IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Impact Factor 8.066 ⁜ Peer-reviewed & Refereed journal ⁜ Vol. 13, Issue 7, July 2026

DOI: 10.17148/IARJSET.2026.13710

Designing Multi-Layered Waste-Derived Technosols for Long-Term In-Situ Passive Treatment of Acid Mine Drainage

Ashok Prajapat[1], Kratika Verma[2]

Department of Mining Engineering, PAHER University, Udaipur[1]

Department of Basic Sciences & Humanities, GITS Udaipur[2]

Abstract: Acid Mine Drainage (ARD/AMD) remains one of the most severe environmental liabilities in the mining sector, characterized by extreme acidity ($pH < 3$) and toxic heavy metal loads. Active chemical neutralization is economically unsustainable post-mine closure. This review synthesizes recent advances in constructing multi-layered, waste-derived **Technosols**—engineered soils constructed from industrial and municipal byproducts—designed for long-term, passive, in-situ treatment of AMD. We evaluate the synergistic mechanisms of combining alkaline wastes (e.g., steel slag, fly ash, bauxite residue) with organic wastes (e.g., spent mushroom compost, anaerobic digestate) to promote concurrent chemical neutralization, sorption, and biological sulfate reduction. This paper outlines the structural layering dynamics, biogeochemical pathways, and critical engineering bottlenecks governing system longevity, hydraulic conductivity, and substrate passivation.

1. INTRODUCTION: THE PASSIVE TREATMENT CHALLENGE

The generation of Acid Mine Drainage occurs when sulfide minerals, principally iron pyrite (FeS_2), are exposed to atmospheric oxygen and water during mining excavations. The self-propagating oxidation cycle is expressed by the fundamental geochemical pathway:

$$FeS_2(s) + \frac{7}{2}O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$$

As the pH plummets, secondary hydrolysis of ferric iron generates further acidity, mobilizing highly toxic elements such as Al, Mn, Cu, Zn, and As.

Traditional passive remediation methods, such as Anoxic Limestone Drains (ALDs) and conventional constructed wetlands, frequently fail over long periods. Limestones suffer from **passivation (or "armouring")**, where ferric iron and aluminum oxide precipitates coat the reactive surfaces, rapidly sealing off the neutralizing mineral from further dissolution.

To overcome this, environmental engineers are shifting toward **Technosols** (engineered soils). By building a multi-layered matrix using diverse industrial and organic waste streams, we can distribute the geochemical reactions sequentially across different zones, neutralizing the acid while preventing any single layer from getting clogged or armored.

2. STRUCTURAL LAYERING STRATEGY OF AN ADVANCED TECHNOSOL

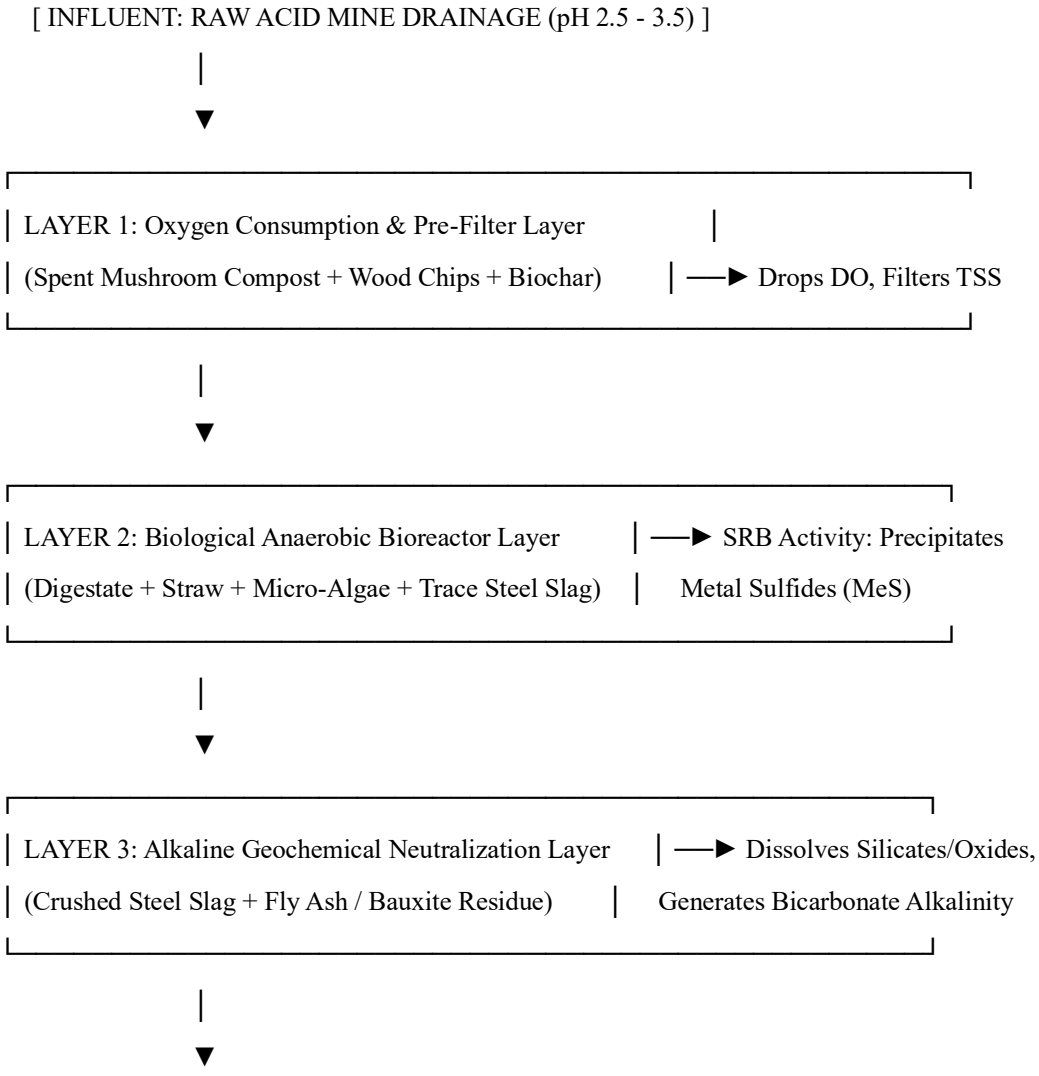
A high-efficiency Technosol operates as a sequential, gravity-fed, vertical bioreactor. Rather than mixing all wastes homogeneously, the materials are stratified into functional operational zones to isolate conflicting geochemical environments.

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Impact Factor 8.066 ⁜ Peer-reviewed & Refereed journal ⁜ Vol. 13, Issue 7, July 2026

DOI: 10.17148/IARJSET.2026.13710



2.1. Layer 1: The Oxic Pre-Filter and Carbon Depletion Zone

The uppermost layer consists of highly porous organic matrices, such as wood chips mixed with coarse biochar and municipal green waste.

- **Mechanisms:** This layer filters out suspended total solids (TSS) and rapidly consumes dissolved oxygen (DO) via aerobic microbial respiration. Stripping the oxygen is essential to protect the lower anaerobic layers from oxidization.

2.2. Layer 2: The Biological Sulfate-Reducing Bioreactor

An anoxic environment rich in complex organic substrates (e.g., spent mushroom compost, paper mill sludge, or anaerobic digestate).

- **Mechanisms:** This layer acts as a habitat for **Sulfate-Reducing Bacteria (SRB)** (such as *Desulfovibrio*). The SRB utilize the organic carbon to reduce dissolved sulfate into hydrogen sulfide (H_2S), capturing heavy metals by precipitating them as highly stable, solid metal sulfides (MeS):

$$SO_4^{2-} + 2CH_2O \xrightarrow{\text{SRB}} H_2S + 2HCO_3^-$$

$$H_2S + Me^{2+} \rightarrow MeS(s) \downarrow + 2H^+$$

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Impact Factor 8.066 ⁜ Peer-reviewed & Refereed journal ⁜ Vol. 13, Issue 7, July 2026

DOI: 10.17148/IARJSET.2026.13710

2.3. Layer 3: The Alkaline Neutralization and Secondary Sorption Layer

The final basal layer utilizes alkaline industrial sub-products, such as weathered electric arc furnace steel slag, fly ash, or red mud (bauxite residue).

- **Mechanisms:** Because the upper layers have already stripped out the ferric iron (Fe^{3+}) and aluminum (Al^{3+}), this alkaline layer can safely dissolve and release massive bicarbonate alkalinity without facing the risk of mineral surface passivation. The residual heavy metals are completely locked away through surface adsorption and the precipitation of metal hydroxides ($Me(OH)_2$).

3. COMPARATIVE GEOMECHANICAL MATRIX OF WASTE REAGENTS

To achieve a 30-year operational life, the chosen waste matrix must balance hydraulic conductivity with chemical reactivity.

Waste Sub-Product Class	Primary Active Component	Geochemical Role	Engineering Limitations
Steel Slag (EAF / BOF)	Silicates and Oxides (CaO, MgO)	Intense, prolonged pH elevation; hydroxide precipitation.	High initial pH spikes (> 11); requires initial weathering.
Coal Fly Ash	Alumina-silicates, Lime	Fine-particle adsorption; neutralizing agent.	Low hydraulic permeability; risk of leaching trace metalloids (As, Se).
Spent Mushroom Compost	Cellulosic organic matter	Carbon donor for SRB communities; initial biosorption.	High initial nutrient leaching (N, P); structural compaction over time.
Gasification Biochar	Highly porous fixed carbon	Micro-porous structural anchor; heavy metal sorption.	Low density; can float if the system experiences sudden hydraulic surges.

4. CRITICAL ENGINEERING BOTTLENECKS AND LIFESPAN LIMITS

4.1. The Hydraulic Conductivity Dilemma

As organic wastes decompose and fine metal precipitates ($Fe(OH)_3, ZnS$) accumulate inside the void spaces, the system's hydraulic conductivity naturally drops. If it gets too clogged, the AMD water will pool on top or short-circuit through cracks instead of filtering through the layers. Ongoing research is looking at adding structural bulking agents—like coarse recycled brick or volcanic scoria—to maintain open pore spaces without altering the chemistry.

4.2. Substrate Exhaustion and Carbon Quality Dynamics

SRBs require simple, easily degradable organic acids (like lactate or acetate). While raw organic wastes provide a quick burst of these nutrients early on, they eventually run out, leaving behind tough, non-biodegradable lignocellulosic fibers. Designing a mix that combines fast-acting carbon sources with slow-release organic polymers is crucial to maintaining a steady microbial population for decades.

4.3. Secondary Ecotoxicity Risks

Using industrial wastes like fly ash or bauxite residue carries a risk: if the internal chemistry shifts, these materials could leach trace toxins like arsenic, chromium, or selenium into the environment. The design must ensure the internal pH stays tightly regulated to keep these specific trace elements immobilized.

5. CONCLUSION

Multi-layered, waste-derived Technosols present a highly sustainable, circular-economy solution for managing acid mine drainage. By turning industrial liabilities (slag, ash, and organic composts) into functional environmental assets, this approach establishes a self-sustaining biogeochemical system. Stratifying these materials into dedicated functional zones successfully manages the long-standing issue of mineral passivation. Looking ahead, research must focus on building predictive hydro-geochemical models to precisely match the sizing, layer thickness, and site-specific lifespan of these engineered soils against the changing chemistry of deep mine water inflows.

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Impact Factor 8.066 ⁜ Peer-reviewed & Refereed journal ⁜ Vol. 13, Issue 7, July 2026

DOI: 10.17148/IARJSET.2026.13710

REFERENCES

[1]. Genty, T. et al. (2012). Dissolution of calcitic marble and dolomitic rock in high iron concentrated acid mine drainage: Application to anoxic limestone drains. *Environmental Earth Sciences*, 66, 2387–2401.

[2]. Johnson, D. B., & Hallberg, K. B. (2005). Acid mine drainage remediation options: a review. *Science of the Total Environment*, 338(1-2), 3–14.

[3]. Kusin, F. M. (2013). A review of the importance of hydraulic residence time on improved design of mine water treatment systems. *World Applied Sciences Journal*, 26, 1316–1322.

[4]. Muhammad, S. N. et al. (2015). Passive treatment of acid mine drainage using mixed substrates: Batch experiments. *Procedia Environmental Sciences*, 30, 157–161.

[5]. Skousen, J., & Ziemkiewicz, P. (2005). Performance of passive treatment systems on coal mine drainage. *Mine Water and the Environment*, 24(4), 196–203.

[6]. Zipper, C., Skousen, J., & Jage, C. (2018). *Passive Treatment of Acid-Mine Drainage*. Virginia Cooperative Extension, Publication 460-133, Virginia Tech.