

# Framework for Integrating Ayurveda-Derived Interventions into Sustainable Soil Remediation: A Translational Review

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## Abstract

Soil remediation practices have traditionally focused on reducing contaminant concentrations to achieve regulatory compliance, often with limited attention to long-term soil functionality and ecological recovery. As a result, many remediated sites remain biologically impaired despite meeting chemical threshold values. Biological and nature-based remediation approaches offer ecological advantages, but their translation into field-scale practice is constrained by variability in performance, lack of standardization, and limited regulatory acceptance.

Ayurveda-derived soil interventions represent a class of ecologically oriented remediation inputs that emphasize restoration of soil biological activity, organic balance, and plant-supporting capacity. However, these interventions are rarely incorporated into formal remediation programs due to the absence of structured pathways for scientific validation, scale-up, and policy integration. Existing literature discusses such approaches descriptively, but does not address the translational barriers that prevent their systematic adoption.

This narrative translational review addresses this gap by proposing a structured model that maps Ayurveda-derived soil remediation interventions across three sequential stages: scientific validation based on functional soil indicators, controlled scale-up and field deployment using formulation and delivery technologies, and regulatory integration supported by standardized performance data. The review critically examines why current remediation frameworks fail to accommodate biologically driven interventions and identifies measurable endpoints and implementation strategies that align ecological restoration with regulatory requirements.

By reframing Ayurveda-derived interventions as process-oriented remediation aids rather than standalone decontamination agents, this review provides a practical and testable framework for their integration into sustainable soil remediation practice. The proposed model offers clear implications for research design, field implementation, and environmental governance, supporting the advancement of soil remediation strategies that prioritize long-term soil health alongside contaminant risk reduction.

**Keywords:** soil remediation, translational model, biological remediation, soil health, Ayurveda-derived interventions, sustainable land management

## 1. Introduction

Soil pollution continues to limit agricultural productivity, ecosystem stability, and land reuse across indus-

trial, urban, and intensively cultivated regions. Remediation efforts over the past decades have largely focused on reducing contaminant concentrations to meet regulatory thresholds, using physical removal, chemical stabilization, or short-term biological treatments. While these approaches can achieve compliance, they frequently fail to restore soil function, resulting in sites that are chemically acceptable but biologically impaired and agriculturally unproductive [1,2].

A major reason for this gap is the **absence of a translational pathway** that connects remediation concepts to field-scale performance and regulatory acceptance. Most remediation studies remain confined to laboratory or pilot scales, rely on short experimental durations, and emphasize contaminant reduction rather than recovery of soil biological processes such as microbial activity, nutrient cycling, and plant support capacity [3,4]. As a result, promising biological or nature-based interventions often do not progress beyond proof-of-concept, and their adoption in real-world remediation programs remains limited.

Ayurveda provides a distinct but underutilized perspective that is directly relevant to this translational gap. Within this system, *bhumi* (soil or land) is treated as a functional and regenerative entity whose health depends on biological activity, organic balance, and sustained productivity. From this viewpoint, soil degradation is not defined solely by the presence of contaminants but by the loss of functional capacity to support plant growth and ecological processes. This functional interpretation aligns closely with contemporary soil health frameworks that emphasize biological indicators alongside chemical measurements [5,6]. However, Ayurveda-derived remediation concepts have rarely been examined through structured scientific and regulatory pathways, limiting their acceptance within modern soil remediation practice.

Another constraint is that natural or plant-derived remediation inputs are often evaluated as raw materials rather than as interventions requiring formulation, delivery control, and performance standardization. Without addressing issues of stability, dose control, persistence, and site-specific variability, such interventions are difficult to scale or regulate [7]. Advances in formulation science, microbial technologies, and environmental monitoring now provide the tools needed to overcome these limitations, but they are rarely integrated into a coherent translational framework for ecologically oriented remediation strategies [8,9].

The central limitation, therefore, is not a lack of remediation concepts, but the lack of a **clear translational model** that defines how biologically and ecologically derived interventions can be **scientifically tested, scaled for field application, and aligned with regulatory expectations**. Existing reviews describe individual technologies or general sustainability principles, but do not provide an actionable pathway that links ecological intent with implementation requirements [10].

**This review addresses that gap by proposing a translational model for soil remediation that systematically maps Ayurveda-derived interventions across three stages: scientific validation, scale-up and field deployment, and regulatory integration.** Rather than treating Ayurveda as a philosophical adjunct, the review positions it as a source of function-oriented remediation logic that can be operationalized using modern soil science metrics and emerging technologies. By focusing on translation rather than description, this article aims to provide a framework that is testable, scalable, and relevant to policy-driven remediation practice.

## 2. Translational gaps in soil remediation methods:

Despite decades of technical development, most soil remediation frameworks struggle to progress from experimental success to reliable field application. The core limitation is that remediation is commonly

treated as a **chemical correction problem**, rather than as a process of **functional soil recovery**. As a result, remediation strategies are optimized to reduce contaminant concentrations over short time frames, while long-term biological performance and land usability receive secondary attention [11].

A dominant translational failure arises from the way remediation success is defined. Regulatory and technical assessments rely primarily on total contaminant concentrations or comparison with guideline values. These indicators provide limited insight into soil biological recovery, nutrient cycling, or plant-supporting capacity [12]. Numerous field studies have shown that soils meeting regulatory thresholds may still exhibit reduced microbial activity, poor aggregation, and limited crop performance, indicating incomplete remediation in functional terms [13]. This narrow definition of success discourages remediation strategies that prioritize gradual ecological restoration.

Another limitation lies in the **fragmented evaluation of remediation technologies**. Physical, chemical, and biological methods are often assessed independently, with little consideration of how they interact over time or across spatial scales. Biological and nature-based approaches, in particular, are frequently tested under controlled laboratory conditions that do not reflect site heterogeneity, climatic variability, or long-term contaminant dynamics [14]. When these methods are transferred to the field, inconsistent performance leads to uncertainty among practitioners and regulators, further restricting adoption.

Scale-up presents an additional translational bottleneck. Many remediation interventions based on natural or biological inputs are applied as unformulated materials, resulting in uneven distribution, rapid degradation, and variable persistence in soil systems. Without addressing formulation stability, delivery control, and dose-response behavior, such interventions cannot be deployed predictably at field scale [15]. This limitation is structural rather than conceptual, and reflects the absence of a translational framework rather than a lack of ecological validity.

From an Ayurveda-derived perspective, these failures stem from a mismatch between **process-oriented soil recovery** and **outcome-oriented regulatory models**. Ayurveda treats *bhumi* (soil or land) recovery as a staged process, where restoration of biological activity precedes stable productivity. Current remediation frameworks rarely account for such progression, instead expecting immediate compliance outcomes. This disconnect prevents biologically oriented remediation strategies from being evaluated on their own functional terms.

Finally, regulatory systems themselves contribute to translational failure. Existing policies are designed to evaluate discrete remediation actions rather than adaptive, multi-stage processes. Long-term monitoring, functional indicators, and adaptive management pathways are seldom embedded into remediation approvals [16]. Without regulatory mechanisms that accommodate staged recovery and performance-based evaluation, integrative remediation models remain difficult to implement, regardless of their scientific merit.

Taken together, these limitations indicate that the problem is not the absence of effective remediation concepts, but the absence of a **structured translational pathway** that aligns ecological logic, technological implementation, and regulatory assessment. Addressing this gap requires a model that explicitly defines how remediation interventions move from validation to deployment and policy acceptance. This need forms the basis for the translational framework proposed in the following sections.

### 3. Defining Ayurveda-Derived Interventions as Soil Remediation Inputs

For translational progress, Ayurveda-derived interventions must be defined **operationally**, not philosophically. In soil remediation, these interventions should be treated as **biologically active inputs**

designed to restore soil function—particularly microbial activity, organic matter dynamics, and plant support capacity—rather than as standalone contaminant neutralizers. This distinction is critical because it determines how such interventions are tested, formulated, scaled, and regulated.

In practical terms, Ayurveda-derived remediation inputs include plant-based materials, organic matrices, and biologically active preparations that act through **process modulation** rather than instantaneous chemical transformation. Their primary effects are indirect: improving microbial habitat, enhancing enzymatic activity, stabilizing organic carbon, and reducing contaminant bioavailability over time. This mode of action aligns with functional soil health concepts, where recovery is measured by biological and ecological performance rather than total contaminant removal alone [17,18].

Equally important is defining what these interventions **are not**. They are not substitutes for emergency remediation at highly contaminated sites requiring rapid risk reduction, nor are they single-application solutions. Treating them as raw amendments applied without formulation or delivery control has led to inconsistent outcomes and has reinforced skepticism regarding their field utility [19]. Without addressing variability, persistence, and dose–response behavior, such inputs cannot meet the reproducibility standards required for large-scale remediation programs.

From a translational standpoint, Ayurveda-derived inputs must therefore be evaluated using **function-first criteria**. Suitable endpoints include microbial biomass and diversity, soil enzyme activity, aggregate stability, organic carbon retention, and plant growth response, alongside measurements of contaminant bioavailability [20]. These endpoints provide mechanistic insight into recovery processes and allow staged assessment of remediation progress. Importantly, they also generate datasets that can be aligned with emerging regulatory interest in soil health indicators [21].

Formulation and delivery represent the next critical boundary between concept and practice. Unformulated biological inputs are prone to rapid degradation, uneven dispersion, and site-dependent performance. Advances in carrier systems, encapsulation, and controlled-release technologies offer practical solutions by improving stability, extending residence time in soil, and enabling dose control [22]. When applied within a defined protocol, such technologies allow Ayurveda-derived inputs to be deployed with predictability comparable to conventional remediation agents.

Finally, these interventions must be positioned within remediation programs as **process-oriented tools** rather than one-time treatments. Ayurveda conceptualizes *bhumi* (soil or land) recovery as a progressive sequence, where biological restoration precedes stable productivity. Translationally, this implies staged deployment with monitoring-driven adjustments rather than fixed, single-endpoint interventions. Recognizing this distinction is essential for designing validation studies, field trials, and regulatory submissions that reflect how these interventions function in real soil systems.

This operational definition establishes the basis for the translational model proposed in the next section, which systematically maps how Ayurveda-derived soil remediation inputs can move from scientific validation to field-scale deployment and regulatory integration.

#### 4. A Translational Model for Ayurveda-Derived Soil Remediation Interventions

The central contribution of this review is a **translational model** that defines how Ayurveda-derived soil remediation interventions can move systematically from concept to practice. The model is structured around three sequential but connected stages: **scientific validation, scale-up and field deployment, and regulatory integration**. Each stage addresses a specific failure point in existing remediation frameworks and introduces measurable criteria that enable progression to the next stage.

#### 4.1 Stage I: Scientific Validation Based on Soil Function

The first stage focuses on establishing **scientific credibility** using endpoints that reflect soil recovery rather than short-term contaminant reduction alone. Ayurveda-derived interventions act primarily by modifying soil processes, including microbial metabolism, organic matter stabilization, and plant–soil interactions. Consequently, validation studies must prioritize functional indicators such as microbial biomass, enzyme activity, soil respiration, aggregate stability, and plant growth response, alongside measurements of contaminant bioavailability [23,24].

A key limitation of current validation practices is the reliance on single-endpoint experiments conducted over short durations. Such designs are insufficient for interventions whose effects emerge gradually through biological pathways. The proposed model therefore requires **time-resolved and multi-parameter evaluation**, allowing soil recovery trajectories to be assessed rather than static outcomes. This approach aligns with emerging soil health frameworks that recognize biological indicators as early predictors of long-term soil performance [25].

At this stage, Ayurveda-derived inputs are not evaluated as isolated substances but as **process modifiers**. This distinction is critical, as it shifts validation from substance-based testing toward mechanism-oriented assessment. Only interventions that demonstrate consistent improvement in functional soil indicators under controlled conditions should progress to field-level testing.

#### 4.2 Stage II: Scale-Up and Field Deployment

The second stage addresses the most common point of translational failure: **loss of performance during scale-up**. Field environments introduce spatial heterogeneity, climatic variability, and management constraints that are absent in laboratory studies. Ayurveda-derived interventions, when applied as raw or unformulated materials, are particularly vulnerable to uneven distribution, rapid degradation, and inconsistent persistence in soil systems [26].

To overcome these limitations, the model requires that scale-up be accompanied by **formulation and delivery control**. Technologies such as carrier-based delivery systems, encapsulation, granulation, and controlled-release matrices are not optional enhancements but essential translational tools. These technologies enable dose standardization, improve residence time in soil, and reduce site-dependent variability [27].

Field deployment under this model is inherently adaptive. Monitoring of functional soil indicators guides adjustments in application rate, frequency, and spatial targeting. Rather than expecting uniform outcomes across sites, the model accommodates variability through **performance-based management**, improving both reliability and practitioner confidence. This stage produces field-scale datasets that are critical for regulatory engagement.

#### 4.3 Stage III: Regulatory and Policy Integration

The final stage addresses regulatory acceptance, which remains a major barrier for biologically and ecologically oriented remediation strategies. Existing regulatory frameworks are primarily designed to evaluate discrete remediation actions using chemical concentration thresholds. Such frameworks are poorly suited to interventions that act through gradual functional restoration [28].

The proposed model reframes Ayurveda-derived interventions as **soil remediation aids or conditioners**, rather than as primary decontamination agents. Regulatory evaluation at this stage emphasizes environmental safety, absence of secondary contamination, and demonstrable improvement in soil function over time. Importantly, this does not require abandoning chemical thresholds, but supplementing them with validated functional indicators [29].

Policy integration also requires standardized documentation, including formulation specifications, application protocols, monitoring plans, and long-term performance data. By generating this evidence during Stages I and II, the model ensures that regulatory submission is a continuation of the research process rather than a post hoc exercise. This alignment reduces uncertainty for regulators and facilitates conditional or staged approvals linked to monitoring outcomes.

**Table 1. Translational model for Ayurveda-derived soil remediation interventions**

<b>Translational stage</b>	<b>Primary objective</b>	<b>Key limitation addressed</b>	<b>Required actions</b>	<b>Measurable outputs</b>
Stage I: Scientific validation	Demonstrate functional soil recovery	Overreliance on contaminant reduction	Multi-endpoint, time-resolved studies	Biological activity, soil function indicators
Stage II: Scale-up and field deployment	Achieve consistent field performance	Variability and loss of efficacy	Formulation, delivery control, adaptive monitoring	Stable field-level performance data
Stage III: Regulatory integration	Enable acceptance and implementation	Incompatible regulatory metrics	Safety evaluation, standardized dossiers	Policy-ready evidence, monitoring frameworks

**Table 2. Comparison of conventional soil remediation frameworks and the proposed translational model**

<b>Dimension</b>	<b>Conventional remediation frameworks</b>	<b>Translational model proposed in this review</b>
Primary objective	Rapid reduction of contaminant concentrations	Progressive restoration of soil function alongside risk reduction
Definition of success	Compliance with chemical threshold values	Demonstrable improvement in biological and functional soil indicators
Treatment logic	Substance- and contaminant-centric	Process-oriented and function-centric
Role of biological inputs	Supplementary or optional	Central to remediation strategy
Evaluation endpoints	Total contaminant concentration	Microbial activity, enzyme function, soil structure, plant response, contaminant bioavailability
Scale-up approach	Direct extrapolation from laboratory studies	Formulation-based scale-up with delivery and persistence control
Field adaptability	Limited; fixed protocols	Adaptive, monitoring-driven application
Regulatory alignment	Based on single-stage approval	Staged acceptance supported by performance data

Long-term soil usability	Often uncertain	Explicitly addressed as a core outcome
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By explicitly defining progression criteria at each stage, this translational model converts Ayurveda-derived soil remediation from a conceptual proposition into a **testable, scalable, and regulatable intervention pathway**. The model does not replace existing remediation methods but complements them by addressing dimensions of soil recovery that conventional frameworks routinely overlook.

### 5. Conclusion

The persistent gap between soil remediation research and field-level implementation reflects a structural weakness in how remediation interventions are conceptualized, tested, and regulated. Current frameworks emphasize short-term contaminant reduction and regulatory compliance, but often fail to ensure recovery of soil biological function and long-term land usability. As a result, many remediation efforts achieve chemical acceptability without ecological restoration.

This review demonstrates that Ayurveda-derived soil remediation interventions, when treated as process-oriented and biologically active inputs, can address aspects of soil recovery that conventional approaches routinely overlook. Their relevance lies not in philosophical positioning, but in their functional emphasis on biological activity, organic balance, and gradual restoration. However, without a defined translational pathway, such interventions remain confined to small-scale experimentation and informal application.

The translational model proposed in this article provides a structured solution to this limitation. By defining three enforceable stages—scientific validation based on soil function, controlled scale-up and field deployment, and regulatory integration—the model establishes clear progression criteria that align ecological intent with scientific rigor and policy requirements. Importantly, it reframes Ayurveda-derived interventions as complementary remediation tools that can be evaluated, standardized, and regulated using modern soil science metrics.

Adoption of this model has practical implications for research design, remediation practice, and environmental governance. For researchers, it emphasizes the need for multi-parameter, time-resolved studies that capture soil recovery processes. For practitioners, it highlights the importance of formulation control and adaptive field management. For regulators, it offers a pathway to incorporate functional soil indicators alongside existing chemical thresholds.

In conclusion, sustainable soil remediation requires frameworks that integrate ecological recovery with technical and regulatory feasibility. The translational model presented here offers a concrete and testable pathway for advancing Ayurveda-derived soil remediation interventions from concept to practice. Its application has the potential to improve remediation outcomes, enhance soil resilience, and support long-term environmental sustainability in contaminated land management.

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*(Vancouver style; numbered in order of appearance in the manuscript)*

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