Acidification of Soils: Mechanisms, Consequences, and Mitigation Technologies

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ABSTRACT

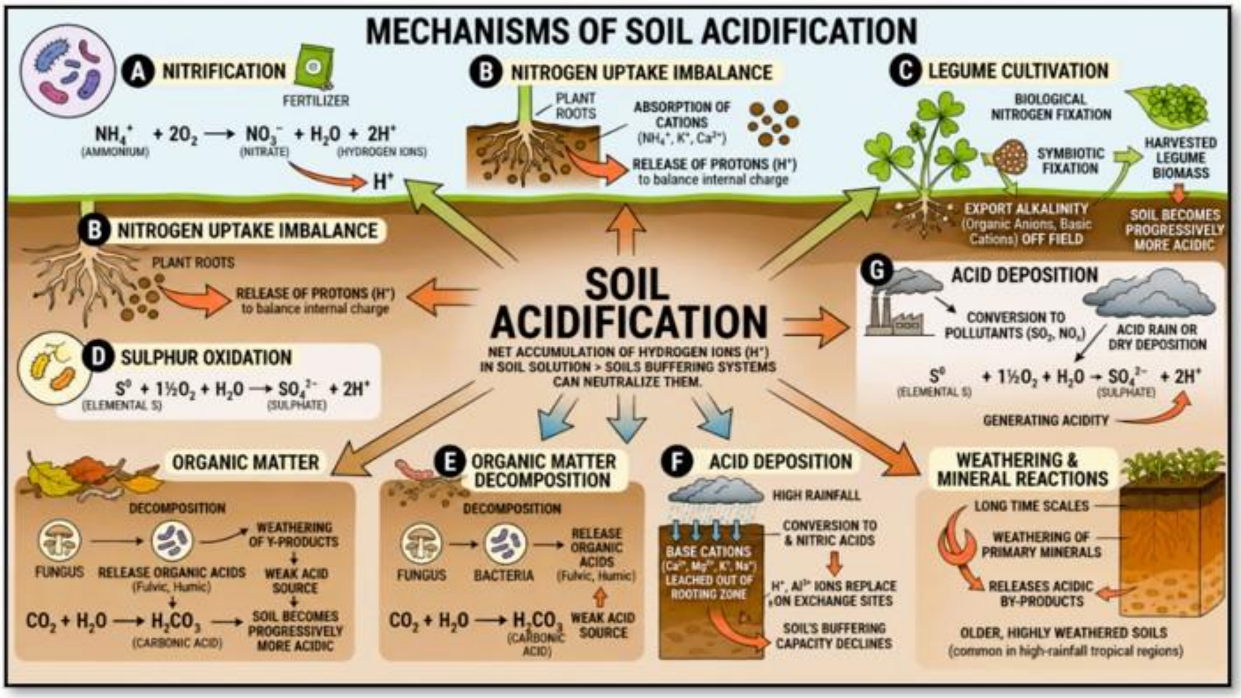
Soil acidification is a pervasive and progressive form of land degradation that constrains agricultural productivity worldwide. It results from natural pedogenic processes together with anthropogenic drivers such as nitrogen fertilization, legume cultivation, and acid deposition. This article synthesizes current understanding of the chemical mechanisms of soil acidification, its consequences for crop production and ecosystem health, and the amendment technologies now supported by global and Indian evidence for its mitigation.

INTRODUCTION:

Soil pH governs nutrient availability, microbial activity, and root health, making its decline through acidification one of the most consequential forms of soil degradation. Globally, nearly half of the world's arable soils have become acidic (pH ≤ 6.5), and the area continues to expand under intensive nitrogen fertilization (Zhang *et al.*, 2023). A landmark nationwide assessment in China documented a significant, fertilizer-driven decline in cropland pH over just two decades (Guo *et al.*, 2010), while forest soils in North America have shown comparable acidification and base-cation depletion linked to acid deposition (Fenn *et al.*, 2006). In India, acid soils are recognized as a major degradation problem, particularly across the humid North-Eastern, Himalayan, and southwestern region (ICAR and NAAS, 2010). This article outlines the mechanisms, consequences, and mitigation technologies relevant to this widespread problem.

Mechanisms of soil acidification

Acidification occurs when hydrogen ion (H^+) inputs to the soil exceed its buffering capacity. The dominant driver in cultivated soils is **nitrification**, the microbial oxidation of ammonium fertilizers to nitrate, which releases H^+ directly into solution and has been identified as the principal cause of large-scale cropland acidification (Guo *et al.*, 2010; Goulding, 2016). A closely related process is **cation–anion uptake imbalance**: when plant roots absorb more cations than anions, they exude protons to maintain charge balance, and this mechanism can dominate acidification below the topsoil (Hettithanthri *et al.*, 2026). **Legume cultivation** contributes similarly, as biological nitrogen fixation involves proton release that is compounded when alkalinity is exported through harvested biomass (Goulding, 2016). **Base-cation leaching** of Ca^{2+}, Mg^{2+}, and K^+ under high rainfall further erodes soil buffering capacity, a process well documented in both cropland and forest systems (Guo *et al.*, 2010; Fenn *et al.*, 2006). Additional contributors include **sulphur oxidation**, **organic matter decomposition** (releasing organic acids and carbonic acid), **acid deposition** of atmospheric SO_2 and NO_x, and long-term **mineral weathering**, all of which alter the soil's underlying buffering chemistry over time.



Different Mechanisms involved in Soil Acidification

Consequences of Soil Acidification

As pH declines, aluminium and manganese are solubilized into forms toxic to root growth, while the availability of phosphorus, calcium, and magnesium falls sharply, together restricting crop yield and threatening food security in intensively cultivated regions (Zhang *et al.*, 2023; Guo *et al.*, 2010). In India's North-Eastern Hill region, up to 91% of soils are acidic and nearly two-thirds show strong acidity (pH < 5.5), where aluminium toxicity is the principal constraint on productivity of rice and other staple crops

(Majumdar *et al*., 2022; Das and Avasthe, 2021). Acidification also disrupts microbial communities and nutrient cycling, and, at depth, subsoil acidity is especially difficult to correct because it commonly escapes detection until severe, with surface liming often failing to reach it (Hettithanthri *et al*., 2026).

Mitigation Technologies

- **Liming:** Calcitic and dolomitic lime remains the most established amendment, with a recent global meta-analysis confirming an overall positive effect on soil pH across lime materials and soil types (Makaza *et al*., 2026; Goulding, 2016). In India, ICAR has developed cost-effective liming technologies tailored to acid-soil regions (Das and Avasthe, 2021).
- **Organic and inorganic amendments:** A worldwide meta-analysis of 832 observations found that lime, biochar, industrial by-products, manure, and straw all improve soil pH and crop yield, though their effectiveness depends on initial soil properties (Zhang *et al*., 2023).
- **Biochar application:** Biochar neutralizes acidity through a liming effect, cation exchange, and complexation of aluminium by oxygen-containing surface functional groups, while also enhancing the soil's long-term acid-buffering capacity (Dai *et al*., 2017). A global meta-analysis of 232 studies confirmed its lime-enhancing potential across diverse climates and farming systems (Zhang *et al*., 2025).
- **Region-specific management in India:** Practical, cost-effective packages combining lime, acid-tolerant crop varieties, balanced fertilizer use, and organic inputs are recommended for the North-Eastern Hill region and other acid-soil tracts (Majumdar *et al*., 2022), building on the extent and spatial mapping of degraded acid soils.

CONCLUSION

Soil acidification arises from an interplay of nitrification, cation-uptake imbalance, legume cultivation, base-cation leaching, and acid deposition, and its consequences for nutrient availability, aluminium toxicity, and crop productivity are well documented across global and Indian contexts. Encouragingly, an expanding evidence base on liming, biochar, and integrated regional management strategies now offers practical, cost-effective pathways to restore acid-affected soils and safeguard long-term agricultural sustainability.

REFERENCES

Dai, Z., Zhang, X., Tang, C., Muhammad, N., Wu, J., Brookes, P. C., and Xu, J. (2017). Potential role of biochars in decreasing soil acidification—A critical review. Science of the Total Environment, 581–582, 601–611.

Das, S. K., & Avasthe, R. (2021). Soil acidity management in NEH region of India for doubling farmers income. Indian Farming, 71(2).

Fenn, M. E., Huntington, T. G., McLaughlin, S. B., Eagar, C., Gomez, A., and Cook, R. B. (2006). Status of soil acidification in North America. U.S. Geological Survey.

Goulding, K. W. T. (2016). Soil acidification and the importance of liming agricultural soils with particular reference to the United Kingdom. Soil Use and Management, 32(3), 390–399.

Guo, J. H., Liu, X. J., Zhang, Y., Shen, J. L., Han, W. X., Zhang, W. F., Christie, P., Goulding, K. W. T., Vitousek, P. M., and Zhang, F. S. (2010). Significant acidification in major Chinese croplands. Science, 327(5968), 1008–1010.

Hettithanthri, O., O'Connor, J., Solaiman, Z., and Bolan, N. (2026). Unravelling subsoil acidification: Mechanisms, consequences and remediation. Soil Use and Management. Advance online publication.

Indian Council of Agricultural Research (ICAR) and National Academy of Agricultural Sciences (NAAS). (2010). Degraded and wastelands of India: Status and spatial distribution.

Majumdar, S., Wanniang, S. K., and Behera, U. (2022). Acid soil management in north eastern hill region of India. Indian Farming, 72(3).

Makaza, W., Khiari, L., and El Achaby, M. (2026). The meta-analysis study on the effects of the quality of lime materials on the soil physicochemical properties and crop yields in acid soils. Frontiers in Soil Science, 6, Article 1725559.

Zhang, S., Zhu, Q., de Vries, W., Ros, G. H., Chen, X., Muneer, M. A., Zhang, F., and Wu, L. (2023). Effects of soil amendments on soil acidity and crop yields in acidic soils: A world-wide meta-analysis. Journal of Environmental Management, 345, Article 118531.

Zhang, N., Xing, J., Wei, L., Liu, C., Zhao, W., Liu, Z., Wang, Y., Liu, E., Ren, X., Jia, Z., Wei, T., Siddique, K. H. M., and Zhang, P. (2025). The potential of biochar to mitigate soil acidification: A global meta-analysis. Biochar, 7, Article 49.