

Dicotyledonous Tap-Root Plants As Biological Agents For Restoring Sodicity And Subsoil Compaction In Degraded Alluvial Landscapes of Bhatpar Rani

Aman Tiwari^{1*}, Anil Kumar Dwivedi², Ram Autar Verma³

¹*Assistant Professor, Department of Botany, M.M.M.P.G. College, Bhatpar Rani, Deoria (U.P.) India

²Pearl Lab, D.D.U. Gorakhpur University, Gorakhpur (U.P.) India

³Department of Botany, M.M.M.P.G. College, Bhatpar Rani, Deoria (U.P.) India

*Corresponding Author: Aman Tiwari; Email: amantiwarihere@gmail.com

(Received -15April2026/Revised-28April2026/Accepted-15May2026/Published-20May2026)

Abstract

The Indo-Gangetic Plains experience significant ecological degradation due to sodicity, subsoil compaction, and the widespread excavation of fertile topsoil for brick manufacturing. In the Bhatpar Rani region of Deoria, these anthropogenic pressures transform productive agricultural land (T1) into structurally compromised brick kiln sites (T2). The excavation of the upper 20–30 cm horizon depletes the soil's biologically active layer, causing a sharp decline in organic carbon and accelerating the formation of impermeable calcic kankar pans. Traditional chemical amendments, such as gypsum application, typically yield only transient surface amelioration and fail to remediate these hardened deeper horizons.

This study evaluates a biological recovery pathway (T3) utilizing an eight-species consortium of multipurpose dicotyledonous legumes: *Sesbania aculeata*, *Sesbania rostrata*, *Crotalaria juncea*, *Tephrosia purpurea*, *Clitoria ternatea*, *Vigna radiata*, *Vigna unguiculata*, and *Stylosanthes hamata*. These species function as ecological engineers, utilizing robust taproot systems to execute biomechanical biotillage. By exerting high axial pressures, the roots physically fracture compacted subsoil layers, establishing stable biopores that restore hydraulic conductivity and vertical drainage. Additionally, this vegetative cover facilitates subsoil carbon sequestration and hydraulic redistribution, drawing moisture from deeper alluvial strata to sustain the upper rhizosphere. Results indicate that this legume-mediated restoration significantly enhances primary nutrient cycling (N, P, K) and microbial biomass while effectively phytostabilizing heavy metals such as Pb, Cu, and Zn. Implementing this botanical intervention provides a self-sustaining, low-input framework for reclaiming degraded alluvial landscapes and promoting long-term ecological stability in Northern India.

Keywords: Biomechanical Biotillage; Bio-amelioration; Indo-Gangetic Plains; Pedogenic Recovery; Rhizosphere Engineering; Root-Mediated Macroporosity; Subsoil Hardpans.

Introduction

The Global and Regional Context of Land Degradation

Land degradation is recognized as a persistent decline in the biological, chemical, and economic productivity of terrestrial ecosystems. It arises from a complex, often synergistic interplay between natural environmental shifts and unsustainable anthropogenic interventions. On a global scale, assessments by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2018) indicate that land degradation has reached a critical threshold, fundamentally compromising the well-being of billions of people and acting as a primary driver of species extinction. The Food and Agriculture Organization further emphasizes this planetary crisis, estimating that approximately one-third of the world's soils are already degraded (FAO, 2021).

Within this global crisis, the Indo-Gangetic Plains (IGP) of Northern India represent one of the most vital yet challenged agro-ecological frontiers. Stretching from Punjab to West Bengal, the IGP is characterized by deep alluvial deposits that have historically served as the agricultural backbone of South Asia. However, this region is currently facing severe physical, chemical, and biological degradation, transitioning from a dynamic ecosystem into a structurally compromised substrate. The mechanics of this deterioration are driven by destructive processes that systematically fracture the soil's architectural framework. A primary natural driver in Northern India is "sodicity," a condition where the excessive accumulation of exchangeable sodium (Na^+) causes soil clay particles to chemically disperse. This dispersion destroys natural micro-aggregates, leading to surface crusting and severe structural failure (Bronick & Lal, 2005; Toth, 2022).

Research Objectives and Experimental Framework

To achieve a comprehensive understanding of the root-soil interactions and the pedogenic recovery driven by these species, the study is structured around the following specific objectives:

1. **Characterization of Degradation:** To quantify the extent of physical and chemical soil degradation caused by brick kiln activities (T1 vs. T2), specifically documenting the destruction of the humus layer, increases in compaction, and the baseline depletion of the "biological engine."
2. **Evaluation of Biogeochemical Recovery:** To evaluate the trajectory of soil fertility restoration (T2 vs. T3), focusing on the recovery of Soil Organic Carbon (SOC) and the

replenishment of primary macronutrients (Nitrogen, Phosphorus, and Potassium) mediated by legume biomass and biological nitrogen fixation.

3. **Assessment of Biomechanical Structural Repair:** To examine the efficacy of root-induced "biotillage" in alleviating physical constraints, specifically measuring alterations in soil bulk density, porosity, and the restoration of water-holding capacity.
4. **Monitoring Heavy Metal Dynamics:** To assess the accumulation of kiln-derived heavy metals specifically lead (Pb), copper (Cu), and zinc (Zn) in degraded horizons, and to evaluate if the established vegetative cover stabilizes or alters the bioavailability of these potentially toxic elements.
5. **Rejuvenation of Soil Biological Activity:** To study the role of the selected dicot species in restoring subterranean biodiversity, quantified through changes in Microbial Biomass Carbon (MBC) and the reactivation of essential soil enzymatic processes.
6. **Analysis of Seasonal Dynamics:** To analyze these physical, chemical, and biological properties across varying seasonal conditions (pre-monsoon, monsoon, and post-monsoon), recognizing that moisture availability and temperature drastically dictate the pace of natural pedogenic recovery in subtropical environments.

Effectively, by bridging the gap between root-mediated physiological mechanisms and field-scale ecological recovery, this research seeks to demonstrate that transitioning from passive chemical remedies to active, multipurpose botanical strategies offers a practical, low-input, and self-sustaining pathway for restoring the most structurally compromised landscapes of the Indo-Gangetic Plains.

Materials and Methods

To comprehensively evaluate the transition of degraded alluvial soils from a state of structural collapse to one of pedogenic recovery, this research employed a dual-phase methodological framework. The first phase consisted of a systematic literature synthesis to identify the most effective biological agents for subterranean restructuring. The second phase involved a rigorously designed, multi-seasonal field experiment to quantify the biomechanical and biogeochemical impacts of these agents.

Methodological Framework for Systematic Synthesis

Prior to the establishment of the field trials, a systematic review was conducted to inform the selection of plant species and the conceptual framework for biological reclamation. This review was structured to ensure transparency, reproducibility, and scientific rigor, aligning strictly with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines.

Study Area: Agro-Ecological and Pedological Profile

The field experiment was conducted in Bhatpar Rani, located within the Deoria district of eastern Uttar Pradesh, India. This region was deliberately selected as it represents widespread ecological degradation occurring across the eastern stretch of the Indo-Gangetic Plains.

Experimental Design and Field Layout

To accurately isolate and quantify the impact of biological restoration, the field experiment was laid out in a Randomized Complete Block Design (RCBD) with three spatially and temporally distinct comparative land states. These states were selected to represent the full trajectory of land degradation and subsequent botanical recovery:

- **T1: Pre-degradation (Undisturbed Agricultural Soil):** These plots served as the ecological and agronomic baseline. They were situated on adjacent, highly productive agricultural lands that had never been subjected to brick kiln excavation. These soils retained their natural A-horizon (topsoil), possessing an intact humus layer, standard bulk density, and uncompromised microbial communities.
- **T2: Degraded State (Active Brick Kiln Site):** These plots represented the nadir of land degradation. They were established on abandoned brick kiln sites where the upper 20 to 30 centimeters of fertile topsoil had been mechanically excavated for brick molding. These plots were completely devoid of vegetative cover, severely depleted of soil organic matter, heavily compacted by heavy machinery, and exposed directly to surface sealing and solar baking.
- **T3: Biologically Reclaimed State (Post-Intervention):** These were formerly degraded T2 sites that had been subjected to the strategic biological intervention framework developed during the systematic review. In these plots, the consortium of multipurpose dicot legumes was introduced and managed specifically to drive biomechanical biotillage and pedogenic recovery.

Each land state (T1, T2, T3) was replicated across five distinct experimental blocks to account for spatial micro-variability in the alluvial plain. Individual plot sizes were standardized at 10 m × 10 m, with 2-meter buffer zones maintained between plots to prevent cross-contamination of root systems and lateral water movement.

Results

The empirical findings of this comprehensive, multi-season field and analytical investigation delineate the severe multidimensional degradation inflicted upon the alluvial landscapes of Eastern Uttar Pradesh by continuous, unregulated brick kiln excavation. Concurrently, the

extensive data substantiates the systematic biophysical and biogeochemical recovery catalyzed by the strategic introduction of a multipurpose dicotyledonous legume consortium. To accurately capture the full, complex trajectory of this ecological transition, the analytical data was rigorously stratified across three strictly defined comparative land states. These states include the undisturbed agricultural baseline representing optimal historical pedological conditions (T1), the actively degraded and subsequently abandoned brick kiln sites representing the nadir of ecological and structural collapse (T2), and the biologically reclaimed soils evaluated twenty-four months post-intervention (T3). The quantitative results conclusively confirm that while mechanical topsoil excavation systematically fractures the pedospheric architecture, targeted biological amelioration utilizing functionally diverse, deep-rooting native species successfully reverses these notable structural, chemical, and biological deficits.

Physical Compaction, Textural Collapse, and Hydrological Failure

In the undisturbed T1 plots, representative of the fertile, calcareous soils of the Deoria, Gorakhpur, and greater Indo-Gangetic regions, the soil exhibited a balanced loam to silty-loam texture highly conducive to optimal root proliferation, aeration, and general agronomic productivity. However, in the T2 sites, the mechanical stripping of the topsoil, compounded by the continuous compressive shear forces of heavy transport machinery and localized thermal baking from the kiln firing zones, resulted in severe physical densification. While typical agricultural bulk density (BD) in the T1 soils maintained a healthy, friable state at $1.32 \pm 0.05 \text{ g/cm}^3$, the T2 exposed horizons demonstrated extreme subsoil compaction. In these degraded zones, localized bulk densities surged to a highly restrictive $1.69 \pm 0.07 \text{ g/cm}^3$. This severe compaction essentially eliminated native macroporosity, replacing a naturally structured soil matrix with an impermeable, monolithic calcic hardpan that physically restricts root elongation. Furthermore, mechanical sieve analyses indicated a drastic, highly detrimental shift in the particle size distribution of the degraded soils. In the actively degraded kiln zones, the proportional sand fraction skyrocketed, reaching an alarming $87.40 \pm 3.5\%$ in the most severely impacted clusters. Concurrently, the vital silt and clay fractions—which are strictly essential for moisture retention, stable aggregate formation, and maintaining a viable cation exchange capacity (CEC) experienced a proportional collapse. This increase in sand content, caused by the removal of clay during excavation and wind erosion of the exposed surface, made the T2 soils more prone to further weathering and structural degradation.

This architectural collapse directly precipitated a severe hydrological crisis within the soil profile. Moisture content, evaluated via gravimetric analysis, consistently maintained an

optimal field capacity of approximately $55.40 \pm 2.6\%$ in the T1 baseline soils during standard measurement intervals. In stark contrast, moisture levels plummeted drastically to a critically low $17.80 \pm 1.5\%$ in the T2 kiln vicinities. The intrinsic capacity of the soil to retain water against gravitational pull and high evaporative demand was effectively destroyed, rendering the degraded landscape highly susceptible to severe seasonal desiccation and making traditional crop survival impossible without massive, unsustainable artificial irrigation.

Chemical Exhaustion and Extreme Sodic Stress

The chemical degradation observed in the T2 state was equally very high, driven fundamentally by the total loss of organic buffering agents. The core "biological engine" of the soil—the Soil Organic Carbon (SOC) pool—was virtually eradicated by the excavation process. In the undisturbed T1 baseline, SOC levels averaged a robust $1.48 \pm 0.14\%$, reflecting decades of sustainable organic matter accumulation and humification under traditional agricultural practices. Conversely, in the T2 excavated layers, SOC declined to $0.26 \pm 0.04\%$. This near-total loss of labile and recalcitrant carbon eliminated the primary energy source required to fuel subterranean microbial metabolism, effectively rendering the soil chemically exhausted and biologically dormant.

Simultaneously, the soil reaction (pH) exhibited a severe shift toward high alkalinity, a characteristic hallmark of heavily degraded sodic terrains in Eastern Uttar Pradesh and analogous to the "Usar" soils of the region (Yadav & Singh, 2021). While the T1 baseline maintained a slightly alkaline to near-neutral pH of 7.35 ± 0.12 , the T2 excavated layers recorded sharp pH surges, averaging 8.85 ± 0.25 . In localized, highly stressed patches immediately adjacent to the firing zones, the chemical parameters reached highly toxic physiological thresholds. In these specific T2 micro-environments, the pH spiked to an extreme 9.75, accompanied by an Electrical Conductivity (EC) of 4.88 dS/m.

The Exchangeable Sodium (Na^+) concentration in these severely degraded horizons peaked at an extreme 54.20 Meq/L. This accumulation of monovalent sodium ions triggered severe clay dispersion on a microscopic level. The dispersive action of sodium forces clay platelets apart, destroying any remaining natural micro-aggregates and leading to the formation of dense, impermeable surface crusts. These sodic crusts completely halted vertical water infiltration, triggering surface runoff during precipitation events and cementing the subsoil into a concrete-like state during dry, pre-monsoon periods.

Biomechanical Biotillage and the Reduction of Bulk Density

The primary mechanism of physical recovery in the T3 plots was biomechanical biotillage. Unlike mechanical subsoiling, which often results in temporary and structurally unstable

fracturing, the robust tap-root systems of the leguminous consortium functioned as continuous biological subsoiling agents. Over the reclamation cycle, root-induced axial and radial pressures penetrated and fractured the compacted calcic hardpans.

Over the two-year reclamation period, continuous root penetration gradually fractured the compacted hardpan. Quantitative undisturbed core sampling revealed that the bulk density in the T3 plots, which had previously reached a restrictive 1.69 g/cm^3 in the T2 state, demonstrated a statistically significant reduction ($p < 0.01$), stabilizing at a highly functional $1.40 \pm 0.05 \text{ g/cm}^3$. This reduction in density indicates a loosening of the soil structure, making it more suitable for root growth and agricultural use.

Seasonal Variations and Climatic Resilience

The properties of degraded and recovering soils in the Indo-Gangetic Plains change with the seasonal monsoon cycle.

Pre-Monsoon (Dry Season) Vulnerability vs. Hydraulic Redistribution

The pre-monsoon summer phase (April through June) subjects the regional alluvium to elevated thermal stress, with surface temperatures frequently exceeding 45°C . In the unshaded T2 sites, prolonged desiccation reduced surface moisture to below the permanent wilting point ($<12\%$). This high evaporative demand enhanced capillary rise, drawing saline groundwater upward and depositing sodium salts on the surface, thereby increasing sodicity.

Conversely, the T3 biologically reclaimed plots exhibited profound drought resilience through the physiological mechanism of "hydraulic redistribution." The deep-penetrating, lignified tap-roots of perennial species accessed stable moisture reserves located deep within the unexcavated alluvial strata. During nocturnal periods, when transpirational demand ceased, these deep roots passively pulled water upward and released it into the critically dry, shallow topsoil. This continuous, biological nocturnal irrigation kept the T3 upper rhizosphere hydrated, preventing the devastating secondary salinization seen in T2, and maintaining the viability of the microbial biomass throughout the harshest summer months.

Monsoon Dynamics and Heavy Metal Buffering

The onset of the high-intensity monsoon season (July through September) introduced a influx of precipitation. In the highly compacted T2 zones, the intense rainfall immediately resulted in surface sealing, generating destructive surface runoff that scoured the exposed landscape. Furthermore, post-monsoon data indicated a spike in heavy metal accumulation in T2 soils as rains "scrubbed" particulate matter from the kiln infrastructure.

In stark contrast, the T3 plots utilized the monsoon rains as a mechanism for purification. The dense above-ground canopy of the legume consortium physically absorbed the kinetic energy

of the raindrops, totally preventing splash erosion. The water then funneled down the extensive network of root-induced biopores, penetrating deeply into the profile. This vertical infiltration effectively flushed the displaced sodium ions (Na⁺) safely out of the active root zone, while the phytostabilized (chelated) heavy metals remained safely immobilized in the organic matrix, preventing a toxic spike in localized metal mobility

Comparative Data Tables

Table 1: Comparative Soil Physical and Hydrological Properties across Land States

| Soil Parameter | T1 (Undisturbed Baseline) | T2 (Degraded Kiln Site) | T3 (Reclaimed State 24 Months) |
|-----------------------------------|---------------------------|-------------------------|--------------------------------|
| Bulk Density (g/cm ³) | 1.32 ± 0.05 | 1.69 ± 0.07 | 1.40 ± 0.05 |
| Total Porosity (%) | 49.6 ± 2.1 | 35.8 ± 3.2 | 47.2 ± 2.4 |
| Water-Holding Capacity (%) | 55.40 ± 2.6 | 17.80 ± 1.5 | 45.60 ± 2.8 |
| Sand Fraction (%) | 61.20 ± 3.4 | 87.40 ± 3.5 | 71.80 ± 3.6 |
| Silt & Clay Fraction (%) | 38.80 ± 3.4 | 12.60 ± 3.5 | 28.20 ± 3.6 |

Table 2: Comparative Soil Chemical and Biological Properties across Land States

| Soil Parameter | T1 (Undisturbed Baseline) | T2 (Degraded Kiln Site) | T3 (Reclaimed State - 24 Months) |
|------------------------------|---------------------------|--------------------------|----------------------------------|
| pH (1:2.5 suspension) | 7.35 ± 0.12 | 8.85 ± 0.25 (up to 9.75) | 7.58 ± 0.16 |
| Soil Organic Carbon (%) | 1.48 ± 0.14 | 0.26 ± 0.04 | 1.02 ± 0.08 |
| Exchangeable Sodium (Meq/L) | 18.5 ± 2.2 | 54.2 ± 4.5 | 21.8 ± 2.6 |
| Available Nitrogen (kg/ha) | 242 ± 16 | 138 ± 8 | 224 ± 15 |
| Available Phosphorus (kg/ha) | 21.4 ± 1.8 | 9.8 ± 1.2 | 18.2 ± 1.5 |
| Microbial Biomass (µg/g) | 315.2 ± 21.4 | 46.2 ± 6.8 | 282.6 ± 17.4 |

| Soil Parameter | T1 (Undisturbed Baseline) | T2 (Degraded Kiln Site) | T3 (Reclaimed State - 24 Months) |
|------------------------------|---------------------------|-------------------------|----------------------------------|
| Dehydrogenase (µg TPF/g/24h) | 64.2 ± 5.6 | 14.8 ± 1.6 | 56.4 ± 4.8 |

Table 3: Comparative Heavy Metal Concentrations (Total Mass vs. Bioavailability trends)

| Heavy Metal Parameter | T1 (Background Baseline) | T2 (Exposed Total Concentration) | T3 (Bioavailability Reduction Status) |
|-----------------------|--------------------------|----------------------------------|---------------------------------------|
| Iron (Fe) - mg/kg | 12,400 ± 500 | 18,450 ± 980 | High Chelation / Stabilized |
| Copper (Cu) - mg/kg | 38.5 ± 4.2 | 144.2 ± 9.6 | 38% Reduction in Bioavailability |
| Zinc (Zn) - mg/kg | 45.2 ± 5.1 | 126.5 ± 8.4 | 29% Reduction in Bioavailability |
| Chromium (Cr) - mg/kg | 22.4 ± 3.5 | 79.8 ± 6.5 | Stabilized via pH modification |
| Lead (Pb) - mg/kg | 14.8 ± 2.6 | 67.4 ± 5.8 | 31% Reduction in Bioavailability |
| Arsenic (As) - ppm | 1.2 ± 0.4 | 5.4 ± 0.7 | Highly Immobilized in Organic Matrix |

Discussion

The findings of this study demonstrate a notable functional divergence between the anthropogenically degraded brick kiln sites (T2) and the biologically reclaimed agricultural soils (T3). The degradation documented in the T2 state is not merely a superficial loss of fertility; it is a systemic collapse of the soil's physical architecture, biogeochemical cycling, and hydrological buffering capacity. The removal of the upper 20–30 cm of the pedosphere effectively obliterates the complex, self-sustaining ecosystem that characterizes the undisturbed alluvial baseline (T1). The successful transition to the T3 state confirms that ecological recovery in the Indo-Gangetic Plains cannot be achieved through isolated chemical amendments, but rather requires a holistic, nature-based intervention. The deployment of the eight-species dicotyledonous legume consortium acts as a multi-trophic catalyst, initiating a

series of biophysical and biochemical feedback loops that restore the soil matrix. The following subsections critically interpret the precise mechanisms driving this pedogenic rejuvenation.

Conclusion and Broader Implications

The extensive degradation of the Indo-Gangetic Plains, driven by the rapid expansion of the brick manufacturing industry, represents one of the most severe ecological and agrarian crises in Northern India. The deliberate mechanical excavation of the upper 20 to 30 centimeters of the pedosphere does not merely reduce agricultural yield; it severely disrupts the terrestrial ecosystem. By stripping away the humic A-horizon, the essential "biological system" of the soil biological activity is reduced, leaving behind a structurally collapsed, chemically toxic, and biologically sterile subsoil. The findings of this research provide a definitive, data-driven framework for reversing this devastation. Moving beyond the myopic scope of traditional agronomic repair, this study conclusively demonstrates that the reclamation of these severely compromised alluvial landscapes requires a paradigm shift a transition away from passive, isolated chemical amendments toward a biological restoration approach.

The Fallacy of Passive Chemical Amendments

To understand why the plant-based approach is more effective, it is useful to examine the limitations of conventional chemical treatments. For decades, the standard institutional response to sodic, compacted, and degraded wastelands has been the heavy application of mineral gypsum (calcium sulfate) coupled with intensive mechanical tillage. While the theoretical chemistry of gypsum application where introduced calcium displaces toxic, dispersive sodium from the soil cation exchange complex is fundamentally sound, its field-scale application on excavated brick-kiln sites is inherently flawed.

Chemical amendments affect only the surface soil chemistry. Gypsum can temporarily improve the ionic balance in the top few centimeters of a degraded kiln site, but it does not improve soil structure or biological activity. It cannot physically penetrate the dense, calcic *kankar* hardpans that form in the exposed subsoils of the Bhatpar Rani and Gorakhpur regions (Parihar et al., 2013). Because the underlying physical architecture remains heavily compacted and devoid of macroporosity, the required vertical leaching of the displaced sodium cannot occur. Consequently, the soil becomes locked in a "re-salinization trap." During the intense, prolonged dry seasons characteristic of the subtropical climate, the unabated capillary rise simply draws the leached salts and localized heavy metals back to the surface.

Moreover, chemical treatments do not add organic carbon to the soil or restore the microbial communities needed for nutrient cycling. When a chemical amendment washes away or its localized reaction reaches equilibrium, the soil remains entirely dependent on further artificial,

external inputs. This creates a reliance on continuous chemical inputs rather than restoring self-sustaining edaphic functions. The terrestrial ecosystem never achieves self-sufficiency; it merely exists on life support, remaining highly vulnerable to the kinetic shocks of monsoon flooding and the thermal stress of summer droughts.

References

1. Bardgett, R. D., & van der Putten, W. H. (2014). Belowground biodiversity and ecosystem functioning. *Nature*, 515(7528), 505–511. <https://doi.org/10.1038/nature13855>
2. Bronick, C. J., & Lal, R. (2005). Soil structure and management: A review. *Geoderma*, 124(1-2), 3–22. <https://doi.org/10.1016/j.geoderma.2004.03.005>
3. Chen, G., & Weil, R. R. (2009). Root growth and yield of maize as affected by soil compaction and cover crops. *Soil and Tillage Research*, 103(1), 116–124.
4. Chopra, C. L., & Kanwar, J. S. (1991). *Analytical agricultural chemistry*. Kalyani Publication, New Delhi.
5. Dey, H. S., Tayung, K., & Bastia, A. K. (2010). Occurrence of nitrogen-fixing cyanobacteria in local rice fields of Orissa. *Environment*, 55, 207–212.
6. Food and Agriculture Organization of the United Nations (FAO). (2021). *State of knowledge of soil biodiversity: Status, challenges and potentialities*. FAO.
7. Kirrolia, A., Bishnoi, N. R., & Singh, R. (2012). Effect of shaking, incubation temperature, salinity and media composition on growth traits of green algae *Chlorococcum* sp. *Journal of Algal Biomass Utilization*, 3(1), 46–53.
8. Koz, B., Cevik, U., & Akbulut, S. (2012). Heavy metal analysis around Murgul (Artvin) copper mining area of Turkey using moss and soil. *Ecological Indicators*, 20, 17–23.
9. Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, 304(5677), 1623–1627.
10. Li, P., Lin, C., Cheng, H., Duan, X., & Lei, K. (2015). Contamination and health risks of soil heavy metals around a lead/zinc smelter in southwestern China. *Ecotoxicology and Environmental Safety*, 113, 391–399.
11. Nusrat, A., & Mahadev, P. D. (1991). Environmental impact of brick loam quarrying on agricultural soil. *The Indian Geographical Journal*, 6, 83–88.
12. Pandhal, J., Snijders, A., Wright, P., & Biggs, C. A. (2008). A cross-species quantitative proteomic study of salt adaptation in a halotolerant environmental isolate using ¹⁵N metabolic labeling. *Proteomics*, 8(11), 2266–2284.

13. Parihar, A. K. S., Dixit, V., & Kumar, A. (2013). Physico-chemical characteristics of calcareous soils in district Deoria and Gorakhpur of Eastern Uttar Pradesh. *International Journal of Agricultural Science and Technology*, 2(1), 1–8.
14. Prieto, I., Armas, C., & Pugnaire, F. I. (2012). Water release through plant roots: new insights into its consequences at the plant and ecosystem level. *New Phytologist*, 193(4), 830–841.
15. Rajonee, A. A., & Uddin, M. J. (2018). Changes in soil properties with distance in brick kiln areas around Barisal. *Open Journal of Soil Science*, 8(3), 118–128. <https://doi.org/10.4236/ojss.2018.83009>
16. Ravankhah, N., Mirzaei, R., & Masoum, S. (2016). Determination of heavy metals in surface soils around the brick kilns in an arid region. *Journal of Geochemical Exploration*, 176, 1–27.
17. Saha, M. K., Sarkar, R. R., Ahmed, S. J., Sheikh, A. H., & Mostafa, M. G. (2021). Impacts of brick kiln emission on agricultural soil around brick kiln areas. *Nepalese Journal of Environmental Science*, 9(1), 01–10. <https://doi.org/10.3126/njes.v9i1.34918>
18. Sharma, R., & Sarita. (2025). Evaluating heavy metal pollution in soil near brick kilns: Seasonal trends and pollution indices in Haryana, India. *Oriental Journal of Chemistry*, 41(1), 209–216. <http://dx.doi.org/10.13005/ojc/410125>
19. Singh, Y. P., Gautam, K., Nayak, A. K., et al. (2025). Assessing the influence of changes in land use-land cover on soil properties of degraded sodic lands in Indo-Gangetic plains. *Scientific Reports*, 15(1), 3094. <https://doi.org/10.1038/s41598-025-30949-8>
20. Six, J., Bossuyt, H., Degryze, S., & Denef, K. (2004). A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research*, 79(1), 7–31. <https://doi.org/10.1016/j.still.2004.03.008>
21. Srivastava, R. K., & Yetgin, A. (2024). An overall review on influence of root architecture on soil carbon sequestration potential. *Theoretical and Experimental Plant Physiology*, 36, 165–178. <https://doi.org/10.1007/s40626-024-00323-6>
22. Toth, T. (2022). Review of sodic soil reclamation with a snapshot of current research activity. *Agrochemistry and Soil Science*, 71(1), 163-181.
23. Wahsha, M., Bini, C., Fontana, S., Wahsha, A., & Zilioli, D. (2012). Toxicity assessment of contaminated soils from a mining area in Northeast Italy by using lipid peroxidation assay. *Journal of Geochemical Exploration*, 113, 112–117.

24. Wu, S., Zhou, S., & Li, X. (2011). Determining the anthropogenic contribution of heavy metal accumulations around a typical industrial town: Xushe, China. *Journal of Geochemical Exploration*, 110, 92–97.
25. Yadav, V. K., & Singh, D. V. (2021). The soil properties and cyanobacterial diversity of "Usar" soils. *International Journal of Scientific and Research Publications*, 11(8), 177–183. <http://dx.doi.org/10.29322/IJSRP.11.08.2021.p11624>
26. Yadav, V. K., & Singh, D. V. (2022). Cyanobacteria as a natural biotechnological tool for bio-reclamation of "Usar" soils. *International Journal of Scientific Research in Biological Sciences*, 9(5), 57–61.
27. Keen, B. A., & Raczkowski, H. (1921). The relation between the clay content and certain physical properties of a soil. *The Journal of Agricultural Science*, 11(4), 441-449.
28. Walkley, A., & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science*, 37(1), 29-38.
29. Subbiah, B. V., & Asija, G. L. (1956). A rapid procedure for the estimation of available nitrogen in soils. *Current Science*, 25(8), 259-260.
30. Olsen, S. R., Cole, C. V., Watanabe, F. S., & Dean, L. A. (1954). Estimation of available phosphorus in soils by extraction with sodium bicarbonate. *USDA Circular* 939.