing environmental conditions.

Soil pollution is a complex issue, one that has long-term consequences, and as such cannot be ignored: Heavy metals is one thing, organics is another, nutritional deficiencies are another, and the reaction of the body, the treatment for each of those things can be very different. But at the policy level, when it comes to rule making, it's easy to bundle all pollutant sources together in a basket because that's a very simplistic view of the world. It's a one-size-fits-all approach, she said, that results in rules less strong than what is necessary to deal with the specific problems caused by various pollutants.

As one transitions from research to action, one can't really separate the political from the challenges. And even though researchers know a lot about soils pollution and how that affects agriculture, it is rarely turned into actual regulation that makes sense and works. It takes time for evidence to accumulate and years or decades can elapse between the moment when an innovative new research result is achieved and the moment when even the most practical of policies are enacted. That can be especially challenging because decision makers don't always have boots on the ground when it comes to ascertaining the best facts and best-practice principles.

Presently soil contamination is largely a result of haphazard regulations and standards that are arrived at on the basis of, in some cases, flimsy research. However, we will only care for and take good care of our natural ecosystems, the sole habit that preserves the health of the soil and the future for our coming generations, by continuing to protect and be brave in combating soil imbalances.

2. Literature review

Moreover, the role of the present situation of global soil pollution for sustainable agriculture management is also important from the global environment governance and the agriculture development point of view. Since then, multiple forms of pollution reduction and greener land stewardship have emerged, trying to mitigate the negatives as well as possible, and in combination with activist groups, to re-introduce as much fertility/productivity to the land as possible and at least preserve what the farmer isn't destroying [2].

These are generally specified for the maximum value of soil contamination [21]. Recently, reports of international comparisons of rates have been criticized for limited international relevance and for the fact that the definitions are local and variable [3, 17]. Some have claimed that "systematic approaches" have been taken when researching affected sites - if only a small increment in the right direction[3]. These so-called standards are signposts for thinking about soil health and are also associated with regulatory nudges that can give some assurance that the soil is being managed that way. However, it may differ from region to region and enforcement strength of such laws may differ greatly from practice (e.g., the Chinese "10-Point Soil Plan" was hailed to have facilitated corporate sustainability, but also to have revealed some governance gaps [13]. Recent progress in the field of integrated monitoring at different scales has led to the identification of areas of concentrated contamination (so-called 'hot spots'), but also to the development of innovative methodologies for monitoring of soil health and effect of monitoring-time-dependent regulation[10]. Furthermore, these baselines can be used as baselines for intervention policy which could inform agricultural practices to move towards a more sustainable path, towards the type of sustainability that we have captured here using the empirical evidence [3]. This harmonization/matching should be directed towards an interface between cognitions of soil science and political instruments, in order to promote sustainable management of soils [14] and for an integrated approach to their management[7, 9].

Instead, it is embodied by land use planning and pollution control. Land use and agricultural legislation, including county ordinances that unreasonably limit farmers' right to farm, and the import of toxic waste. These can include more environmentally-friendly farming practices (organic farming, crop rotations) and a reduction in manufactured inputs used. And these types of standards are perfectly suited for regenerative soils that grow more while taking less risk for long-term contamination[13].

An economic incentive mechanism for sustainable reduction: It was realized that financial instruments such as green finance and Environmental, social and governance (ESG) or soil governance were not so much an alternative to the legal regulation mechanism, but a complement to it [4, 16]. Although some critics would argue that such regulation is unfairly biased towards certain special interests, incentives for investment in 'green' technologies or tax payments to encourage environmentally responsible agricultural practices and penalties for polluters are profit-seeking devices subordinated to policy goals. Apart from imposing the need for compliance, it also imposes the need for innovation for eco-agriculture [14].

In addition, there is an important dimension of strategy that is centered around improved cooperation and better best practice through cross-border regulation. This will enable countries with similar erosion issues to work cooperatively to share information and technologies and make common decisions on policy options. It is in such partnerships that we can collaborate on: "1) making science-informed risk decisions, 2) agreeing on common standards and 3) [open and honest transparency]. In this way, a policymaker learns from mistakes and successes of other policy makers and is able to propose a regulation that tackles a very complicated task, such as adversarial control (as soil management) [15].

While there has been some advancement, more attention must be made to closing the gaps remaining and making progress to adapt regulatory frameworks to the changes of environment and farming system. Previous research on soil contamination Previous studies have promoted the research on soil contamination[1, 6, 19], but most of them were either narrowed down to a specific pollutant [21-23] but most of them were either narrowed down to a specific pollutant [5, 10-12]. Few integrate governance indicators alongside biophysical indices. This study addresses that gap by applying composite indices (CLI, WRRI, NDS, ACE) while systematically evaluating regulatory frameworks (MCRS), thereby contributing both methodologically and policy-wise.

3. Materials and methods

3.1. Sampling design and site stratification

To characterize spatial heterogeneity in soil contamination, a multistage stratified sampling approach was adopted across ten agro-ecological regions. Sampling was conducted between March and September 2023, covering seasonal variability and ensuring representativeness of both irrigated and rainfed systems [5, 21]. Data on soil background levels were obtained from national monitoring archives and validated with field-specific baseline studies [6]. Each region was divided into five zones based on land use intensity (LUI), proximity to industrial and agricultural contamination sources (D), and dominant soil texture classes (ST), derived from satellite-based land cover and geological maps [24]. The stratification index (S_i) for each zone was defined as:

$$S_i = \alpha_1 \cdot LUI_i + \alpha_2 \cdot \frac{1}{D_i} + \alpha_3 \cdot ST_i \quad (1)$$

Where $\alpha_1, \alpha_2, \alpha_3$ are weighting coefficients determined by principal component analysis (PCA); D_i is the Euclidean distance (km) to the nearest contamination hotspot; ST_i is the standardized numerical index for soil texture.

To ensure statistical representativeness, the sample size per stratum n_h was determined using Neyman allocation:

$$n_h = \frac{N_h \cdot \sigma_h}{\sum_{j=1}^{L} N_j \cdot \sigma_j} \cdot n \quad (2)$$

Where N_h population of stratum h; σ_h estimated standard deviation in stratum h; n desired sample size; L number of strata (here, L=5). A total of 100 composite soil samples were collected following a 10 × 10 m regular grid pattern within each zone at a depth of 0–15 cm, consistent with surface soil contamination studies [2, 25].

3.2. Analytical framework for soil contaminants

3.2.1. Heavy metal analysis and contaminant load

Heavy metals (Pb, Cd, As) were quantified using inductively coupled plasma mass spectrometry (ICP-MS) following microwave-assisted digestion (EPA 3051A). These laboratory methods are widely validated in soil contamination research [6, 12], ensuring both accuracy and comparability with international standards. The contaminant load index (CLI) per sample was derived as:

$$CLI_i = \sum_{m=1}^{M} \left(\frac{C_{i,m} - C_{b,m}}{SD_{b,m}} \right)^2 \quad (3)$$

Where $C_{i,m}$ concentration of metal mmm in sample i; $C_{b,m}$ background mean and standard deviation for metal m; M number of heavy metals analyzed. This multivariate index enables normalization across elements and accounts for their deviation from natural baselines [2, 6].

To correct for instrumental or procedural bias, contaminant concentrations were normalized using a blank-adjusted mass-based equation:

$$C_{m,adj} = \frac{(A_m - A_0) \cdot V_d}{m_s \cdot f_d} \quad (4)$$

Where A_m signal intensity of the sample and blank; V_d volume of digestate (mL); m_s mass of dry soil (g); and f_d dilution factor.

3.2.2. Pesticide residue quantification

Pesticide residues, as a DDT, atrazine, lindane) were extracted using QuEChERS followed by GC-MS analysis. This protocol has been successfully applied in multiple recent studies of persistent organic pollutants in agricultural soils [21]. To assess cumulative pesticide burden, a weighted residue risk index (WRRI) was introduced:

$$WRRI_i = \sum_{p=1}^{P} \left(\frac{C_{i,p}}{ARfD_p} \cdot w_p \right) \tag{5}$$

Where $C_{i,p}$ concentration of pesticide p in sample i; $ARfD_p$ acute reference dose for pesticide p; w_p relative environmental persistence score

This formulation enables the integration of toxicological thresholds with persistence potential, thereby reflecting ecological risk [11, 23].

3.3. Soil fertility and buffering capacity

3.3.1. Nutrient imbalance index (FDI+)

Nitrogen and phosphorus contents were analyzed using Kjeldahl and UV-visible spectrophotometry methods, respectively. Integrated nutrient assessment is essential to capture imbalances linked with over-fertilization, as emphasized in recent global reviews [9]. A normalized nutrient deviation score (NDS) was computed:

$$NDS_i = \sqrt{\left(\frac{N_i - N_{opt}}{\sigma_N} \right)^2 + \left(\frac{P_i - P_{opt}}{\sigma_P} \right)^2} \tag{6}$$

Where N_i, P_i measured concentrations for sample i ; N_{opt}, P_{opt} optimal nutrient levels (center of recommended ranges); σ_N, σ_P standard deviations from background nutrient levels. This metric corrects for natural nutrient variability while measuring anthropogenic excess or deficiency [7, 8].

$$ACE_i = CEC_{base,i} \cdot \left(1 - \beta \cdot \frac{CLI_i}{\max(CLI)} \right) \tag{7}$$

Where β empirical sensitivity coefficient (determined via regression analysis); CLI_i contaminant load index, $CEC_{base,i}$ baseline (uncontaminated) CEC for that soil type. This accounts for reduced nutrient-holding capacity caused by contamination-induced degradation of soil colloids [18].

3.4. Policy and regulatory evaluation metrics

All sampled areas were linked with national or regional legislations. The regulatory framework was mapped by taking into account the legal elements and the field enforcement data, which made it possible to compute the Multi-Criteria Regulatory Score (MCRS) with high policy relevance [9; 24]. These were categorized as:

- Preventative protocols (like chemical application limits)
- Remediation mandates (like phytoremediation, amendments)
- Enforcement and compliance instruments

A Multi-Criteria Regulatory Score (MCRS) was calculated as:

$$MCRS_i = \sum_{k=1}^{K} \left(\frac{x_{j,k} - \mu_k}{\sigma_k} \cdot w_k \right) \tag{8}$$

Where $x_{j,k}$ score of regulation j under criterion k; μ_k mean and standard deviation across all policies for criterion k; w_k expert-assigned weight for criterion k. Evaluation criteria included legal clarity, scientific integration, compliance enforcement, and stakeholder inclusivity [3, 13, 16].

3.5. Modeling remediation effectiveness

To validate interventions (like phytoremediation, composting), a generalized linear mixed model (GLMM) was fitted to the contaminant data from field trials:

$$Y_{ijk} = \gamma_0 + \gamma_1 T_i + \gamma_2 P_j + \gamma_3 (T_i \cdot P_i) + u_k + \epsilon_{ijk} \quad (9)$$

Where Y_{ijk} observed reduction in contaminant i in plot j, replicate k; T_i treatment effect (like phytoremediation); P_i plot characteristics (like baseline CLI, OM); u_k random effect of environmental variation; ϵ_{ijk} residual error term. This model accounts for treatment heterogeneity and random spatial or climatic variability over time [5, 12].

3.6. Statistical processing

All data preprocessing and statistical modelling were performed in R (v4.3) and Python (v3.10, using *statsmodels* and *scikit-learn*). Statistical significance was defined as p<0.05), and multicollinearity was assessed using variance inflation factors (VIF < 5). For hypothesis testing across treatments and soil types, Multivariate Analysis of Variance (MANOVA) was applied:

$$Wilk's\ \Lambda = \frac{|\mathbf{E}|}{|\mathbf{E}+\mathbf{H}|} \quad (10)$$

Where **E** error sum-of-squares matrix, and **H** hypothesis sum-of-squares matrix

Dimensionality reduction and correlation mapping among variables were conducted via Principal Component Analysis (PCA) and Canonical Correspondence Analysis (CCA) to explore drivers of contamination variance [1, 19]. Sampling depth was restricted to 0–15 cm, which may underestimate contamination at deeper soil layers [10, 20]. Further, the six-month field validation period constrains long-term inference; extended trials are recommended for future research [11, 12].

4. Results

4.1. Heavy metal contamination profiles across agricultural regions

Persistent pollutants including heavy metals (HMs) such as lead (Pb), cadmium (Cd) and arsenic (As) accumulate in agricultural soils from the application of fertilizers, wastewater irrigation, and atmospheric deposition. The multi-element pollution levels in the sampling zones of ten regions were quantified using the contaminant load index (CLI). These results are in agreement with international publications that establish urban–industrial borders as hotspots for heavy metals pollution. For instance, Wan et al. also recorded such type of clustering of Pb and Cd in intensively farmed peri-urban areas [6]. The integrated assessment of pollution intensity allows to obtain an overall view of the contamination degree of the region by means of the determination of standard deviations from the regional background values. The data presented below represent not just the geographic extent of heavy metals, but also their statistical extent beyond the “acceptable” levels. For example, contaminant loads are much lower, and soil health indicators are higher than in areas around industry and high cropping intensity.

Table 1. Spatial Distribution of Heavy Metal Concentrations and Contaminant Load Index (CLI) Across Agricultural Zones

Region	Zone	Pb (mg/kg)	Cd (mg/kg)	As (mg/kg)	Pb Z-score	Cd Z-score	As Z-score	CLI
Kirkuk	K1	16.5	0.82	3.1	1.86	1.07	0.87	4.87
Kirkuk	K2	21.9	1.10	4.2	3.11	1.73	1.75	10.70
Nineveh	N1	13.2	0.60	2.9	0.94	0.33	0.63	1.90
Nineveh	N2	20.4	0.94	3.8	2.69	1.47	1.50	8.37
Anbar	A1	11.0	0.52	2.5	0.29	0.07	0.31	0.67
Salahaddin	S1	18.1	0.88	3.4	2.23	1.27	1.13	6.50
Diyala	D1	14.0	0.72	3.0	1.20	0.73	0.75	3.47
Babil	B1	19.8	1.02	4.1	2.91	1.60	1.63	9.62
Wasit	W1	12.5	0.57	2.6	0.71	0.23	0.38	1.32
Basrah	BA1	22.3	1.20	4.5	3.29	1.93	2.00	11.84

According to Table 1, Basrah (BA1) and Kirkuk (K2) show the highest CLI values, indicating that these soil samples are significantly polluted with multiple metals. Specifically, lead (Pb) and cadmium (Cd) levels are consistently above two standard deviations from the background at these locations. On the other hand, A1 and W1 have low CLI values, suggesting they are less affected by industrial activities and have better soil quality. Moderate pollution from metals like lead and arsenic has been observed in Diyala and Nineveh. In Babil (B1), the elevated levels of arsenic and cadmium could point to the long-term application of agrochemicals. Overall, the geographic patterns of CLI align with both human activities and their proximity to pollution sources.

4.2. Pesticide residue load and associated ecotoxicological risk

The environmental persistence and potential ecological risk of pesticide residues were also estimated. The detection of prohibited pesticides like DDT and lindane indicate poor enforcement of pesticide laws which is consistent with other reports in Nigeria and South East Asia where pesticide residues were found several years even after banning[11, 21]. That means policing is as important as scientific cleanup. DDT, Lindane and Atrazine could be detected at each sampling site in A horizon. Most of the organochlorines were also omnipresent and widespread in the all regions, indicating their persistent environmental occurrence, although some compounds were prohibited. Toxicological load at each spot was calculated using amoxicillin toxicity limits, WRRI data (Weighted Residue Risk Index) and environmental half-live values. The high WRRI values of these soils show that they are the liquors or hotspots or those are the localities of high pesticides use or long time contamination which is active till now and affect site environment and has risk for soil biota and ground water.

Table 2. Concentrations of Pesticide Residues and Weighted Residue Risk Index (WRRI) in Agricultural Zones

Region	Zone	DDT (mg/kg)	Lindane (mg/kg)	Atrazine (mg/kg)	Total Residue (mg/kg)	WRRI
Kirkuk	K1	0.12	0.06	0.25	0.43	2.22
Kirkuk	K2	0.18	0.09	0.32	0.59	3.15
Nineveh	N1	0.09	0.05	0.20	0.34	1.78
Nineveh	N2	0.16	0.08	0.28	0.52	2.85
Anbar	A1	0.07	0.04	0.18	0.29	1.52
Salahaddin	S1	0.15	0.07	0.30	0.52	2.94
Diyala	D1	0.11	0.05	0.22	0.38	2.06
Babil	B1	0.20	0.10	0.35	0.65	3.48

Region	Zone	DDT (mg/kg)	Lindane (mg/kg)	Atrazine (mg/kg)	Total Residue (mg/kg)	WRRI
Wasit	W1	0.10	0.04	0.19	0.33	1.70
Basrah	BA1	0.23	0.12	0.40	0.75	3.95

Table 2. (*Continued*)

The WRRI was highest at Basrah (BA1), Babil (B1), and Kirkuk (K2), representing a poor risk status due to the historical and exacerbated current misuse. The little residue causes a carry-over break above an application of so much residue per 2 applications. Although lindane and DDT were prohibited in Iraq, these compounds were found in few samples which indicated either its persistence or contra-band use. This due to less pesticide pressure where the lowest WRRI was reached in Anbar (A1) and Wasit (W1). The most common herbicide was atrazine, which was also found in vegetable row crop areas. These findings illustrate the importance of regulation of pesticide application and control of pesticide residue.

4.3. Nutrient overload and soil fertility imbalance

Excessive use of fertilisers, in particular N and P, also causes leaching and eutrophication and even permanent loss of soil productivity. The high NDS in Basrah and Babil were in agreement with Egypt Nile Delta, as many nutrients source would have already increased heavy metal stress[20]. These related factors all emphasise the requirement for a combination of nutrient and contaminant control[7]. Regional nutrient contents were related to agronomic optima. Scoring of deviation was performed as Nutrient Deviation Score (NDS). Thus, an increasing NDS would be indicative under physiological aspects of the definition as 'bad nutrient management', since 'too much nutrient input as far as the plant needed' is concerned. Similarly, spatial dimensions with active over-application can interdigitate spatial domains with high levels of contaminant loading, which are shared resources for inducing soil degradation. This constitutes a basis for fertilizer management and for proper use of the nutrients.

Table 3. Measured Nitrogen and Phosphorus Levels and Nutrient Deviation Score (NDS)

Region	Zone	N (mg/kg)	P (mg/kg)	Optimal N	Optimal P	NDS
Kirkuk	K1	65	48	35	25	3.42
Kirkuk	K2	72	55	35	25	4.69
Nineveh	N1	62	45	35	25	3.01
Nineveh	N2	70	52	35	25	4.28
Anbar	A1	55	38	35	25	2.26
Salahaddin	S1	68	50	35	25	3.98
Diyala	D1	61	44	35	25	2.85
Babil	B1	75	57	35	25	5.14
Wasit	W1	58	41	35	25	2.56
Basrah	BA1	78	60	35	25	5.56

Max NDSs at Basrah (BA1 = N > 70 mg/kg; P > 55 mg/kg), Babil (B1 = N > 70 mg/kg; P > 55 mg/kg), and Kirkuk (K2 = N > 70 mg/kg; P > 55 mg/kg) were found here. Those findings may reflect heavy fertilization, perhaps to counteract low-yielding crop grown in soils of poor quality, the researchers say. The NDS for Wasit and Anbar reflect an appropriate fertilizer management. The strong relation between nutrient deviation and contaminant indices, implies a similar fundamental cause of loss of fertility and contamination resulted due to inappropriate chemical inputs application. In that way integrated nutrient management research includes these factors.

4.4. Soil retention capacity and adjusted cation exchange capacity (ACE)

Cation exchange capacity (CEC) shows how well does a soil hold onto nutrient, vital for good growth, and also how much is affected by changes in PH. HGH contaminant loads, in particular, can be absorbed on soil colloids and vie for binding positions with other critical cations, and suppress the binding and retention of nutrients in general. The effect of this combination on adjusted CEC (ACE) was investigated by evaluating combined CLI observations and baseline CEC. The negative association of CLI and ACE are in agreement with simulation models even though they predict that contamination decreases fertility through competition for nutrient retention cations[18, 19]. ACE measures the loss of nutrient-holding capacity of soil because of contaminant presence. This information revealed the parts of the soil that requires amelioration to correct the chemical soil characteristics and increased productivity in agriculture clubs.

Table 4. Baseline CEC, Contaminant Load Index (CLI), and Adjusted CEC Across Regions

Region	Zone	Baseline CEC (cmol/kg)	CLI	Adjusted CEC (cmol/kg)	Percent Reduction (%)
Kirkuk	K1	25.0	4.87	21.5	14.0
Kirkuk	K2	26.2	10.70	18.2	30.5
Nineveh	N1	24.5	1.90	22.7	7.3
Nineveh	N2	25.7	8.37	19.4	24.5
Anbar	A1	24.8	0.67	23.9	3.6
Salahaddin	S1	26.0	6.50	20.9	19.6
Diyala	D1	25.2	3.47	22.1	12.3
Babil	B1	26.8	9.62	19.0	29.1
Wasit	W1	24.6	1.32	23.3	5.3
Basrah	BA1	27.0	11.84	17.5	35.2

BA1 and K2 had the maximum relative changes with normalization of CEC (reduction >30% compared to uncorrected values for corrected heavy metals interference). This German Formula derived value was similar to that for a heavy-metal disrupted nutrient binding site. The difference was smaller for A1 and W1 with lower CLI and contaminant pressure. Mild trend of decreased complexity was observed in Babil (B1) and Ninawa (N2). These results have started to sketch a picture of pollution's effects on the health, and for the long term, the nutrient flows, of the key mechanisms to agricultural productivity and healthy soils.

4.5. Regional comparison via normalized contaminant index (NCI)

The Normalized Contaminant Index (NCI) is employed as a map visualizing regional differences of average pollutant concentrations normalized by the geographical background level. Districts under > 120% threshold (Basrah, Babil, Kirkuk) were identified to treat these nodes as priority intervention areas, as in Spain or China models that were deriving hotspot mapping[13, 17]. NCI also has a potential for cross-element standardization that the raw values lack, and can be for sorting regions by the level of contamination. Summary of lead (Pb) and cadmium (Cd) in the ratio of NCI value is proposed by highlighting the importance of high ratio axis. A final point is that it might be the case as well that comparisons like this can be of use to environmental regulators or system managers or land-use planners, for example, that wish to deploy their policies (in space) smartly.

Table 5. Lead and Cadmium NCI Scores by Region

Region	Zone	Pb (mg/kg)	Pb Background	Pb NCI (%)	Cd (mg/kg)	Cd Background	Cd NCI (%)
Kirkuk	K1	16.5	10.0	65.0	0.82	0.5	64.0

Region	Zone	Pb (mg/kg)	Pb Background	Pb NCI (%)	Cd (mg/kg)	Cd Background	Cd NCI (%)
Kirkuk	K2	21.9	10.0	119.0	1.10	0.5	120.0
Nineveh	N1	13.2	10.0	32.0	0.60	0.5	20.0
Nineveh	N2	20.4	10.0	104.0	0.94	0.5	88.0
Anbar	A1	11.0	10.0	10.0	0.52	0.5	4.0
Salahaddin	S1	18.1	10.0	81.0	0.88	0.5	76.0
Diyala	D1	14.0	10.0	40.0	0.72	0.5	44.0
Babil	B1	19.8	10.0	98.0	1.02	0.5	104.0
Wasit	W1	12.5	10.0	25.0	0.57	0.5	14.0
Basrah	BA1	22.3	10.0	123.0	1.20	0.5	140.0

Table 5. (*Continued*)

For Pb and Cd Sum through NCI value >120% represent high accumulation of these metals (at BA1) and BA3 (Ba'qubah) and BA2 (al-Qadisiyah). Kirkuk (K2) and Babil (B1) are next which indicate possible impact of contamination in industrial zones in the north and south. Too low values were obtained in Ninevah (N2), and in the case of cadmium, likely with some legacy of uncaught irrigation contamination. Anbar (A1) and Wasit (W1) are at background level, the background or not-too-high levels are kept, which are consistent with their being control/low-risk region. This NCI methodology is useful in specifying those ones, which should be immediately rectified in an ongoing manner.

4.6. Multivariate drivers of soil degradation (PCA Analysis)

Associations among soil health variables Principal Component Analysis (PCA) was performed using Z standardized values for contaminants, nutrient status, and buffering capacity during standardization. The PCA indicates that the contamination variables correlate as observed in the European soil health monitoring[19]. The negative loading of ACE once again supported the trade-off between contamination pressure and soil fertility. This approach confines high dimensional information into an optimal number of a few components that capture a large fraction of a variance. PC1 was related to a pollution process in general, and PC2 to nutrient over-enrichment. The negative loadings of ACE on the contamination factors very clearly showed the ability of the contaminant to impede the adsorbed nutrients in soils.

Table 6. Principal Component Loadings for Soil Health Variables

Variable	PC1 (Contamination)	PC2 (Nutrient Overload)	PC3 (Residual)
Lead (Pb)	0.91	0.14	0.09
Cadmium (Cd)	0.89	0.19	0.08
Arsenic (As)	0.85	0.22	0.13
WRRI	0.80	0.41	0.09
NDS	0.66	0.53	0.19
ACE	–0.88	–0.25	–0.10

PC1 accounts for 49% of the variance, and it consisted predominantly of heavy metal and pesticides concentrations. The mineral imbalances exhibited significant correlations with PC2 (29%). ACE was also negatively and strongly associated with PC1, indicating reduced soil buffering and nutrient retention. Such a multi-dimensional approach would also offer an integrated assessment of soil degradation, as soil degradation is a system one and can not be fully under-stood outside its cage.

4.7. Effectiveness of regional regulatory frameworks

A national MCRS based on a farmer focus was calculated by area for rule of law, enforcement and environmental outcomes. To measure the conditional effect on a country of the enforcement of the regulation practice for soil quality, these scores were regressed for the countries against the axes CLI, WRRI, NDS and ACE. These results contributed to the knowledge on the efficacy of new governance instruments for soil conservation.

Table 7. Multi-Criteria Regulatory Scores and Soil Health Indicators by Region

Region	MCRS	Avg CLI	Avg WRRI	Avg NDS	Avg ACE (cmol/kg)
Kirkuk	4.0	7.79	2.69	4.05	19.8
Nineveh	4.2	5.14	2.32	3.64	21.1
Anbar	4.8	0.67	1.52	2.26	23.9
Salahaddin	4.1	6.50	2.94	3.98	20.9
Diyala	4.3	3.47	2.06	2.85	22.1
Babil	3.9	9.62	3.48	5.14	19.0
Wasit	4.6	1.32	1.70	2.56	23.3
Basrah	3.5	11.84	3.95	5.56	17.5

Anbar, Wasit and Diyala are examples of high MCRS (highly urbanized and relatively developed) governorates with very good soil health as indicated by low CLI and WRRI along with high ACE score. Babil and Basrah on the other hand had low results and illustrate the difficulties for effective compliance or surveillance. The inverse U-shaped relationship between MCRS and CLI suggests that the governance has success in environmental abatement. The present data further document the need for policy standardisation and compliance in high-risk environments.

4.8. Field validation of soil remediation strategies

Field experiments were conducted in high contaminant load index areas to verify the feasibility of those proposed remediation techniques. In consonance with experimental results of juncea-stimulated remediation, a combinatory phytoremediation and organic amendment (Plot P3) synergistic effect was observed[5, 12]. This confirms that low-cost bioremediation can be applied in severely contaminated zones. Selected plots Five plots located in areas of high CLI and WRRI values were selected. Chosen plots Five plots were selected from regions with elevated values of CLI and WRRI. Phytoremediation with Brassica juncea, organic compost amendments, and phytoremediation-organic amendment combination taken in three replications each. Soil samples were taken monthly over a six-month period to document contaminant concentrations, changes in soil organic matter and increases in pH buffering. Results were compared with control plots without intervention. Table 8 contains empirical examples of biophysical-based interventions that improve soil quality restoration and reduce contamination levels.

Table 8. Results of Field Trials for Soil Remediation Over a Six-Month Period

Plot	Region	Treatment Type	Initial Pb (mg/kg)	Final Pb (mg/kg)	Reduction (%)	Organic Matter (%) Δ	pH Change
P1	Babil	Phytoremediation	21.0	10.2	51.4	+1.1	+0.2
P2	Kirkuk	Organic Compost	19.5	9.5	51.3	+1.3	+0.4
P3	Basrah	Phyto + Compost	22.8	9.0	60.5	+1.6	+0.5
P4	Nineveh	Phytoremediation	20.0	11.2	44.0	+0.9	+0.3

Plot	Region	Treatment Type	Initial Pb (mg/kg)	Final Pb (mg/kg)	Reduction (%)	Organic Matter (%) Δ	pH Change
P5	Anbar	Control (No Treatment)	18.3	17.0	7.1	+0.2	+0.0

Table 8. (*Continued*)

In Basrah, the highest reduction of lead (60.5%) accompanied with the highest increases of organic matter content (+1.6%) and pH stability (+0.5) were registered in Plot P3 that received combined treatment of phytoremediation and compost. This has confirmed the synergistic effect of organic inputs combined with hyperaccumulator species. Significant reductions (>44% Pb) were obtained by compost treatment alone (P2) for Kirkuk and also in combination with phytoremediation alone (P1, P4), which indicates individual efficiencies. For once, the anbar control plot (P5) was left untreated and only showed small changes again showing the need for treatment. This evidence identifies the on-field potential of biological and organic methodology (as agricultural practice) for the remediation of moderately-high contaminated agricultural soils.

The findings are of diagnostic and practical importance: diagnostics - they reveal the synergism of different indices (CLI, WRRI, NDS, ACE, NCI) for solving the problem of soil degradation; practice - could be used for justification of measures of improvement and policy intervention. This dualism is central in the development of the sustainable soil governance arrangements [2-4].

5. Discussion

Findings may potentially contribute to the elucidation of spatial pattern of soil contamination of farmland and effectiveness of policy provisions and schedule of clean-up. Thanks to the joint investigation of the concentration of heavy metal and pesticide residue, calculation of nutrient imbalance, and monitoring employing a series of advanced soil quality indices of CLI, WRRI, NDS, as well as the ACE, the current results provide a full description of soil degradation in mothballed soils during continuous cropping. Therefore, findings from these studies suggest that pollution does follow the anthropogenic pressure gradient with agrochemical over application and attraction by industrial perimeters and bad governance all of which closely correspond to the observed trend from the dynamics of global soil pollution[2, 6]. This supports the international literature that local enforcement capacity is not independent of soil governance[3, 15, 17]. Our research is the first to combine MCRS with contamination indices to make a policy-science chain of relationships by multidimensional which does not exist in soil studies [4].

The highest contamination by heavy metals was found in areas of Basra, Babil and Kirkuk in Iraq where there was a high concentration of runoff from either agricultural or industrial sources. This finding is consistent with previous results reported by Wanet et al. [6], which showed that the hot spot areas of metal contamination are the urban-industrial boundary enclave areas when wastewater irrigation and past pollution are present in the influence area. Further, an overlap of nutrient enrichment and metal toxicity in the same areas further increases the complexity of the compounding environmental stressors present there. This entanglement indicates the need for integrated soil management strategies that balance different aspects of soil management including organic abatement [5, 8], nutrient balancing [7], and more stricter monitoring [6]. This double pressure has been emphasized in other arid and semi-arid systems, as for example in the Eastern Nile Delta, where Abd-Elatyet al. [20] reported synergistic contamination effects through concurrent fertilizer abuse and accumulation of trace elements.

The integration of pesticide residue analysis and the WRRI revealed ongoing environmental risks linked to persistent organic pollutants (POPs), even in zones where certain chemicals have been restricted for years. The detection of DDT and Lindane supports global findings by Yaashikaa and Kumar [11] stressed that legacy pesticides remain bioavailable in the soil long after regulatory bans, posing latent threats to ecosystems and food safety. Such findings demonstrate the persistent gap between regulatory bans and field-level compliance, reinforcing calls for stronger international conventions on pesticide monitoring [11, 21]. This highlights the challenge of managing chemical residues in developing countries where monitoring infrastructure may be insufficient or inconsistently enforced.

One of the significant contributions of this study is the development and application of composite soil health indicators such as the CLI and ACE. Theoretically, this contributes to the emerging literature on integrated soil indices [1, 19], while practically, it provides regulators with actionable metrics for prioritizing interventions [3, 16]. These metrics not only enable inter-regional comparison but also link biogeochemical deterioration to quantifiable contaminant levels. The inverse correlation between CLI and ACE provides empirical validation for conceptual models in prior literature that suggest a direct trade-off between contamination intensity and soil fertility indicators such as cation exchange capacity, organic matter content, and microbial diversity [2, 19].

The Principal Component Analysis (PCA) demonstrated that contamination variables (Pb, Cd, As) cluster strongly with WRRI and NDS, indicating a dominant latent factor of anthropogenic chemical stress. Negative loading of ACE in PC1 confirms the degradative impact of contamination on soil nutrient retention capacity. These findings complement national-scale cluster analyses in Europe, where Seaton et al. [19] found that contamination indicators often oppose fertility metrics in multivariate soil health models. This reinforces the need for integrated soil management that addresses contamination, fertility, and biological activity concurrently.

Our field validation trials offer evidence-based confirmation that remediation strategies such as phytoremediation, compost amendments, and integrated treatments can effectively reduce contaminant loads and restore soil function. The best results were obtained from the combined treatment approach, which aligns with previous experiments showing that organic amendments improve soil structure and microbial activity, thereby enhancing the phytoextraction potential of hyperaccumulator species [2, 7]. These findings support the broader consensus that bioremediation approaches, particularly those that integrate physical and biological processes—offer scalable, cost-effective solutions for restoring moderately contaminated soils [11].

The regulatory analysis shows that higher Multi-Criteria Regulatory Scores (MCRS) correlate with improved soil conditions, demonstrating the role of policy in shaping environmental outcomes. Managerially, this confirms that policy enforcement matters as much as scientific remediation. Comparable evidence has been observed in China's "10-Point Soil Plan," which improved sustainability outcomes where enforcement was strongest [13]. However, disparities in MCRS between regions such as Anbar and Basrah reveal the inconsistencies in enforcement and resource allocation across the country. Similar findings were reported in Spain by Ramón and Lull [17], where regional governance gaps led to fragmented soil protection outcomes despite national policy frameworks. These results point to the urgent need for harmonized regulations and stronger institutional mechanisms to support soil health in Iraq.

Despite its strengths, the study has several limitations. Limitations also include reliance on national baseline data that may differ in accuracy across regions[6]. Future research should explore AI-assisted soil diagnostics[25] and remote sensing for broader spatial monitoring [20]. While CLI, WRRI, and NDS provide robust composite indicators, they depend heavily on available baseline data, which may vary in accuracy across regions. In regions with limited historical monitoring, such as Basrah, assumptions regarding background levels may introduce error margins. This study focused primarily on topsoil (0–15 cm), which underestimate deeper contamination, especially in areas with long-term pesticide or wastewater application

[6]. The field trials were conducted over six months—a relatively short period for observing full ecological recovery or plant uptake cycles, as many bioremediation strategies require multiple growing seasons for optimal performance [11].

In light of these findings, future research should explore vertical soil profiles to assess contamination at greater depths and potential groundwater interaction. Additionally, expanding the use of remote sensing and AI-based soil diagnostics may enhance spatial coverage and reduce sampling costs. Longitudinal studies over multiple seasons could validate the durability and scalability of remediation approaches. Socio-economic analysis could be included to improve the understanding of policy implementation and farmer responses, which are generally not seen in the environmental literature.

The research results extend the knowledge of additivity models for chemical stressors and response in regulatory landscapes in soil quality in agro-ecosystems. Results and methods presented here should be applicable on a more general scale for other developing regions experiencing issues of agricultural intensification and environmental degradation in a rapid way. To achieve the soil-based SDGs for food security and environmental safeguarding as well as sustainable land management, their integrated, place-based (locally-adapted) pathways to SDGs should be SLM approaches [4].

6. Conclusions

The study has a comprehensive view towards soil pollution by integrating physical, ecological and governance dimensions to respond to the sustainability challenge of agriculture in a holistic way. The study highlights that levels of contamination with heavy metals and pesticide residuals, combined with nutrient inequity and lax enforcement of regulations, are driving soil health and long-term productivity to a tipping point that has severe repercussions. By integrating different indicators with a regulatory impact assessment framework, this study has created both a broad and a more fragmented diagnostic tool.

The findings reveal some clear patterns: contamination is most severe in areas with high land use and weak governance, while better soil health indicators are associated with stricter enforcement. Additionally, an interesting challenge posed by this paper is whether the connection between government actions and soil quality, both empirically and theoretically, aligns with our frameworks. It's crucial to recognize that soil health is influenced not only by environmental factors but also by how institutions respond to these challenges.

This also serves as a new validation of how effective practical remediation technologies can be. Field trials have shown that using both phytoremediation and organic treatments can significantly reduce harmful elements in the soil while boosting its fertility and overall health. It suggests that restoration is not just a technical fix applied to a site, but an ecosystem response that depends on the balance of plants and the soil microbiota. This also suggests that low-cost natural solutions can be developed for contaminated agro systems and are needed for low-cost technologies in the resource-poor areas. The influences have theoretical and practical implications. In addition to offering insight into the applicability of composite indices for capturing the multi-dimensional nature of the relationship between contamination and governance, this research is also another step forward in our state of knowledge. Operationally speaking, it translates to concrete action items related to prevention, compensation, incentives and surveillance. A particularly interesting finding for policy purposes, especially in relation to development of agriculture in the countries of the Region, is that the results clearly indicate that any administrative decision must be based on scientific diagnosis and remedial action at regional level.

Although the data of chemical and physical properties of soil and groundwater provided valuable information, there were some limitations in this study, such as: (1) shallow sampling range for soil, and bottom contamination may be underestimated if deeper soil sampling was conducted; (2) Sampling time was 6 months, and the follow-up time was too short. It is suggested that research of adequate scale and season across a gradient of soil depths and socioeconomic barriers to policy implementation is required to bridge such gaps. In conclusion, while pollution control is not a silver bullet for a resilient agriculture, it nevertheless requires proper governance mechanisms, strong regulatory frameworks and long-lasting engagement of communities. Together with other work, this research tells us that it is possible to combine science assessments and governance tools, and gives us important lessons for maintaining soil health and food security for generations to come.

Conflict of interest

The authors declare no conflict of interest

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